Biological synthesis of copper nanoparticles using plants, microorganisms and other natural resources

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Keywords:

Copper
Nanoparticle
Biosynthesis
Biological systems
Microorganism
Plants
Mushrooms
Food product

Article history:

Received 30.11.2025
Received in revised form 24.03.2025
Accepted 30.06.2026

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DOI:
10.24263/2304-974X-2026-15-2-12

Abstract

Introduction. This article summarizes current approaches to the biosynthesis of copper nanoparticles using various biological systems.

Materials and methods. The study materials consisted of scientific publications indexed in international scientometric databases. The methodology was based on the systematization, comparative analysis, and generalization of research findings related to the biosynthesis of copper nanoparticles. Articles published between 2020 and 2025 were used for the preparation of this review.

Results and discussion. It was established that various biological systems (extracts of plants, food products and food waste, algae, mushrooms, microorganisms, and their metabolic products) contain a wide range of biologically active compounds, including polyphenols, proteins, polysaccharides, enzymes, and organic acids, which can simultaneously act as reducing and stabilizing agents during the formation of copper nanoparticles. It was shown that the choice of biological system and biosynthesis parameters, including medium pH, temperature, concentration and chemical nature of the precursor, biosynthesis duration, and component ratio, significantly affect the size, morphology, degree of aggregation, colloidal stability, and properties of the synthesized copper nanoparticles. Particular attention was paid to the mechanisms of copper ion bioreduction, as well as the formation and stabilization of nanoparticles when different biological systems are used for their biosynthesis. The analyzed data indicate that aqueous extracts of plants, food products, and food waste are promising materials for the biosynthesis of copper nanoparticles due to their availability, low cost, and high content of natural reducing compounds. The use of microorganisms (bacteria, fungi, and yeast) for nanoparticle biosynthesis provides better control over the formation of nanostructures with desired sizes and properties. The generalization of current research results confirms the significant potential of biosynthesized copper nanoparticles for the development of functional nanomaterials that can be applied in the food industry, agriculture, and environmental technologies. At the same time, despite significant advances in the biosynthesis of copper nanoparticles, further studies are required to facilitate the transition of these technologies from laboratory-scale investigations to industrial applications.

Conclusions. The results of this review can be used for the further development of effective biotechnological approaches to nanomaterial synthesis in the context of sustainable development.

Introduction

In modern biotechnology and nanoscience, there is a rapidly growing interest in the development of environmentally friendly and cost-effective methods for the synthesis of nanomaterials, particularly nanoparticles. Due to their unique physicochemical properties, including a high surface area-to-volume ratio, quantum confinement effect, enhanced reactivity, and the possibility of surface functionalization, nanoparticles are widely used in various fields (Antonio-Perez et al., 2023; Luque-Jacobo et al., 2023). Particular attention is being paid to copper nanoparticles (CuNPs), which exhibit antimicrobial, antioxidant, catalytic, and photocatalytic properties (Chaerun et al., 2022; Naikoo et al., 2021). Consequently, CuNPs are considered promising materials for applications in the food industry, agriculture, as well as resource-saving and environmentally sustainable technologies (Rautela et al., 2025; Vincent et al., 2022).

Physical methods (inert gas condensation, laser ablation, physical vapor deposition, laser pyrolysis, high-energy ball milling) and chemical methods (chemical vapor synthesis, hydrothermal synthesis, microwave-assisted synthesis, sol-gel method, plasma-assisted chemical vapor deposition, solvothermal synthesis, polyol synthesis, and microemulsion technique) are commonly applied for nanoparticle synthesis (Kumari et al., 2023). However, these methods have several significant limitations, including the use of toxic reagents, high energy consumption, and the generation of hazardous by-products (Chakraborty et al., 2022; Pathak et al., 2024).

In the context of global challenges related to environmental pollution, antimicrobial resistance, and the transition to sustainable technologies, green methods for nanoparticle synthesis are becoming increasingly relevant (Antonio-Perez et al., 2023). The biosynthesis of CuNPs using microorganisms, algae, fungi, plant extracts, and food waste represents a promising direction in modern biotechnology, as it enables the integration of metal ion bioreduction processes with their stabilization through natural biomolecules. Microbial systems play a particularly important role in these processes due to their ability to perform complex metabolic and enzymatic mechanisms of copper ion reduction. This opens up opportunities for integrating nanoparticle biosynthesis with bioremediation, biosorption, and waste valorization processes (Akintelu et al., 2021; Saleem et al., 2025).

Given the substantial number of studies in this field, contemporary scientific data require systematization. At the same time, many review papers focus on summarizing data related to the biosynthesis of CuNPs using specific biological systems or on narrow aspects of the biosynthesis process, which complicates the formation of a comprehensive understanding of the underlying patterns of CuNP biosynthesis. In addition, data on the molecular mechanisms of bioreduction, the role of different classes of biomolecules, and their influence on nanoparticle nucleation, growth, and stabilization remain insufficiently systematized. Another important scientific challenge is the lack of a systematic analysis of the influence of synthesis conditions on the physicochemical characteristics of nanoparticles, including their size, morphology, stability, and functional properties. This significantly limits the possibilities for the controlled synthesis of nanomaterials with tailored characteristics for specific practical applications (Banger et al., 2025; Siddiqi and Husen, 2020).

Thus, there is an urgent need for a comprehensive synthesis of current knowledge on the biosynthesis of copper nanoparticles, taking into account the diversity of biological systems, the mechanisms of CuNP biosynthesis, and the factors determining the properties of biosynthesized nanoparticles, as well as their role in addressing current challenges in applied microbiology and biotechnology.

Materials and methods

The search and analysis of scientific sources were conducted using the international scientometric databases Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar.

Scientific articles published between 2020 and 2025 were used for the preparation of this review, focusing on the biosynthesis of copper nanoparticles using various biological sources, including plants, algae, mushrooms, spices and herbs, food products and food waste, bacteria, fungi, and yeast. Full texts of relevant articles were obtained for further assessment. The selected publications were analyzed according to the following criteria: type of biological material, conditions of nanoparticle biosynthesis, nanoparticle size and morphology, nanoparticle properties, and their potential practical applications. The obtained experimental data were systematized and summarized in order to identify different strategies for the biosynthesis of copper nanoparticles and the prospects for their practical application in food technology and agriculture.

Results and discussion

Plants for the biosynthesis of copper nanoparticles

Leaf extracts

A considerable number of publications in the scientific literature address the use of leaf extracts from various plants for the biosynthesis of CuNPs. The extraction method and solvent selection are among the key factors determining the efficiency of biosynthesis and the properties of CuNPs. Aqueous plant extracts are the most commonly used for the biosynthesis of CuNPs. Typically, the preparation of an aqueous extract involves washing the plant material, drying and grinding it, followed by extraction of the plant biomass in distilled water. Extraction is most often carried out at temperatures of 60–100 °C for 10–60 minutes, followed by filtration of the resulting solution. Aqueous extracts contain a significant amount of hydrophilic compounds capable of effectively reducing copper ions and stabilizing the synthesized nanoparticles (Abdelhai et al., 2024; Al Musayeib et al., 2024; Joshi et al., 2025). Methanolic and ethanolic extracts provide isolation of less polar or specific biologically active compounds. Such solvents provide more efficient extraction of phenolic compounds, flavonoids, and other nonpolar substances (Kimta et al., 2025; Labaran et al., 2024).

Agricultural and cultivated plants represent an accessible and renewable source of biomass for the synthesis of CuNPs with high biological activity. In particular, leaf extract of *Mangifera indica* is used to obtain predominantly spherical nanoparticles with sizes ranging from 30 to 90 nm, which exhibit pronounced antioxidant and antimicrobial properties (Shah et al., 2024). Extracts of *Daucus carota* (both wild and cultivated forms) were employed for the synthesis of crystalline CuNPs with an average size of about 42.6 nm, which demonstrate cytotoxic activity against hepatocellular carcinoma cells (Abbas et al., 2025). Mint leaf extracts, due to the high content of flavonoids and terpenoids, facilitate the biosynthesis of copper oxide nanoparticles (CuONPs) with sizes around 19 nm. These nanoparticles have been shown to be effective against both Gram-positive and Gram-negative bacteria, including *Staphylococcus aureus* and *Escherichia coli* (Baral et al., 2025). Basil extracts (*Ocimum basilicum*, *Ocimum sanctum*) provided formation of nanoparticles with sizes ranging from 13 to 18 nm, with broad potential applications across various fields (Wang et al., 2024; Ullah et al., 2024). An aqueous extract of *Stevia rebaudiana* was applied to synthesize CuNPs with sizes ranging from 51 to 53 nm and moderate colloidal stability (zeta potential of approximately +10.8 mV) (Abdelhai et al., 2024). Leaf extract of *Azadirachta indica* enables the production of spherical CuONPs with sizes around 50 nm. These nanoparticles have been shown to possess antifungal activity against *Colletotrichum gloeosporioides*, a fungus responsible for anthracnose, the main cause of mango crop spoilage (Joshi et al., 2025).

Wild and invasive plants are also of significant interest as raw materials for the biosynthesis of nanomaterials, as their use allows the utilization of biomass that is often considered waste, as well as the control of the spread of undesirable plant species. In particular, invasive species such as *Lantana camara* and *Senna spectabilis* can be used for the production of CuONPs with antifungal properties against *Corynespora cassiicola*. These fungi infect plants, including forest stands (Yadava et al., 2025). An aqueous extract of dandelion leaves (*Taraxacum officinale*) enables the synthesis of CuONPs with sizes of about 26.7 nm with high antibacterial and photocatalytic activity (Kasthuri et al., 2024). Leaf extract of *Jatropha curcas* contains flavonoids, tannins, and alkaloids, which act as reducing and stabilizing agents during the biosynthesis of CuNPs with sizes of 10–12 nm (Ghosh et al., 2020). Desert plants, particularly *Citrullus colocynthis* (Nazir et al., 2023) and *Ephedra alata* (Atri et al., 2023), were applied for the synthesis of nanoparticles with sizes ranging from 15 to 17 nm, which possess high potential in photocatalytic processes, particularly in the removal of organic dyes from water. Using an aqueous extract of *Hyptis suaveolens*, spherical CuNPs with an average size of 7.2 nm have been obtained (Shubhashree et al., 2022). The aqueous leaf extract of *Avicennia marina* contains carbohydrates (D-mannose, D-fructose) and phenolic compounds, which enable the biosynthesis of CuNPs. Depending on concentration, these nanoparticles can be used either as plant growth stimulators or as herbicides (Essa et al., 2021). *Cissus vitiginea*, a wild perennial plant common in tropical regions of India, contains antioxidants in its leaf extract that participate in the synthesis of spherical CuNPs with sizes ranging from 5 to 20 nm (Wu et al., 2020). Special attention has been given to ferns, particularly *Adiantum venustum*, whose extracts contain biologically active compounds such as quercetin and kaempferol, capable of effectively reducing copper ions to the nanoscale and stabilizing the resulting CuONPs (Kimta et al., 2025). There are reports on the use of extracts from the inedible fruits of the evergreen shrub *Ligustrum lucidum* for the biosynthesis of spherical CuONPs with sizes of about 22 nm (Ogwuegbu et al., 2024).

Among trees of importance for the food industry and medicine, *Moringa oleifera* attracts considerable attention. Moringa leaves contain flavonoids and phenolic compounds, which ensure the efficient reduction of copper ions and the formation of stable nanoparticles with pronounced antioxidant and antimicrobial properties (Das et al., 2020). Leaves of *Alstonia scholaris* are rich in alkaloids and flavonoids. The use of *Alstonia scholaris* leaf extract enables the synthesis of CuNPs with various morphologies, including triangular and cylindrical shapes (Labaran et al., 2024). *Hagenia abyssinica* is a traditional medicinal plant of Ethiopia. Its' leaves contain compounds (polyphenols, tannins) capable of acting as ligands that bind copper ions and promote the formation of crystalline nanostructures (Murthy et al., 2020). Leaf extracts of *Cassia fistula* provide the synthesis of spherical CuONPs with sizes ranging from 15 to 25 nm and pronounced antibacterial and cytotoxic activity (Tyagi et al., 2024).

Among herbs and shrubs of importance for the food industry and medicine, thyme should be noted. In particular, CuNPs with an average size of about 60 nm were obtained using an aqueous extract of *Thymus fedtschenkoi* leaves (Dehnoee et al., 2024). Extracts of *Euphorbia serpens* (Idrees et al., 2025) and *Heliotropium bacciferum* (Hamdy et al., 2024) contain specific phytochemical components, such as terpenoids and tannins, which prevent the oxidation and aggregation of CuONPs.

Depending on the selected plant source and biosynthesis conditions, the characteristics of nanoparticles obtained using leaf extracts of different plants may vary significantly (Table 1).

Various copper salts are used as sources of copper ions, serving as precursors during nanoparticle biosynthesis. The choice of a specific precursor has a substantial impact on the reduction kinetics, morphology, size, and stability of the resulting CuNPs. Copper sulfate is most commonly applied as a precursor, typically in the form of pentahydrate ($CuSO_4 \times 5H_2O$). Its popularity is due to its high solubility in water, availability, and stability (Alshammari, 2023; Philip, 2025). Copper nitrate is also a widely used precursor, more often applied in the form of trihydrate ($Cu(NO_3)_2 \times 3H_2O$) (Abbas et al., 2025).

Table 1

Biosynthesis of copper nanoparticles using plant leaves

Plant	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Acacia cornigera	Aqueous extract, 10 mM $CuSO_4$, 50 °C, pH 7, 0.5 h	CuNPs, non-spherical 63–153 nm, zeta potential +9.6 mV	Solorzano Toala et al., 2024
Aegle marmelos	Aqueous extract, 1 mM CH_3COOCu, 80 °C, 2 h	CuONPs, almost spherical ~200 nm, PDI 0.09	Tarangini et al., 2024
Alstonia scholaris	Methanol extract, 0,1 M $CuSO_4$, 1:9 ratio	CuNPs, triangular, cylindrical, polygonal, spherical	Labaran et al., 2024
Cassia fistula	Aqueous extract, $CuCl_2 \times 2H_2O$ (1.34 g in 100 mL), mixing, 1 h	CuONPs, mostly spherical 15–25 nm, PDI 0.712	Tyagi et al., 2024
Ziziphus spina-christi	Aqueous extract, 10 mM $CuSO_4 \times 5H_2O$, 80 °C,1 h	CuONPs, spherical 13.4–30.9 nm	El-Abeid et al., 2024
Lupinus arcticus	Aqueous extract, 1 mM $CuSO_4$, 25 °C, 12 h	CuNPs, spherical 10–85 nm (mostly 30–50 nm)	Saeedi et al., 2025
Crossandra infundibuliformis	Aqueous extract, $CuSO_4 \times 5H_2O$, 18-20 °C, pH 7	CuNPs, spherical 2–20 nm, zeta potential –17.9 mV	Philip et al., 2025
Daucus carota	Aqueous extract, 4 mM $Cu(NO_3)_2 \times 3H_2O$, 60 °C, pH 7, 3-4 h	CuNPs, mostly spherical and oval, mean size 58.3 nm	Abbas et al., 2025
Euphorbia serpens	Aqueous extract, $Cu(CH_3COO)_2$ (2 g in 100 mL), 60 °C, 2 h	CuONPs, mean size 20,39 nm, zeta potential +32.1 mV, PDI 1	Idrees et al., 2025
Ocimum basilicum	Aqueous extract, 0,25 M $Cu(NO_3)_2 \times 3H_2O$, 25 °C, 3 h	CuNPs/CuONPs, spherical, mean size 20–30 nm, zeta potential –5 mV	Wang et al., 2024
Ocimum sanctum	Ethanol extract, 1 mM $CuSO_4 \times 5H_2O$, direct sunlight, 1 h	CuNPs, quasispherical ~60,3 nm, zeta potential –17.3 mV, PDI 0.26	Ashokkumar et al., 2024
Opuntia ficus indica	Aqueous extract, 0,1 M $Cu(CH_3COO)_2$, 60 °C	CuONPs, spherical 65 nm	Soliman et al., 2025
Pterocarpus santalinus	Aqueous extract, 10 mM $CuSO_4$, 60 °C, 0,5 h	CuONPs, mean size 10.62 nm	Babulla et al., 2024
Rhus microphylla	Aqueous extract, 0,1 mM $CuSO_4 \times 5H_2O$, 60 °C, 3 h	CuONPs, spherical, mean size 32.45 nm	Al Musayeib et al., 2024
Thymus fedtschenkoi	Methanol-aqueous extract (70:30), 40 mM $CuSO_4$, pH 12, 0.5 h	CuNPs, Spherical-elliptical 50–75 nm, zeta potential 15.5 mV	Dehnoee et al., 2024

Copper (II) acetate – $Cu(CH_3COO)_2$ – is another common precursor (Idrees et al., 2025). There are also reports on the use of copper(I) acetate – CH_3COOCu; however, in most cases this precursor leads to CuONPs formation (Tarangini et al., 2024). Copper chloride is used less frequently, typically in the form of dihydrate ($CuCl_2 \times 2H_2O$) (Tyagi et al., 2024).

Plant roots

Extracts from the roots of various plants are also used for the biosynthesis of CuNPs (Table 2), although the number of recent studies in this area remains limited.

Table 2

Biosynthesis of copper nanoparticles using plant roots

Plant	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Biebersteinia multifida	Ethanol extract, 50 mM $CuSO_4$, 60 °C, 2 h	CuNPs, semi-spherical, mean size 29 nm	Issa et al., 2025
Krameria sp.	Aqueous extract, 0.3 M $CuSO_4 \times 5H_2O$, 70 °C, pH 11, 3 h	CuNPs, spherical 5.2–7.7 nm	Alshammari et al., 2023
Lannea discolor	Aqueous, methanol or acetone extract, 1 mM $CuSO_4$, 25 °C and 80 °C, 24 h	CuNPs, spherical 20–104 nm; zeta potential from –43.3 to –13.4 mV	Rambau et al., 2024
Senna didymobotrya	Methanol extract, 12.5 mM $CuSO_4 \times 5H_2O$, 80 °C, pH 3.0, 4 h	CuNPs, spherical 5.55–63.60 nm, zeta potential –69.4 mV	Sadia et al., 2021

Analysis of scientific sources indicates the successful use of root extracts from different plants for the synthesis of CuNPs with controlled morphological characteristics. In particular, the use of methanol, acetone, and aqueous root extracts of Lannea discolor results in the formation of predominantly spherical nanoparticles with sizes ranging from 20 to 104 nm (Rambau et al., 2024). When Senna didymobotrya root extract is used, CuNPs are synthesized within a size range from 5.55 to 63.60 nm (Sadia et al., 2021). In the case of Biebersteinia multifida, the application of an ethanol root extract promotes the formation of hemispherical nanoparticles with an average size of about 29 nm (Issa et al., 2025). Aqueous root extracts of Krameria sp. are rich in tannins and enable the formation of highly dispersed spherical CuNPs with an average size of approximately 6.16 nm (Alshammari et al., 2023).

Flowers

In recent years, the scientific literature has also reported isolated studies on the use of flower extracts for the biosynthesis of CuNPs and CuONPs (Table 3).

Table 3

Biosynthesis of copper nanoparticles using plant flowers

Plant	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Acacia saligna	Aqueous extract, 0.1 mM $CuSO_4 \times 5H_2O$, 65–70 °C, pH 7, 4 h	CuONPs, spherical, mean diameter 8.488 nm	Abdullah, 2025
Bauhinia variegata	Aqueous extract, 50 mM $CuSO_4$, 80 °C	CuNPs, polydisperse with rough surface 8.721 nm	Kumar et al., 2024
Lonicera japonica	Aqueous extract, 0,1 M $CuCl_2$, 80 °C, 8 h	CuNPs, 2–4 nm, zeta potential –0.087 mV	Yu et al., 2025
Passiflora	Aqueous extract, 0.1 M $Cu(NO_3)_2$, 20 °C, pH 9, 24 h	CuNPs/CuONPs, spherical 10–20 nm	Sahib et al., 2025

Available data indicate that the use of flower extracts enables the production of nanoparticles with small sizes, typically in the range of 2–20 nm, which is important in terms of their physicochemical and biological properties. It was shown that the use of extracts from certain flower species (*Bauhinia variegata*, *Lonicera japonica*, *Passiflora*, *Saussurea lappa*) promotes the formation of CuNPs (Kumar et al., 2024; Yu et al., 2025; Sahib et al., 2025), whereas the use of others (*Acacia saligna*) results in the formation of CuONPs (Abdullah, 2025). This is likely due to differences in the chemical composition of the phytoextracts.

Seeds

The number of studies on the biosynthesis of CuNPs using plant seed extracts (Table 4) remains limited. In most cases, seeds are previously being grounded to obtain biologically active compounds, after which extraction is carried out using water or organic solvents, particularly ethanol.

Table 4

Biosynthesis of copper nanoparticles using plant seeds

Plant	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Chenopodium quinoa	Aqueous extract, $CuSO_4 \times 5H_2O$ (3.5% m/w), 80 °C, 3 h	CuNPs, cubical 8.41 nm	Hassan et al., 2023
Foeniculum vulgare	Ethanol extract, $CuSO_4 \times 5H_2O$, 60 °C, pH 7, 3 h	CuNPs, spherical 20–40 nm, zeta potential –32.1 mV, PDI 0.25	Huang et al., 2025
Nigella sativa	Aqueous extract, 0.05 M $CuSO_4 \times 5H_2O$, 80 °C, 150 rpm	CuNPs, 98.23 nm	Kumar et al., 2023
Silybum marianum	Aqueous extract, $Cu(CH_3COO)_2 \times H_2O$ (10 g in 100 mL of extract), 50 °C, 2 h	CuONPs, spherical 15 nm, zeta potential –16.9 mV, PDI 0.136	Iqbal et al., 2022

It has been shown that the use of seed extracts from plants such as *Nigella sativa*, *Chenopodium quinoa*, and *Foeniculum vulgare* promotes the formation of CuNPs (Kumar et al., 2023; Hassan et al., 2023; Huang et al., 2025). At the same time, the use of Silybum marianum seed extract leads to the formation of CuONPs (Iqbal et al., 2022). Such differences in biosynthesis products are likely result from the specific chemical composition of the respective phytoextracts and their redox properties. In particular, Silybum marianum seed extracts are characterized by a high content of the silymarin complex, which includes silybin A – a compound with a pronounced reducing potential (Iqbal et al., 2022). In turn, Chenopodium quinoa seeds contain significant amounts of phenolic compounds, such as quercetin, ferulic acid, and gallic acid, which also play an important role in the reduction of copper ions and the stabilization of the formed nanoparticles (Hassan et al., 2023).

A comprehensive scheme of biosynthesis of CuNPs using plant-derived materials provided in Figure 1.

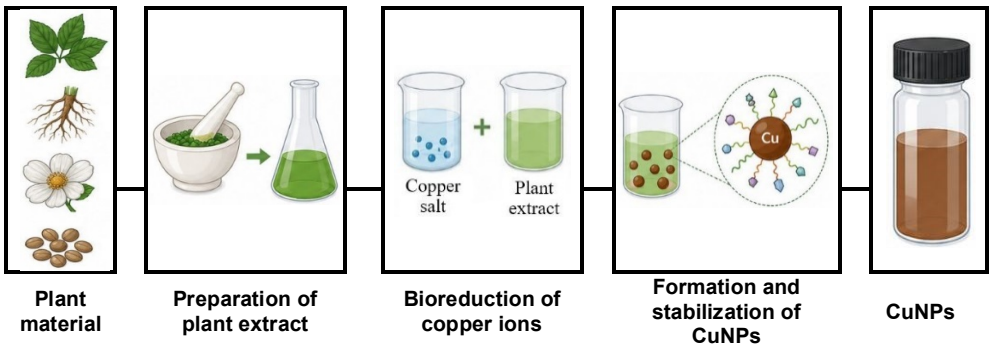

Figure 1. Biosynthesis of CuNPs using plant-derived materials

Mechanisms of copper nanoparticle biosynthesis using plants

The biosynthesis of copper nanoparticles using plant extracts is based on the ability of biologically active compounds to reduce copper ions (Cu^{2+}) to the metallic state (Cu^0) or to oxide forms (CuO, Cu_2O), as well as to stabilize the formed nanostructures.

Various classes of phytochemical compounds are involved in this process, acting both as reducing agents and as capping agents, which determines the efficiency of nucleation and the subsequent growth of nanoparticles (Soliman et al., 2025).

An important role in bioreduction is played by polyphenols and phenolic compounds, which act as electron donors. Their activity is provided by the presence of hydroxyl (–OH) and carbonyl (C=O) groups capable of participating in redox reactions (Dehnoee et al., 2024). This group includes phenolic acids (gallic, ellagic, chlorogenic, *p*-coumaric), flavonoids (quercetin, kaempferol, epicatechin, luteolin, flavanol glycosides), and tannins (Al Musayeib et al., 2024). Polyphenols reduce copper ions and stabilize the surface of nanoparticles. They adsorb onto the nanoparticle surface through π-electron interactions of aromatic rings or hydrogen bonding of hydroxyl groups. This organic shell creates repulsive forces (electrostatic or steric), which prevent nanoparticle aggregation and ensure their stability in solution (Philip et al., 2025).

Nitrogen-containing compounds, in particular alkaloids, proteins, amino acids, and amides present in plant extracts, also play an important role in the biosynthesis of CuNPs and CuONPs. Alkaloids are capable of interacting with copper ions through amino groups, ensuring both their reduction and the subsequent stabilization of nanoparticles. They participate in nucleation processes, promoting the formation of primary nuclei of the metallic or oxide phase (Yu et al., 2025). Proteins and amino acids perform a dual function: they can reduce metal ions while simultaneously capping the particle surface, forming a stable organic layer (Sazak et al., 2023).

Terpenoids and steroidal compounds also participate in the processes of bioreduction and stabilization of nanoparticles. Compounds such as phytol, carotol, β-bisabolene, limonene, α- and β-pinene, as well as saponins, can act as auxiliary reducing agents and stabilizers. They impart specific biological properties to the nanoparticles, which is important for their further practical applications (Abbas et al., 2025).

In addition, carbohydrates present in plant extracts play a significant role in the biosynthesis of copper nanoparticles. Due to the presence of hydroxyl and carbonyl groups, mono- and polysaccharides can act as natural reducing agents, converting Cu^{2+} ions into Cu^0 or oxide forms. At the same time, they are capable of stabilizing the formed nanoparticles by creating a protective layer on their surface (Ashokkumar et al., 2024).

In the case of using plant root extracts, phenolic compounds and flavonoids play a key role in the biosynthesis of CuNPs. For example, quercetin facilitates the reduction of copper ions through π-electron interactions (Sadia et al., 2021). Tannins, particularly catechins and proanthocyanidins, as well as rhataniatannic acid, effectively reduce copper ions and contribute to the stabilization of the formed nanoparticles by creating an organic layer on their surface (Alshammari et al., 2023). Root extracts may also contain terpenoids and alkaloids that participate in reduction-stabilization processes, including citraconic anhydride and γ-sitosterol (Issa et al., 2025).

Algae for the biosynthesis of copper nanoparticles

Marine algae

Species of marine algae from different taxonomic groups are employed in CuONPs and CuNPs biosynthesis. The most studied are brown algae, particularly *Cystoseira myrica* (Soureshjani et al., 2021), *Macrocystis pyrifera* (Araya-Castro et al., 2020), *Sargassum vulgare* (Marzban et al., 2022), *Sargassum cervicorne* (Anwar et al., 2024) and species of *Turbinaria*

genera (Anbalagan et al., 2024). Brown algae aside, CuONPs biosynthesis research also involve green (*Ulva lactuca*) (Hamouda et al., 2023) and red (*Pterocladia capillacea*) (Aboeita et al., 2022) algae (Table 5).

Table 5

Biosynthesis of copper nanoparticles using marine algae

Plant	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Cystoseira myrica	Aqueous extract, $CuSO_4 \times 5H_2O$ (1 g / 200 mL), 100 °C, pH 12, 20 min	CuONPs, mean size 12–26 nm	Soureshjani et al., 2021
Macrocystis pyrifera	Purified protein fractions, 2 mM $CuSO_4$, 45 °C, 48 h	CuONPs , spherical, 2–50 nm	Araya-Castro et al., 2020
Pterocladia capillacea	Aqueous extract, $CuSO_4 \times 5H_2O$, 18–20 °C, pH 7	CuONPs, mean size 62 nm, zeta potential –16,8 mV	Aboeita et al., 2022
Sargassum cervicorne	Aqueous extract, 0.05 M $CuSO_4 \times 5H_2O$, 18–20 °C, 24 h	CuNPs, spherical, 2.6–3 nm	Anwar et al., 2024
Sargassum longifolium	Aqueous extract, 10 mM $CuSO_4$, 18–20 °C, 6 h	CuONPs, 40–60 nm	Rajeshkumar et al., 2021
Sargassum vulgare	Algae polysaccharides, 3 mM $CuSO_4 \times 5H_2O$, 70 °C, 24 h	CuONPs, spherical, 40–50 nm	Marzban et al., 2022
Turbinaria sp.	Aqueous extract, $Cu(NO_3)_2$, 60 °C, 24 h	CuNPs/CuONPs, almost rectangular, 18 nm	Anbalagan et al., 2024
Ulva lactuca	Aqueous extract, 9 mM $CuSO_4$, 18–20 °C, 2 h	CuONPs, rod-shaped (width 10–40 nm, length 46–65 nm), zeta potential –0.195 mV	Hamouda et al., 2023

In most cases, marine algae-mediated nanoparticles biosynthesis is performed using aqueous extracts of biomass. Such extracts are obtained by boiling or ultrasound treatment that results in extracting biomolecules that act as nanoparticles reducers and stabilizers (Soureshjani et al., 2021; Aboeita et al., 2022). There are reports on purified biomolecules fractions, particularly proteins or water-soluble polysaccharides, that play key role in nanostructures formation and stabilization (Araya-Castro et al., 2020; Marzban et al., 2022).

The use of different species of brown algae allows to obtain nanoparticles with different physicochemical properties. For example, synthesis of CuONPs with size range from 12 to 26 nm was provided with aqueous extracts of *Cystoseira myrica* and *Sargassum latifolium* (Soureshjani et al., 2021). The use of protein fractions from *Macrocystis pyrifera* provides formation of spherical CuONPs in size range 2–50 nm (Araya-Castro et al., 2020). At the same time *Sargassum cervicorne* extracts allow for thevsynthesis of amorphous, highly thermostable CuNPs with size around 3 nm (Anwar et al., 2024).

Green macroalgae, particularly species of *Ulva*, *Enteromorpha* and *Codium* genera, are characterized by complex and diverse biochemical composition. They contain considerable amounts of proteins, carbohydrates, lipids and pigments, particularly chlorophylls, as well as wide spectrum of secondary metabolites, such as phenolic compounds, flavonoids, terpenoids, amines and amides. These components provide metals ions reduction and further stabilization of nanoparticles formed. Different green algae species allow for the synthesis of copper nanoparticles with various morphology and sizes. The use of *Ulva lactuca* provides synthesis of rod-shaped CuONPs. Moreover, same specimen was used to obtain hexagonal silver-copper nanocomposites with size range 10–35 nm (Hamouda et al., 2023).

Red marine algae are characterized by a high content of specific bioactive compounds that play a key role in metal nanoparticles biosynthesis processes. One of the red algae notable features is a high content of polysaccharides, which can act as natural reducers turning metal ions into zero-valency state as well as stabilizing agents that prevent nanoparticles aggregation. Moreover, red algae contain broad spectrum of bioactive macromolecules, including proteins, amino acids, phenolic compounds and uronic acids. These components provide expressing antioxidant properties, which are important for running reduction reactions during nanoparticles synthesis (Aboeita et al., 2022).

Freshwater algae

Among freshwater algae applied for nanoparticles biosynthesis most notable are filamentous green macroalgae *Cladophora glomerata*. Using specifically its' extracts allows the obtaining of spherical CuONPs in size range 40–50 nm. Biochemical composition of *Cladophora glomerata*, particularly presence of fatty acids, phenolic compounds and proteins, provides effective copper ions reduction and obtained nanoparticles stabilization (Kumar et al., 2025).

Green filamentous algae *Oedogonium* sp. were used for synthesis of CuNPs with expressed antimicrobial activity, specifically against phytopathogenic bacteria, such as citrus cancer agent *Xanthomonas citri*. It opens a perspective of using biogenic CuNPs for plants protection against bacterial infections (Waqif et al., 2024).

The algae of *Zygnema* sp. genera are another source of biogenic CuONPs. Aqueous extracts from these filamentous algae contain phenolic compounds and flavonoids, which provide synthesis of predominantly spherical nanoparticles with mean diameter around 30 nm (Alsalamah et al., 2024).

Unicellular microalgae *Chlorella ellipsoidea* are often isolated from wastewater. They are used for the biosynthesis of copper sulfide nanoparticles (CuSNPs) with sizes in the range of 9–23 nm. These algae are capable of hyperaccumulating metal ions and can grow in both clean and polluted or wastewater environments. This makes them an accessible and renewable resource for nanoparticle biosynthesis, as well as opening up prospects for combining bioremediation processes with nanobiotechnology (Borah et al., 2022).

Unicellular microalgae *Chlamydomonas reinhardtii* are characterized by a unique ability to combine bioremediation processes with nanoparticle biosynthesis. They are capable of efficiently removing copper ions from wastewater while simultaneously synthesizing CuNPs with sizes below 10 nm. In this process, cell viability is a critical factor that determines the efficiency of both metal sorption and its subsequent reduction (Zvab et al., 2021).

Particular attention is drawn to unicellular algae such as *Asterarcys quadricellulare* and *Coelastrella terrestris*. It has been established that the use of aqueous extracts of these algae leads to the synthesis of CuONPs with variable morphology – ranging from rice-like structures to petal-like forms. This morphological diversity depends on the conditions of biosynthesis and opens up possibilities for the targeted control of nanomaterial properties (Khandelwal et al., 2023; Khandelwal et al., 2024).

The conditions of biosynthesis and the type of freshwater algae used significantly influence the characteristics of the resulting nanoparticles (Table 6).

Mechanisms of copper nanoparticle biosynthesis using algae

Specific biosynthesis mechanisms largely depend on the algal species and the composition of their metabolites. In the case of the marine alga *Cystoseira myrica*, the process occurs in two stages: first, stable complexes of copper ions with ligands (e.g., sodium citrate) are formed, followed by their reduction under the activity of biomolecules from the algal extract in an alkaline medium. The pigment fucoxanthin plays an important role in this process; due to the presence of electron-donating groups, it effectively interacts with copper ions, ensuring both their reduction and the stabilization of the resulting CuONPs (Soureshjani et al., 2021).

Table 6

Biosynthesis of copper nanoparticles using freshwater algae

Algae	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Asterarcys quadricellulare	Aqueous extract, $CuSO_4 \times 5H_2O$, 60 °C, pH 11, 24–72 h	CuONPs, rice-like or petal-like structures, 4.76–13.70 nm	Khandelwal et al., 2023
Chlamydomonas reinhardtii	Living cells, TAP medium (wastewater simulation), 10 mg/L $CuCl_2 \times 2H_2O$, 26–28 °C, pH 7.7–8, 24–72 h	CuNPs, spherical, <10 nm	Zvab et al., 2021
Chlorella ellipsoidea	Aqueous extract, 2 mM $CuCl_2 \times 2H_2O$, 2 mM Na_2S, 40 °C, 4 h	CuSNPs, predominantly spherical, 9–23 nm	Borah et al., 2022
Cladophora glomerata	Aqueous extract, 1 M $Cu(NO_3)_2 \times 3H_2O$, 80 °C, pH 7–8, 24 h	CuONPs, spherical, 40–50 nm	Kumar et al., 2025
Coelastrella terrestris	Aqueous extract, $CuSO_4 \times 5H_2O$, 60 °C	CuONPs, rice-like or petal-like structures, 4.26–28.51 nm	Khandelwal et al., 2024
Oedogonium sp.	Aqueous extract, 1–10 mM $Cu(CH_3COO)_2$, 37 °C, pH 5–9, 24 h	CuNPs, spherical, 15–32 nm, zeta potential –30.172 mV	Waqif et al., 2024
Zygnema sp.	Aqueous extract, 1 mM $Cu(CH_3COO)_2$, 80 °C, 18 h	CuONPs, spherical, mean diameter 30.06 nm	Alsalamah et al., 2024

When using extracts of *Turbinaria* sp., the reduction of copper ions is driven by polyphenols and polysaccharides. The hydroxyl groups of biomolecules act as active centers that initiate nanoparticle nucleation and promote the subsequent stabilization of the colloidal system (Anbalagan et al., 2024). In the case of *Ulva lactuca*, the biosynthesis mechanism is associated with the presence of amines, amides, proteins, and pigments in the aqueous extract. It was established that N–H groups are directly involved in bioreduction processes, while alcohol and aldehyde groups initiate the nucleation stage of CuONPs (Hamouda et al., 2023).

During nanoparticle biosynthesis using *Pterocladia capillacea* extract, sulfated polysaccharides, particularly galactose sulfates, as well as uronic acids, play a leading role (Aboeita et al., 2022). The potential use of polysaccharides from *Sargassum vulgare* for CuONPs biosynthesis was also investigated. Their hydroxyl (–OH) and aliphatic (–CH) groups ensure efficient nanoparticle formation by creating a stable protective layer and preventing aggregation (Marzban et al., 2022). A protein-mediated mechanism of CuONPs synthesis was also identified when using purified protein fractions of *Macrocystis pyrifera*. The reduction of copper ions occurs with the participation of tyrosine residues in proteins, while the carboxyl groups of aspartic and glutamic acids regulate nanoparticle growth. Additional stabilization is provided by cysteine, which contains thiol groups capable of binding to the nanoparticle surface (Araya-Castro et al., 2020).

The mechanisms of nanoparticle biosynthesis exhibit pronounced species specificity and are determined by the characteristics of the metabolic profile, including in the case of freshwater algae. For example, when using an aqueous extract of *Asterarcys quadricellulare*, the synthesis of CuONPs occurs in two stages. At the first stage, biomolecules (proteins, carbohydrates, and lipids) reduce Cu^{2+} ions to the zero-valent state (Cu^0), after which, at the second stage, they are oxidized by dissolved oxygen in the medium to form CuO. Further stabilization is provided by proteins, polysaccharides, and long-chain fatty acids, which form a protective coating around the nanoparticles (Khandelwal et al., 2023).

When using an aqueous extract of *Chlorella ellipsoidea*, a single-stage mechanism of CuSNPs synthesis is observed. Phytochemical components of the extract (proteins, carbohydrates, exopolysaccharides, and phenolic compounds) bind copper ions and promote their interaction with sulfide ions, ensuring the simultaneous formation of the nanoparticle core and stabilizing shell (Borah et al., 2022). An important role of terpenoids and polyphenols was also demonstrated in the biosynthesis of nanoparticles using extracts of freshwater algae *Oedogonium* sp. and *Coelastrella terrestris* (Khandelwal et al., 2024; Waqif et al., 2024).

In the case of using living cells of *Chlamydomonas reinhardtii*, the mechanism of CuNPs biosynthesis is complex and involves several interrelated processes. A determining factor is cell viability, as efficient reduction of copper ions occurs only under conditions of active metabolism. Studies using damaged cells or photosensitive mutants have shown that in the absence of metabolic activity, only soluble copper complexes with cellular components are formed, while the formation of metallic nanoparticles does not occur.

The reduction of copper ions to metallic nanoparticles is associated with intracellular redox processes. An additional factor is the ability of this alga to photoproduce hydrogen, which can act as a reducing agent for Cu^{2+} ions to Cu^0. At the same time, polysaccharides, proteins, and alkaloids ensure the stabilization of the formed CuNPs (Zvab et al., 2021).

Mushrooms for the biosynthesis of copper nanoparticles

Mushrooms are considered promising biological systems for the biosynthesis of copper nanoparticles due to their unique combination of nutritional value and a high content of bioactive compounds. However, the number of contemporary studies in this area remains limited. An important prerequisite for the use of mushrooms in nanobiotechnology is their wide spectrum of secondary metabolites.

Mushrooms of the species *Agaricus bisporus* contain bioactive components with antimicrobial, antiviral, and antitumor properties, as well as polysaccharides with immunomodulatory activity (Sriramulu et al., 2020). Representatives of the genus *Ganoderma*, including *Ganoderma sessile*, are known as medicinal mushrooms with a high content of triterpenoids, sterols, and polysaccharides exhibiting antioxidant and anti-inflammatory activity (Flores-Rabago et al., 2023). Species of the genus *Pleurotus*, in particular *Pleurotus ostreatus* and *Pleurotus cystidiosus*, are characterized by the presence of phenolic compounds and flavonoids, which can act as reducing and stabilizing agents during nanoparticle formation (Kamakshi et al., 2024; Roslan et al., 2025).

The biosynthesis of CuNPs using mushrooms (Table 7) can be carried out either with the involvement of intracellular components or through extracellular metabolites. The preparation of biological material includes washing the mushrooms, drying them, and grinding them into a powder-like state, followed by mixing with distilled water. The resulting suspension is subjected to thermal treatment to extract bioactive compounds (Amirtham et al., 2023). In the case of *Ganoderma sessile*, submerged cultivation is performed, after which the supernatant and aqueous cell extracts are used for the biosynthesis of copper nanoparticles (Rivera-Mendoza et al., 2024).

Mechanisms of copper nanoparticle biosynthesis using mushrooms

The first key stage is the biochemical reduction of copper ions, which, under the action of fungal metabolites, are reduced to zero-valent copper (Cu^0) or transformed into oxide forms (CuO). A decisive role in this process is played by the functional groups of biomolecules, particularly hydroxyl (–OH) and amide groups present in phenolic compounds, proteins, and polysaccharides. These groups can act as electron donors, initiating the reduction of copper ions and the subsequent formation of nanoparticles (Sriramulu et al., 2020). Additionally, it was established that flavoproteins, particularly riboflavin derivatives, are involved in the nucleation

and growth of nanoparticles, promoting the aggregation of copper atoms into stable nanostructures. Enzymatic activity is also an important component: extracellular enzymes such as laccase, lignin peroxidase, and manganese peroxidase are involved in the biotransformation of copper ions and can catalyze redox reactions accompanying nanoparticle formation (Amirtham et al., 2023).

Table 7

Biosynthesis of copper nanoparticles using mushrooms

Mushrooms	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Agaricus bisporus	Aqueous extract, 1 mM $Cu(NO_3)_2$, 18–20 °C, 300 rpm, 24 h	CuNPs, spherical, 10–60 nm, zeta potential –40 mV	Sriramulu et al., 2020
Ganoderma sessile	Aqueous extract of mycelium cells, 5 mM $CuSO_4 \times 5H_2O$, 60 °C, pH 10, 24 h	CuONPs, spherical, 5.2 nm, zeta potential –28.7 mV, PDI 0.67	Flores-Rabago et al., 2023
Ganoderma sessile	Aqueous extract of mycelium cells, 10 mM $CuSO_4 \times 5H_2O$, 60 °C, pH 8, 72 h	CuONPs, spherical, 2.9 nm, zeta potential –21.0 mV	Rivera-Mendoza et al., 2024
Lentinus squarrosulus	Aqueous extract, 5 mM $CuSO_4$	CuNPs, spherical, 200–300 nm	Amirtham et al., 2023
Pleurotus cystidiosus	Aqueous extract, 5 mM $CuSO_4$, 60 °C, 10–20 min	CuONPs, spherical and oval-shaped, 80–110 nm	Kamakshi et al., 2024
Pleurotus ostreatus	Aqueous extract, $CuSO_4 \times 5H_2O$ (1 g in 10 mL of extract), autoclaving (121 °C, 15 min)	CuNPs, irregular shape, 41.56–131.9 nm	Roslan et al., 2025

The second stage involves the stabilization of the formed nanoparticles. Proteins, amino acids, and polysaccharides adsorb onto their surface, acting as stabilizers and preventing aggregation. In addition, the stability of the colloidal system is maintained through electrostatic effects: nanoparticles acquire a negative surface charge, which ensures effective electrostatic repulsion between them and prevents their agglomeration (Flores-Rabago et al., 2023).

Spices and herbs for the biosynthesis of copper nanoparticles

Extracts of various spices and herbs can be applied for the biosynthesis of CuNPs and CuONPs, as they contain phytochemical compounds (phenolic compounds, flavonoids, terpenoids, alkaloids, and tannins) that act as natural reducing and stabilizing agents (Amaliyah et al., 2020) (Table 8).

Aqueous extracts of cinnamon bark and leaves (*Cinnamomum zeylanicum*) contain a wide range of biologically active compounds, including flavonoids, tannins, glycosides, and alkaloids, which enable efficient reduction of copper ions, resulting predominantly in spherical nanoparticles. A key role in this process is played by antioxidant components such as cinnamic acid, eugenol, and cinnamaldehyde, which participate in redox reactions and stabilize the surface of CuNPs (Kothari, 2023; Liu, 2021c).

Seeds of star anise (*Illicium verum*) are rich in anethole and D-limonene – compounds with pronounced antioxidant properties that promote reduction processes. Extracts of nutmeg seeds and mace (*Myristica fragrans*) contain myristic acid, methyleugenol, and other phenolic compounds involved in the reduction and stabilization of nanoparticles (Vijayakumar et al., 2021). Due to the high content of essential oils, as well as mono- and sesquiterpenes, aqueous extracts of caraway seeds (*Carum carvi*) are also used for the biosynthesis of CuONPs (Oraibi et al., 2023).

Table 8

Biosynthesis of copper nanoparticles using spices and herbs

Spices and herbs	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Allium sativum (garlic)	Aqueous extract, 10 mM $CuSO_4 \times 5H_2O$, 18–20 °C, 24 h	CuNPs	Amatya et al., 2020
Carum carvi (caraway)	Aqueous extract seeds, 1 mM $Cu(NO_3)_2 \times 2H_2O$, 45 °C, 12 h	CuNPs, spherical, ~12.4 nm	Oraibi et al., 2023
Cinnamomum zeylanicum (cinnamon)	Aqueous extract of bark, 3 mM $CuSO_4$, 18–20 °C, 24 h	CuNPs, oval-shaped / spherical, mean size ~66.16 nm	Kothari, 2023
Cinnamomum zeylanicum (cinnamon)	Aqueous extract of leaves, 0.3 M $Cu(NO_3)_2 \times 2H_2O$, 65 °C, 24 h	CuONPs, spherical, 19.55–69.70 nm	Liu et al., 2021c
Illicium verum (star anise)	Aqueous extract seeds, 0.5 M $CuSO_4$, 37 °C, 24 h	CuONPs, spherical, 210–270 nm	Vijayakumar et al., 2021
Myristica fragrans (nutmeg)	Aqueous extract seeds, 0.5 M $CuSO_4$, 37 °C, 24 h	CuONPs, spherical, 170–210 nm	Vijayakumar et al., 2021
Myristica fragrans (nutmeg)	Aqueous extract of seed shell, 0.5 M $CuSO_4$, 37 °C, 24 h	CuONPs, spherical, 150–220 nm	Vijayakumar et al., 2021
Piper longum (long pepper)	Aqueous and ethanol extracts of fruit, 0.1 M $CuSO_4 \times 5H_2O$, 35 °C, 24 h	CuNPs, spherical, 35–320 nm	Mahal et al., 2024
Piper retrofractum (Jawan pepper)	Aqueous extract of fruits, 0.1 M $CuSO_4$, 80 °C, pH 8, 1 h	CuNPs, spherical, 2–10 nm	Amaliyah et al., 2020
Zingiber officinale (ginger)	Aqueous extract of root, $CuSO_4$, 90 °C, 12 h	CuNPs, spherical, 60 nm	Abbas et al., 2022
Zingiber officinale (ginger)	Aqueous extract of root, 1 mM $CuSO_4$, L-ascorbic acid, microwaves (700 W), 17 min	CuNPs, spherical and oval-shaped, 11.32–33.70 nm, zeta potential –24.4 mV	Jahan et al., 2020

Extracts of the fruits of *Piper retrofractum* and *Piper longum* contain flavonoids, tannins, steroids, and alkaloids, including piperidine derivatives. These compounds ensure both the reduction of metal ions and the stabilization of the resulting CuNPs (Amaliyah et al., 2020; Mahal et al., 2024).

Mechanisms of copper nanoparticle biosynthesis using spices and herbs

Phytochemical compounds present in spices and herbs play a key role in the biosynthesis of CuNPs and CuONPs. These include a wide range of compounds such as flavonoids, polyphenols, tannins, alkaloids, terpenoids, and saponins. During nanoparticle biosynthesis, they perform a dual function, acting both as reducing agents and stabilizers (Mahal et al., 2024; Kothari, 2023). As bioreducing agents, polyphenols, flavonoids, and ascorbic acid present in ginger are capable of donating electrons or hydrogen atoms, thereby enabling the conversion of copper ions into metallic copper or its oxide forms (Abbas et al., 2022). At the same time, the oxidized forms of these compounds, as well as alkaloids and amides, adsorb onto the surface of nanoparticles, forming a protective layer that prevents their aggregation and uncontrolled oxidation under the influence of atmospheric oxygen (Amatya et al., 2020).

The mechanism of nanoparticle formation has been described for extracts of jawan pepper and nutmeg. At the initial stage, complex formation occurs, during which phytochemical components of the extract interact with copper ions, forming intermediate coordination complexes. The next stage is reduction, which is often accompanied by tautomeric transformations of flavonoids: the transition from the enol to the keto form is associated with the release of hydrogen atoms that participate in the reduction of Cu^{2+} to Cu^{0}. This stage is typically accompanied by a characteristic color change of the reaction medium from blue to green, brown, or black, serving as a visual indicator of nanoparticle formation. Following reduction, nucleation and growth of nanoparticles occur. Stabilization of the nanoparticle surface is achieved through the adsorption of biomolecules containing functional groups such as carbonyl, phenolic, and amide groups (Amaliyah et al., 2020; Vijayakumar et al., 2021).

Food products and food wastes for the biosynthesis of copper nanoparticles

Analysis of the literature indicates usage of various categories of food products and food waste for the biosynthesis of CuNPs and CuONPs (Table 9).

Table 9

Biosynthesis of copper nanoparticles using food products and food wastes

Food products or food wastes	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Actinidia deliciosa (kiwi)	Aqueous extract of fruit peel, 0.1 M $Cu(CH_3COO)_2$, 18–20 °C, ultrasound, 24–48 h	CuONPs, spherical / cubical, 51–62 nm	Ahmed et al., 2025
Allium sativum (garlic)	Aqueous extract of husk, 0.1 M $CuSO_4$, 60 °C, pH 9, 2 h	CuNPs, ellipsoid / spherical, 14 nm, zeta potential –19.3 mV	Senthilkumar et al., 2024
Ananas comosus (pineapple)	Aqueous extract of fruit peel, 20 mM $CuSO_4 \times 5H_2O$, PEG 6000, 80 °C, pH 11, 1 h	CuNPs, spherical, 53–70 nm	Ali et al., 2020
Ananas comosus (pineapple)	Aqueous extract of fruit peel, 25 mM $CuSO_4 \times 5H_2O$, 60 °C, 2 h	CuNPs, spherical, 100–730 nm (mean size 290.5 nm), zeta potential –12.3 mV	Mitra et al., 2024
Citrus limon (lemon)	Aqueous extract of fruit, $CuSO_4$, 18–20 °C, 4 h	CuNPs, spherical, 20–30 nm	Amer et al., 2021
Citrus sinensis (orange)	Aqueous extract of fruit peel, 0.5 M $Cu(NO_3)_2$, 90 °C, pH 12, 10 h	CuONPs, spherical, 14.32–40.77 nm	Albrahim et al., 2025
Citrus sinensis (orange)	Fruit juice, 1 mM $CuSO_4$, 80 °C, microwaves 700 W, 15 min	CuNPs, spherical, 7–21 nm, zeta potential –25.6 mV	Jahan et al., 2021
Juglans regia (walnut)	Aqueous extract of green husk, 1 mM $Cu(CH_3COO)_2$, 18–20 °C, 24 h	CuNPs, spherical, mean size 28 nm	Ahmadi et al., 2023
Malpighia glabra (Barbados cherry)	Fruit juice, 21.9 mM $Cu(CH_3COO)_2$, starch, 40 °C, ultrasound, 2 h	CuNPs, spherical, 22.5 nm, zeta potential –11.8 mV	Nguyen et al., 2024
Mangifera indica (mango)	Aqueous extract of seed kernel, 150 mM $CuSO_4$, 60 °C, 400 rpm, 2 h	CuONPs, spherical or irregular shape, mean size 211 nm, zeta potential –14 mV	Pramanik et al., 2025
Persea americana (avocado)	Aqueous extract of seed kernel, 1 M $CuSO_4$, 25 °C, 2 h	CuNPs, spherical, mean size 21.289 nm	Ibrahim et al., 2023
Salvadora persica (toothbrush tree)	Fruit extract, 10 mM $CuSO_4$, 70 °C, 15 h	CuNPs, spherical, 90–139 nm, zeta potential –25.2 mV	Elhabal et al., 2022

Among these, a distinct group is represented by fruits, from which fruit juice is obtained for CuNPs biosynthesis. All insoluble residues are removed from the juice by centrifugation followed by filtration. For example, orange juice facilitated the rapid synthesis of CuNPs under microwave irradiation (700 W) for 15 minutes (Jahan et al., 2021). The juice of Barbados cherry (*Malpighia glabra*) contains a high amount of ascorbic acid, which ensures efficient reduction of copper ions (Nguyen et al., 2024). Fruit extracts are also utilized. To obtain an extract of *Salvadora persica*, the fruits are crushed and then mixed with an ethanol-water solution (50/50 v/v). After centrifugation, the supernatant is evaporated under vacuum, and for CuNPs biosynthesis, the resulting dry residue is dissolved in water (Elhabal et al., 2022). An aqueous fruit extract of *Citrus limon* provided the synthesis of CuNPs (Amer et al., 2021).

The second group includes food waste, such as mango seed kernels (Pramanik et al., 2025) and avocado seeds (Ibrahim et al., 2023), as well as fruit peels (Mitra et al., 2024) and other secondary plant materials (Ahmadi et al., 2023), the use of which aligns with the principles of the circular economy and green chemistry.

Mechanisms of copper nanoparticle biosynthesis using food products and food waste

The key stage of the process is the bioreduction of copper ions (Cu^{2+}) to atomic copper (Cu^0) under the action of phytochemical compounds present in the extracts. Sources of electrons include polyphenols, flavonoids, tannins, vitamins, and reducing sugars found in extracts of food products and food waste. An important role in this process is played by functional groups of biomolecules – carbonyl, hydroxyl, amino, and methoxy groups – which are capable of binding copper ions through electrostatic interactions and facilitating their reduction (Elhabal et al., 2022).

Flavonoids can undergo transformation from the enol to the keto form, releasing a reactive hydrogen atom that enables the reduction of Cu^{2+} to Cu^0 (Mitra et al., 2024). Ascorbic acid, in turn, is oxidized to ascorbate radicals, which actively interact with copper ions, promoting nanoparticle formation while simultaneously preventing their undesired oxidation, which is critically important for the stability of CuNPs (Nguyen et al., 2024).

Nanoparticle formation proceeds through a sequence of physicochemical stages. During nucleation, primary crystallization centers are formed. The subsequent stage involves particle growth and aggregation, during which their final size and morphology are established. In the case of CuONPs biosynthesis, after the reduction stage, atomic copper may undergo further oxidation to form copper oxide, often induced by thermal treatment, particularly calcination, or by specifically controlled reaction conditions (Albrahim et al., 2025).

The final stage is stabilization and the formation of a surface coating on the nanoparticles. Biomolecules such as proteins, lignins, and saponins adsorb onto the surface of the formed nanoparticles, creating a protective layer. This results in electrostatic repulsion between CuNPs, preventing their aggregation and ensuring high colloidal stability of the system (Pramanik et al., 2025).

Bacteria for the biosynthesis of copper nanoparticles

Thermophiles

Non-pathogenic strain of the thermophilic bacteria *Bacillus anthracis* PFAB2 was isolated from the Panifala hot spring (India). For the biosynthesis of CuONPs, cell wall polysaccharides are used, which are characterized by high thermal stability and have a degradation temperature of about 283.10 °C. These polysaccharides are rich in carboxyl and phosphate functional groups. The presence of these groups gives the polysaccharides a negative charge, creating favorable conditions for effective electrostatic interaction with positively charged copper ions (Banerjee et al., 2024). A strain of *Anoxybacillus rupiensis* BS1 was isolated from the Pasinler hot spring

(Erzurum, Turkey). These bacteria are capable of forming endospores and synthesizing lignin peroxidase, which is active at 60 °C. The biosynthesis of CuNPs involving this enzyme has been studied (Sus et al., 2024).

Psychrophiles

Bacterial consortia including representatives of psychrophilic microorganisms were isolated from Antarctic marine ecosystems. Such microbial communities include representatives of the genera *Marinomonas*, *Rhodococcus*, *Pseudomonas*, *Brevundimonas*, and *Bacillus*. These bacteria can be applied for the biosynthesis of nanoparticles at relatively low temperatures, which opens up prospects for the development of energy-efficient biotechnological processes for the production of CuNPs (John et al., 2021). A psychrotolerant strain *Stenotrophomonas* sp. BS95 was isolated from alpine soil in Iran. For the biosynthesis of CuONPs, the supernatant of cell lysate is used, which contains a large number of enzymes and proteins (Talebian et al., 2023).

Marine bacteria

The use of marine bacteria for the biosynthesis of copper nanoparticles is possible due to the unique adaptive properties of these microorganisms. Marine bacteria have evolved under conditions of high salinity, elevated hydrostatic pressure, limited nutrient availability, and often low temperatures. Such extreme conditions have led to the development of specific metabolic pathways and biomolecules that can effectively participate in the reduction of metal ions and the stabilization of nanoparticles. The bacterium *Pseudomonas aeruginosa* MO1 was isolated directly from seawater. These bacteria are characterized by high metabolic flexibility and the ability to synthesize various secondary metabolites and biopolymers that function as natural reducing agents and stabilizers during nanoparticle formation. With the involvement of such biomolecules, copper ions can be reduced to copper oxide under neutral pH conditions, and the resulting nanoparticles exhibit antimicrobial activity (Tejaswi et al., 2025). *Stenotrophomonas rhizophila* BGNAK1 was isolated from coastal marine sediments of the western coast of India. This species is adapted to marine soil conditions and is characterized by increased resistance to pollutants and heavy metals. The BGNAK1 strain synthesizes various biomolecules, including phenolic compounds and other metabolites, which are involved in the reduction of copper ions and the stabilization of the formed nanoparticles (Karthikeyan et al., 2024).

The actinobacterial strain *Streptomyces* sp. MHM38 was isolated from marine sediments of the Gulf of Suez. These Gram-positive bacteria are known for their high metabolic activity and ability to synthesize a wide range of extracellular enzymes and proteins that can act as reducing and stabilizing agents during nanoparticle formation. In particular, proteins with molecular weight of approximately 10–80 kDa contribute to the formation of stable nanostructures (Bukhari et al., 2021). *Enterococcus thailandicus* E12 was isolated from seawater samples of the Gulf of Suez (Red Sea, Egypt). These bacteria are characterized by an enhanced ability to synthesize nitrate reductase, which plays a key role in the bioreduction of metal ions. This enzyme acts as the main catalyst for the reduction of Cu^{2+} ions to their elemental form, leading to the intracellular formation of nanoparticles (Zaki et al., 2021).

Endophytes

Endophytic bacteria colonize the internal tissues of plants without causing harm and exist in close metabolic interaction with their host plants. During this interaction, endophytic bacteria produce a wide range of secondary metabolites that can act as natural reducing agents and stabilizers in the biosynthesis of nanoparticles. Due to this, endophytic bacteria are capable of effectively catalyzing the reduction of copper ions and ensuring the stabilization of the formed

nanostructures. For example, *Brevibacillus brevis* PI-5 was isolated from the leaves of the medicinal plant *Pulicaria incisa*, which grows in arid regions of the Sinai Peninsula. The PI-5 strain is used for the synthesis of spherical, well-dispersed CuONPs with sizes ranging from 2 to 28 nm (Fouda et al., 2022).

The strain *Bacillus licheniformis* CPJN13S was identified as a plant growth-promoting endophyte. The biosynthesis of CuNPs in a cell-free system using the supernatant of the CPJN13S strain has been studied (Rani et al., 2025a).

Endophytic bacteria *Pantoea agglomerans* CPHN2 belong to the group of plant growth-promoting bacteria. The CPHN2 strain was isolated from the roots and nodules of leguminous plants. When these bacteria were used, hexagonal CuNPs or CuONPs with sizes of 5–35 nm are formed. The nanoparticles biosynthesized using these bacteria exhibit antimicrobial activity and are more effective against *Staphylococcus aureus* and *Bacillus subtilis* compared to nanoparticles obtained using traditional chemical methods (Rani et al., 2025b).

Bacteria from polluted ecosystems

The strain *Serratia* sp. ZTB29 was isolated from zinc-lead ore enrichment sites (India). These bacteria demonstrate resistance to copper ions (up to 22.5 mM) and can be used for the biosynthesis of CuONPs with their subsequent application as nanofertilizers (Singh et al., 2023). *Ralstonia* sp. KF264453 bacterial strain was isolated from soils near a copper deposit (Iran). With the involvement of extracellular metabolites of *Ralstonia* sp. KF264453, the bioreduction of Cu^{2+} ions to metallic copper (Cu^0) occurs, forming nanoparticles with an average size of about 70 nm (Vakili et al., 2025).

Microorganisms inhabiting industrial and municipal wastewater are typically adapted to elevated concentrations of toxic compounds, including heavy metal ions. As a result of this adaptation, they possess well-developed detoxification mechanisms, including metal-binding proteins, transport systems, and reductase enzymes capable of reducing metal ions to their elemental form. *Escherichia* sp. SINT7 bacterial strain was isolated from wastewater (Pakistan). With their involvement, CuNPs were biosynthesized that exhibit photocatalytic activity and can be used for the degradation of organic dyes (Noman et al., 2020a). *Bacillus flexus* FB-1 bacterial strain was isolated from textile industry wastewater in Faisalabad (Pakistan). The biosynthesis of CuNPs using the culture supernatant of the FB-1 strain and their potential application for wastewater treatment have been investigated (Batool et al., 2024).

Proteus mirabilis AB 932526.1 was isolated from activated sludge of wastewater treatment plants. For the biosynthesis of CuNPs, a bioflocculant produced by *Proteus mirabilis* AB 932526.1 is used, which performs a dual function during synthesis: acting both as a reducing agent and as a stabilizer for the formed nanoparticles. The use of biogenic CuNPs for water purification from dyes and excess nutrients has been studied (Nkosi et al., 2025).

Bacillus cereus FM1 and *Bacillus thuringiensis* FM2, isolated from electronic waste landfills (Iran), are characterized by a high level of metal resistance. The FM1 strain tolerates high concentrations of copper ions (MIC = 333 mM when using copper sulfate). Both strains are capable of biosorbing copper ions up to 79.8%. Such properties make these bacteria particularly promising for applications under conditions of high anthropogenic load (Moeini et al., 2024).

Bacteria capable of being used for the biosynthesis of copper oxide nanoparticles were isolated from formation water of the Al-Halfaya oil fields (Iraq). In the course of the study, nine bacterial strains were isolated, including *Klebsiella quasipneumoniae* KP18-31, *Klebsiella pneumoniae* IOB-L, *Klebsiella quasipneumoniae* subsp. *similipneumoniae* 2437, *Bacillus cereus* DBA1, *Bacillus thuringiensis* MSP51 (later identified as a new strain AMHWRB3), *Neobacillus drentensis* ROA042, *Enterococcus faecalis* 2674, *Exiguobacterium mexicanum* AB201, and *Acinetobacter lwoffii* K34. Among the studied microorganisms, the most effective was *Bacillus*

thuringiensis AMHWRB3. Notably, this study represents one of the first examples of using bacteria isolated from oil reservoirs for the biosynthesis of CuONPs (Alshami et al., 2023).

Other polluted environments, including soils near metallurgical enterprises or agricultural lands irrigated with wastewater, are also sources of metal-resistant bacteria. *Klebsiella pneumoniae* NST2 was isolated from the rhizosphere of maize grown on lands irrigated with textile wastewater (Noman et al., 2021). The strain *Klebsiella pneumoniae* SN35 was isolated from agricultural lands polluted with wastewater. Using these bacteria, CuNPs were obtained that can reduce the toxic effects of heavy metals on plants, particularly by increasing wheat resistance to chromium stress (Noman et al., 2020b). *Pseudomonas fluorescens* MAL2 bacterial strain was isolated from soils polluted with heavy metals near metallurgical plants in Egypt. Unlike chemically synthesized analogues, CuNPs biosynthesized using the MAL2 strain demonstrated significant toxicity to the insect *Tribolium castaneum* (a pest of grain and grain products) even at low concentrations (El-Saadony et al., 2020).

Particular attention has been paid to the use of lactic acid bacteria as biologically safe microorganisms with the "Generally Recognized as Safe" (GRAS) status assigned by the U.S. Food and Drug Administration (FDA) (Stabnikova et al., 2023) for the synthesis of metal nanoparticles (Gregirchak et al., 2023; Stabnikov et al., 2025). It has been shown that the probiotic bacterium *Lactobacillus casei* subsp. *casei* can synthesize CuONPs exhibiting high antimicrobial activity and cytotoxic effects against cancer cell lines (Kouhkan et al., 2020).

Mechanisms of copper nanoparticle biosynthesis using bacteria

In bacterial-mediated biosynthesis of CuNPs, both intracellular and extracellular synthesis mechanisms can occur. For this purpose, liquid culture, supernatant, cell-free extracts, specific bacterial metabolites, and other bacterial-derived products may be utilized (Figure 2).

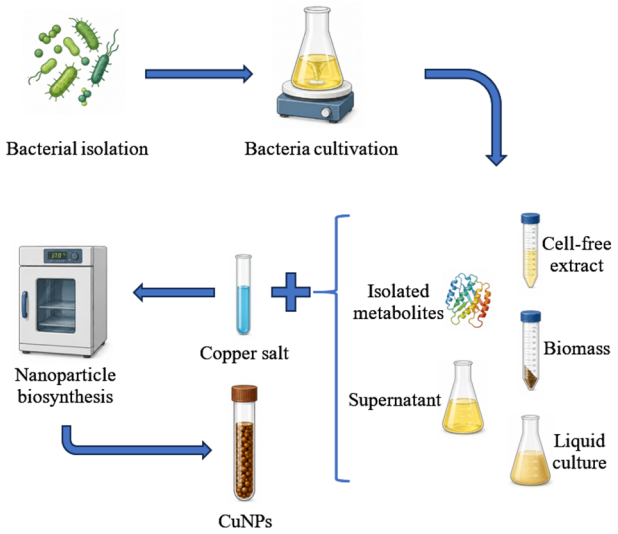

Figure 2. Biosynthesis of CuNPs using bacteria

Intracellular biosynthesis of CuNPs (Table 10) is a component of the bacterial detoxification system that ensures their survival in environments with high concentrations of heavy metals. This process involves the uptake of copper ions from the external environment, their transport into the cell, and subsequent enzymatic reduction to elemental or oxide forms directly within cellular structures.

Table 10

Biosynthesis of copper nanoparticles using liquid bacterial culture

Bacteria	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Desulfamplus magnetovallimortis BW-1	13.9 μM $CuSO_4$ × $5H_2O$, 28 °C, 20 h	CuSNPs, spherical, 69 nm	Park et al., 2022
Enterococcus thailandicus (E12)	5 mM $Cu(NO_3)_2$ × $3H_2O$, 30 °C, 120 h	CuNPs, spherical, 8–18 nm	Zaki et al., 2021
Klebsiella pneumoniae NST2	5 mM $CuSO_4$, 28 °C, 150 rpm, pH 7, 48 h	CuNPs, spherical, 22.44–44.26 nm	Noman et al., 2021
Klebsiella pneumoniae SN35	5 mM $CuSO_4$, 30 °C, 150 rpm, 24 h	CuNPs, spherical, 19.01–47.47 nm	Noman et al., 2020b
Lactobacillus casei subsp. *casei* ATCC 39392	1 mM $CuSO_4$, 37 °C, pH 6.0, 200 rpm, 48 h	CuONPs, spherical, average size 200 nm	Kouhkan et al., 2020
Priestia megaterium AMD 2024	1 мМ $CuSO_4$ × $5H_2O$, 30 °C, 150 rpm, 48 h	CuNPs, 57.73 nm, zeta potential –20.1 mV	Mohamed et al., 2024
Pseudomonas putida	1 mM $CuSO_4$, 30 °C, 150 rpm, 24 h	CuNPs, semispherical, 18.6–43.9 nm, zeta potential –23.4 mV	El-Sayed et al., 2025
Serratia sp. ZTB29	5 mM $CuSO_4$ × $5H_2O$, 28 °C, 150 rpm, 48 h	CuONPs, spherical 20–40 nm, zeta potential –15.4 mV	Singh et al., 2023

The first stage of intracellular biosynthesis is the interaction of Cu^{2+} ions with components of the cell envelope. Positively charged copper ions electrostatically bind to negatively charged groups of the cell wall or are transported into the cell via specialized transport systems (Kashyap et al., 2023).

A key role in the bioreduction process is played by intracellular enzymes. In particular, NADH-dependent reductases facilitate the transfer of electrons from the cofactor NADH to metal ions. As a result, copper ions are reduced to the zero-valent state, followed by a nucleation stage and subsequent nanoparticle formation. The membrane-bound enzyme NADH dehydrogenase-2 can catalyze the reduction of Cu(II) to Cu(I) under aerobic conditions. After reduction, copper atoms begin to aggregate, forming primary nanoclusters. Further growth of nanoparticles occurs through nucleation and coalescence of metal atoms, and their size and morphology largely depend on intracellular conditions such as pH, temperature, and metal ion concentration (Aziz et al., 2024).

Hypothetical models of intracellular nanoparticle formation are based on natural detoxification mechanisms that allow bacteria to survive in environments with high metal concentrations by converting toxic ions into inert nanostructures. In the cytoplasmic reduction model, characteristic of *Enterococcus thailandicus*, copper ions are reduced by nitrate reductase enzymes localized on the periplasmic or cytoplasmic bacterial membrane. This is followed by the nucleation stage and the formation of CuNPs, which typically aggregate in the central part of the cell and are stabilized by cytoplasmic proteins, preventing their uncontrolled release outside the cell (Zaki et al., 2021).

In the periplasmic space, a biomineralization model is realized, which was described in detail for magnetotactic sulfate-reducing bacteria *Desulfamplus magnetovallimortis* BW-1. In this case, copper ions accumulate in the periplasm and interact with sulfide ions (S^{2-}) formed as a result of sulfate reduction. This leads to the formation of CuSNPs. The process occurs under the control of specific proteins, including DegP-like proteins that regulate nucleation and nanoparticle formation (Park et al., 2022).

In the case of intracellular biosynthesis, nanoparticles are localized inside the cell. Therefore, their extraction requires a cell disruption step, for example, using ultrasonic treatment, mechanical disruption, or detergents (Karthikeyan et al., 2024).

The biosynthesis of CuNPs and CuONPs in cell-free systems was studied, particularly using liquid culture supernatants (Table 11).

Table 11

Biosynthesis of copper nanoparticles using cell-free supernatant

Bacteria	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Bacillus licheniformis CPJN13S	5 mM $CuSO_4$, 37 °C, pH 7, 18 h	CuNPs, hexagonal, mean size 12.4 nm, zeta potential –24.7 mV, PDI 0.386	Rani et al., 2025a
Bacillus subtilis MTCC 441	3 mM $CuCl_2$, 18–20 °C, pH 8, 12 h	CuONPs, spherical, 11.47 nm, zeta potential –26.9 mV, PDI 0.43	Kataria et al., 2025
Lactobacillus sp.	1 mM $CuSO_4$, pH 7, 35 min	CuNPs / CuONPs, spherical, 40–110 nm	Hamood et al., 2025
Niallia circulans G9	100 mM $CuSO_4$, 37 °C, pH 7, 120 rpm, 24 h	CuONPs, spherical / hexagonal, 13–100 nm	Aziz et al., 2024
Paenibacillus sp. S4c	100 mM $CuSO_4$, 45°C, pH 7, 120 rpm, 48 h	CuONPs, spherical, 5–40 nm	Aziz et al., 2024
Pantoea agglomerans CPHN2	5 mM $CuSO_4$, 23°C, 6 h	CuNPs / CuONPs, hexagonal 5–35 nm, zeta potential –21 mV	Rani et al., 2025b
Proteus mirabilis	$Cu(CH_3COO)_2 \times H_2O$ (20 g in 200 mL), 37 °C, 24 h	CuONPs, spherical / hexagonal, 13–19 nm	Faiq et al., 2024
Pseudomonas aeruginosa	1 mM $CuSO_4$	CuNPs, spherical, 56.40 nm	Hamady et al., 2024
Pseudomonas aeruginosa MO1	1 mM $CuSO_4$, 18–20 °C, pH 7, 24 h	CuONPs, cubical, 108–252 nm, zeta potential –23 mV	Tejaswi et al., 2025
Ralstonia sp. KF264453	3 mM $Cu(NO_3)_2 \times 3H_2O$, 18–20 °C, 150 rpm, 24 h	CuNPs, spherical, mean size 69.7 nm, zeta potential –5.1 mV, PDI 0.38	Vakili et al., 2025
Staphylococcus haemolyticus	1 mM $Cu(CH_3COO)_2$, 30–35 °C, 72 h	CuONPs, spherical, mean diameter 35 nm	Romi et al., 2024
Stenotrophomonas maltophilia SCS1.1	4 mM $CuSO_4$, 30 °C, pH 8, 48 h	CuONPs, spherical, rectangular, 18.4–31.7 nm	Kashyap et al., 2023
Streptomyces sp. S29	5 mM $CuSO_4$, 28–30 °C, pH 8, 48 h	CuNPs, spherical, square, hexagonal, 25–35 nm, zeta potential –33.7 mV, PDI 0.1–0.546	Elshaer et al., 2023
Streptomyces sp. MHM38	5 mM $CuSO_4$, 30–32 °C, pH 8, 1 h	CuONPs, spherical 1.72–13.49 nm	Bukhari et al., 2021
Streptomyces rochei	1 mM $CuSO_4$, 28 °C	CuONPs, spherical, mean size 10.7 nm, zeta potential –1.3 mV	El-Sherbiny et al., 2022
Xenorhabdus sp. NP2	5 mM $CuSO_4$, 30 °C, 150 rpm, 24 h	CuNPs, spherical 5–20 nm, PDI 0.312	Bharathi et al., 2022

In this case, the main role in nanoparticle biosynthesis is played by cellular metabolites, enzymes, and other biomolecules secreted by bacteria during cultivation. These compounds can simultaneously act as both reducing agents and stabilizers during nanoparticle formation. The extracellular biosynthesis process typically proceeds in several sequential phases. At the initial stage, which can be referred to as the activation or reduction phase, Cu^{2+} ions are reduced to atomic copper (Cu^0). This is followed by the growth phase, during which individual copper atoms combine into small clusters or nuclei. At the final stage, bioactive molecules adsorb onto the surface of the formed nanoparticles, limiting their further growth and preventing aggregation (El-Sherbiny et al., 2025).

In cell-free systems, the reduction of copper ions is provided by various compounds. One of the key mechanisms is the enzymatic reduction of copper ions involving extracellular reductases, which initiate the reduction process (Elshaer et al., 2023). When thermophilic bacteria *Anoxybacillus rupiensis* BS1 are used for the biosynthesis of CuNPs, lignin peroxidase can act as a reducing agent; this enzyme belongs to the class of oxidoreductases and is also capable of catalyzing electron transfer reactions (Sus et al., 2024).

In addition to enzymes, various bacterial metabolites present in cell-free systems (Table 12) play a significant role in the reduction of copper ions. Proteins and amino acids, due to the presence of amino, hydroxyl, and carboxyl groups, are capable of donating electrons, thereby promoting the formation of elemental copper (Rani et al., 2025b). Moreover, secondary metabolites such as polysaccharides, alcohols, and phenolic compounds actively participate in the nucleation and formation of nanostructures (Hamood et al., 2025).

Table 12

Cell-free biosynthesis of copper nanoparticles using bacterial metabolites

Bacteria	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Anoxybacillus rupiensis BS1	Bacterial lignin peroxidase, 100 mM $CuCl_2$, 60 °C, 350 rpm, pH 8, 4 h	CuNPs, spherical and cubical	Sus et al., 2024
Bacillus anthracis PFAB2	Cell wall polysaccharides, 1 mM $CuSO_4$, 45 °C, 12 h	CuONPs, spherical, mean size 702 nm, zeta potential –3.84 mV, PDI 0.437	Banerjee et al., 2024
Brevibacillus brevis PI-5	Aqueous cell-free extract, 5 mM $Cu(CH_3COO)_2 \times H_2O$, 100 rpm, pH 8, 1 h	CuONPs, spherical 2–28 nm	Fouda et al., 2022
Proteus mirabilis AB 932526.1	Purified carbohydrate bioflocculant, 3 mM $CuSO_4$, 18–20 °C, 24 h	CuNPs, spherical, mean size 20 nm	Nkosi et al., 2025
Spirulina platensis	Supernatant of cell lysate, 5 mM $Cu_2(CH_3COO)_4$, 100 °C, 1 h	CuONPs, spherical, 3.75–12.4 нм, zeta potential –21.63 mV	Doman et al., 2024
Stenotrophomonas sp. BS95	Supernatant of cell lysate, 10 mM $CuSO_4 \times 5\ H_2O$, 121°C, pH 7.0, 20 min	CuONPs, spherical, mean size 35.24 nm, zeta potential –28.57 mV, PDI 0.26	Talebian et al., 2023

After the reduction stage, nanoparticle stabilization occurs, which is ensured by biomolecules present in the reaction medium. These compounds adsorb onto the surface of newly formed CuNPs, acting as so-called capping agents. Protein and carbonyl groups form a protective layer that creates a negative zeta potential and, consequently, electrostatic repulsion between particles, preventing their aggregation and ensuring the colloidal stability of the system (Alshami et al., 2023; Kataria et al., 2025).

Fungi for the biosynthesis of copper nanoparticles

Fungi from soil and plants

Soil is one of the most common sources for the isolation of micromycetes that can be used for the biosynthesis of copper nanoparticles (Table 13). *Aspergillus versicolor* EM-CN2 was isolated from agricultural land samples in Sharkia Governorate, Egypt (Ammar et al., 2019). The strain *Aspergillus terreus* AH20 was isolated from soil samples collected in the garden of the Faculty of Science, Al-Azhar University (Egypt) (El-Naggar et al., 2022). Of particular interest is rhizospheric soil – the zone of direct interaction between plant root systems and microorganisms. Recently, the biosynthesis of multimetallic Se-BiO-CuO nanoparticles (selenium - bismuth oxide - copper oxide) using a cell-free aqueous extract of the fungus *Talaromyces haitouensis*, isolated from the rhizosphere, was reported for the first time (Rasheed et al., 2024).

Table 13

Biosynthesis of copper nanoparticles using micromycetes

Fungi	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Biomass			
Shizophyllum commune KF954705	1 mM $CuCl_2 \times 2\ H_2O$	CuNPs, spherical, 40–65 nm	Fatima et al., 2022
Trichoderma harzianum	2 mM $CuSO_4$, 25 °C, 180 rpm, 36 h	CuSNPs, spherical, rod-like, 40–90 nm	Abishad et al., 2022
Cell-free aqueous extract			
Aspergillus flavus	100 mM $CuSO_4 \times 5\ H_2O$, 1% ascorbic acid, heating, stirring, 12 min	CuNPs, spherical, 5–12 nm, zeta potential –26.4 mV	Shende et al., 2021
Aspergillus niger SBA3	15 mM $CuSO_4$, 37 °C, 24 h	CuNPs, spherical, 260 nm, zeta potential +18.8 mV	Noor et al., 2025
Aspergillus terreus BR.1	5 mM $Cu(CH_3COO)_2 \times H_2O$, 100 rpm, pH 8, 1 h	CuONPs, spherical, 15–55 nm, zeta potential –26.6 mV, PDI 0.362	Nassar et al., 2023
Aspergillus versicolor EM-CN2	3 mM $CuSO_4 \times 5\ H_2O$, 30 °C, 72–96 h	CuNPs, round, polygonal, 23–82 nm, zeta potential –10.2 mV, PDI 0.447	Ammar et al., 2019
Phoma glomerata MTCC-2210	100 mM $CuSO_4 \times 5\ H_2O$	CuONPs, spherical, mean size 119 nm, zeta potential –23.5 mV	Ingle et al., 2024
Trichoderma sp.	$CuSO_4 \times 5\ H_2O$, 24–25 °C, 24 h	CuONPs, quasi-spherical, 1.3–30 nm, zeta potential –32.6 mV	Garcia-Marin et al., 2022
Fungal biomass filtrate			
Aspergillus carbonarius	150 mM $CuCl_2$, 18–20 °C, 24 h	CuNPs, cubical, pyramidal, prismatic, 15–84.29 nm	Al-Qaissi et al., 2024
Aspergillus fumigatus SM4	5 mM $Cu(CH_3COO)_2 \times H_2O$, 100 rpm, pH 8, 1 h	CuONPs, spherical, 20–150 nm	Hassan et al., 2025
Aspergillus niger AH1	1 mM $Cu(CH_3COO)_2$, 1 mM Na_2SeO_3, 30 °C, 150 rpm, 24 h	CuSeNPs (bimetallic), spherical, mean size 15 nm, zeta potential –31 mV, PDI 0.18	Attia et al., 2025

Aspergillus niger KY 401431	10 mM $CuSO_4$, 80 °C, 4 h	CuNPs / CuONPs, spherical, 4–10 nm, PDI 0.403	Abd El Rahman et al., 2025
Aspergillus niger	5 mM $Cu(NO_3)_2$, 30 °C, 150 rpm, 96 h	CuNPs, spherical, oval, 3–70 nm	Suood et al., 2021
Aspergillus sydowii FCSRL3	0.1 mM $CuSO_4$, 27 °C, 96–168 h	CuONPs, spherical, mean size 86 nm	Radhakrishnan et al., 2025
Aspergillus terreus AH20	2 mM$Cu(CH_3COO)_2$, 30 °C, 150 rpm, 24 h	CuNPs / CuONPs, spherical, mean size 20 nm, zeta potential –33.7 mV	El-Naggar et al., 2022
Aspergillus terreus	10 mM $CuSO_4$, 30 °C, 180 rpm, pH 6, 48 год	CuONPs, spherical, mean size 15.75 nm	Mousa et al., 2020
Chaetomium globosum	1 mM $CuSO_4$, 96–168 h	CuNPs, spherical, 10–120 nm	Dorjee et al., 2024
Fusarium solani KJ 623702	1 mM $CuSO_4$, 28 °C, 120 rpm, pH 5, 24 h	CuNPs, spherical, 9.97–19.49 nm, zeta potential –34.8 mV	El Sayed et al., 2019
Neurospora crassa	20 mM $CuCl_2$, 25 °C, 60 rpm, pH 7.5, 12 h	CuNPs, spherical, 20–40 nm	Liu et al., 2021a
Penicillium chrysogenum ATCC 48271	2 mM $Cu(CH_3COO)_2 \times 2$ H_2O, 65 °C, 200 rpm, 4 h	CuONPs, spherical (4–15 nm), rod-like (11–53.8 nm)	Shehabeldine et al., 2023
Penicillium pimiteouiense	5 mM $CuSO_4$, 18–20 °C, 6 h	CuONPs, sphrical, 50–60 nm	Zhou et al., 2024
Trichoderma virens	1 mM $CuSO_4$, 96–168 h	CuNPs, spherical, 7–90 nm	Dorjee et al., 2024

In addition to soils, plants are an important source of fungi for the biosynthesis of CuNPs, particularly endophytic fungi that colonize internal plant tissues without causing pathogenic effects. Due to their close interaction with plant metabolism, such microorganisms are capable of producing a wide range of biologically active compounds involved in the reduction of metal ions and the stabilization of nanoparticles. For example, the strain *Aspergillus terreus* BR.1 was isolated from garlic roots (*Allium sativum*) (Nassar et al., 2023). The endophytes strains *Aspergillus sydowii* FCSRL3 and *Aspergillus versicolor* FCPRS11 were isolated from the tissues of the neem tree (*Azadirachta indica*) (Radhakrishnan et al., 2025).

An additional, yet equally important, source for the isolation of micromycetes is organic waste, particularly decaying fruits and vegetables. Such substrates harbor microbial communities with high adaptive potential, capable of active metabolism and the biosynthesis of secondary metabolites. It is from similar organic residues that *Aspergillus niger* STA9 was isolated, whose cell-free filtrate can be used for the biosynthesis of CuNPs (Noor et al., 2020).

Fungi from polluted ecosystems

Polluted ecosystems are an important source for the isolation of micromycetes that can be used for the biosynthesis of CuNPs. Such fungi are adapted to adverse environmental conditions and are characterized by increased tolerance to heavy metals, the ability to bioaccumulate them, and effective participation in bioreduction processes. *Penicillium pimiteouiense* fungus was isolated from soils of the Sossego copper mine in Brazil (Zhou et al., 2024). Another important source is industrial effluents and wastes. The strain *Fusarium solani* KJ 623702 was isolated from soils that had long been irrigated with industrial wastewater (El Sayed et al., 2019). In addition, micromycetes are isolated from coal mines, municipal and industrial waste landfills, as well as sewage systems. Based on the screening of 21 micromycete representatives isolated from polluted

areas of Uzbekistan, the most promising fungi for the biosynthesis of CuNPs were selected: *Fusarium oxysporum*, *Penicillium* sp., *Trichoderma harzianum*, *Alternaria pluriseptata*, *Aspergillus terreus*, *Aspergillus versicolor*, and *Aspergillus oryzae* (Zaynitdinova et al., 2025).

Mechanisms of copper nanoparticle biosynthesis using fungi

From a biological perspective, the ability of micromycetes to synthesize CuNPs should be considered an evolutionarily developed adaptive mechanism aimed at environmental detoxification. Copper ions at high concentrations are toxic to cells. The conversion of soluble Cu^{2+} ions into insoluble zero-valent forms (Cu^0) reduces their toxicity. The activation of nanoparticle biosynthesis processes is often associated with the fungal response to stress caused by the presence of heavy metals in the cultivation medium. Under such conditions, biosorption processes are intensified, during which metal ions are adsorbed onto the cell surface. This is followed by their intracellular or extracellular transformation involving enzymatic and non-enzymatic mechanisms (Abishad et al., 2022). Fungi, particularly representatives of the genera *Aspergillus* and *Penicillium*, are characterized by high tolerance to heavy metals. This ensures their ability to survive and maintain metabolic activity under extreme conditions, including anthropogenically polluted ecosystems (Zaynitdinova et al., 2025).

A key role in the enzymatic reduction of copper ions is played by NADH- or NADPH-dependent nitrate reductases. The mechanism of action of these enzymes is based on the transfer of electrons from reduced cofactors (NADH or NADPH) to copper ions. As a result, copper ions are reduced to the zero-valent state, which is a prerequisite for the formation of metallic nanoparticles, or to oxide forms of copper as a result of subsequent redox transformations (Noor et al., 2020). NADPH plays a particularly important role in this process, often acting as the main electron donor in the extracellular environment, ensuring efficient reduction of copper ions and stabilization of intermediate forms (Zhou et al., 2024).

In addition to nitrate reductase, other fungal enzymes are also involved in the biosynthesis of CuNPs. In particular, it has been established that laccases and NADPH-dependent sulfite reductases can directly or indirectly catalyze the reduction of copper ions (Nassar et al., 2023). Oxidoreductases with broad activity spectra, secreted by fungi such as *Aspergillus* and *Fusarium*, also play an important role. These enzymes not only participate in redox transformations but also contribute to the binding, transport, and detoxification of copper ions, which is critical for microbial survival in metal-rich environments (Noor et al., 2020).

A separate mechanism is associated with the activity of the enzyme urease, particularly in fungi such as *Neurospora crassa*. Urease catalyzes the hydrolysis of urea to form ammonium and carbonate ions, leading to an increase in environmental pH. Under alkaline conditions, carbonate ions interact with copper ions, promoting the formation of copper carbonate nanoparticles. Thus, in this case, biosynthesis occurs not only through direct enzymatic reduction but also via indirect biochemical changes in the environment that initiate nucleation and nanoparticle growth (Liu et al., 2021a).

Phenolic compounds and polyphenols play a particularly important role in the reduction of copper ions, as they are among the most active reducing agents of fungal origin. Due to the presence of multiple hydroxyl groups, especially in ortho- and para-positions, these compounds can efficiently donate electrons, facilitating copper ion reduction. The high reducing potential of phenolic metabolites leads to rapid reaction rates, in some cases allowing nanoparticle synthesis to be completed within minutes. In addition, phenolic compounds exhibit strong chelating ability, promoting copper ion binding, initiating nucleation processes, and forming more ordered and stable nanostructures (Zhou et al., 2024).

Organic acids and carbohydrates also play an important role in the biosynthesis of CuNPs and CuONPs. Organic acids such as citric, oxalic, oleic, and palmitic acids can perform a dual function: they participate in the reduction of metal ions and stabilize the formed nanoparticles by

adsorbing onto their surface and forming a protective layer. Carbohydrates (glucose, fructose) can also act as mild reducing agents, participating in redox processes and promoting gradual nanoparticle formation (Nassar et al., 2023).

Other fungal secondary metabolites are also involved in CuNP biosynthesis. Alkaloids and terpenoids can act as reducing or capping agents, stabilizing the nanoparticle surface and preventing aggregation. Fungal pigments such as naphthoquinones and anthraquinones can function as electron carriers, accelerating electron transfer to copper ions and intensifying the reduction process. Vitamins, including folic acid, may also participate in redox transformations, further contributing to the formation of CuNPs or CuONPs (El Sayed et al., 2019).

Capping and stabilization processes are critical stages in the formation of functionally stable CuNPs or CuONPs. The main capping agents include secreted proteins, peptides, polysaccharides, glycoproteins, and low-molecular-weight secondary metabolites, particularly phenolic compounds and organic acids. Among proteins, special attention is given to enzymes such as triosephosphate isomerase, which may be involved not only in metabolic processes but also in nanoparticle stabilization (Liu et al., 2021b). The attachment of biomolecules to the copper surface occurs through various interactions, including coordination bonds involving amino groups, thiol groups of cysteine residues, hydroxyl groups of phenols, as well as electrostatic interactions with carboxylate groups of cell wall components (Zhou et al., 2024).

Yeast for the biosynthesis of copper nanoparticles

It is important to note that a limited number of studies on the biosynthesis of CuNPs using yeasts were reported in the scientific literature in recent years. Considering this, in order to obtain a more comprehensive overview of the current state of research in this field, the time frame for source analysis was extended back to 2014. Despite this approach, the overall number of relevant publications remained relatively limited. (Table 14). This indicates both the novelty of this research area and its significant potential for further investigation.

Table 14

Biosynthesis of copper nanoparticles using yeast

Yeast	Nanoparticles biosynthesis parameters	Characteristics of nanoparticles	Reference
Biomass (living cells)			
Filobasidium stepposum	2 mM $CuSO_4$, 8 mM $InCl_3$, 20 °C, pH 9, 14–30 days	CuInSNPs (copper-indium-sulphur), various shapes, 3.4–4.9 nm	Arriaza-Echanes et al., 2024
Komagataella phaffii X-33-Cyb5R	$CuSO_4$ (12 mM), 30 °C, pH 4, 36 h	CuNPs, spherical, 40–80 nm	Dong et al., 2025
Rhodotorula mucilaginosa	2.5 mM $CuSO_4$, 30 °C, 230 rpm, pH 7, 24 h	CuONPs, spherical, 51.6–111.4 nm, zeta potential –2.9 mV, PDI 0.43	Hassabo et al., 2022
Biomass (autoclaved)			
Rhodotorula mucilaginosa	$CuCl_2 \times 2\ H_2O$ (100 mg/L), 30 °C, pH 5, 1 h	CuNPs, spherical, mean size 10.5 nm	Salvadori et al., 2014
Yarrowia lipolytica AUMC 9256	$CuSO_4 \times 4\ H_2O$ (450 mg/L), 30 °C, 120 rpm, pH 6, 1.5 h	CuNPs, spherical, 22.34 nm	El-Sayed et al., 2018
Polysaccharides			
Pichia kudriavzevii MH545928.1	3 mM $CuSO_4$, 18–20 °C, 24 h	CuNPs, spherical, polygonal, mean size 20 nm	Tsilo et al., 2023

One of the sources for yeast isolation is marine ecosystems. Twenty yeast isolates were obtained from seawater, beach sand, and coastal areas of the Red Sea shoreline (Giftun Island, Egypt). Among them, *Rhodotorula mucilaginosa* showed the highest efficiency for the biosynthesis of CuONPs (Hassabo et al., 2022).

Psychrophilic yeasts are of particular interest. From soil samples collected in the Ellsworth Mountains near Union Glacier (Antarctica), *Filobasidium stepposum*, *Naganishia uzbekistanensis*, and *Naganishia vishniacii* were isolated. Notably, the use of *Filobasidium stepposum* biomass enabled the synthesis of complex semiconductor nanoparticles of the Cu-In-S (copper - indium - sulphur) type (Arriaza-Echanes et al., 2024).

Yeasts isolated from food and fermented products also represent a promising group for nanoparticle biosynthesis. In particular, the strain *Pichia kudriavzevii* MH545928.1 was isolated from a symbiotic culture of bacteria and yeast used for kombucha production (Kombucha tea SCOBY). The polysaccharides of these yeasts act as natural reducing and capping agents, ensuring the formation of stable CuNPs (Tsilo et al., 2023).

Another important reservoir of metal-resistant yeasts is industrial wastewater and polluted environments. Prolonged exposure to toxic metals promotes the development of efficient detoxification and metal biotransformation mechanisms in these microorganisms. *Rhodotorula mucilaginosa* was isolated from wastewater of the Sossego copper mine (Pará State, Brazil). These yeasts have adapted to extremely high concentrations of copper ions (up to 2000 mg/L) (Salvadori et al., 2014).

Genetically modified yeasts are also of considerable interest, particularly the strain *Komagataella phaffii* (formerly *Pichia pastoris*) X-33-Cyb5R, into which the cytochrome b5 reductase (Cyb5R) gene from *Aspergillus oryzae* has been integrated. The expression of Cyb5R increases yeast tolerance to high concentrations of copper ions (up to 12–14 mM), as this enzyme facilitates electron transfer from NADH to metal ions, promoting their reduction and decreasing toxicity. As a result of this genetic modification, the cells' ability to reduce copper ions and accumulate them intracellularly is enhanced, thereby increasing the efficiency of CuNP biosynthesis (Dong et al., 2025).

Mechanisms of copper nanoparticle biosynthesis using yeasts

The mechanisms of CuNP biosynthesis involving yeasts result from a complex interplay of physicochemical and biological processes occurring at different levels of cellular organization. The initial stage is the biosorption and binding of copper ions by yeast cell structures. The cell wall of *Komagataella phaffii* contains mannoproteins and polysaccharides with various functional groups: carboxyl, hydroxyl, amino, sulfhydryl, and phosphate. These groups act as active binding sites for Cu^{2+} cations through electrostatic interactions and complex formation. A key stage is the bioreduction of copper ions to the zero-valent state. This process can occur via both enzymatic and non-enzymatic pathways. Enzymatic reduction is associated with the activity of oxidoreductases, which facilitate electron transfer from intracellular donors such as NADH to copper ions. Cytochrome b5 reductase plays a particularly important role, catalyzing electron transport and contributing to copper detoxification while simultaneously initiating nanoparticle formation (Dong et al., 2025). Non-enzymatic reduction may occur with the participation of low-molecular-weight compounds. For example, phenolic compounds characteristic of marine yeasts such as *Rhodotorula mucilaginosa* act as effective electron donors (Hassabo et al., 2022). In addition, hydrogen sulfide (H_2S), produced by *Filobasidium stepposum* during the metabolism of sulphur-containing amino acids, can react with metal ions, promoting nanoparticle formation (Arriaza-Echanes et al., 2024).

The localization of nanoparticle biosynthesis depends on yeast species and cultivation parameters. Extracellular synthesis involves the adsorption of copper ions onto the cell wall surface, followed by their reduction and nanoparticle formation. This mechanism has been

described for *Yarrowia lipolytica* and genetically modified yeasts *Komagataella phaffii* (El-Sayed, 2018; Dong et al., 2025). Intracellular synthesis occurs via the transport of copper ions into the cell, where they are reduced by cytoplasmic enzymatic systems. The formed CuNPs may accumulate in the cytoplasm or be deposited in vacuoles, which is considered a cellular defense mechanism against metal toxicity. In this case, nanostructures of various morphologies may form, including needle-like or rod-shaped aggregates (Salvadori et al., 2014).

The final stage is nanoparticle stabilization (capping), which prevents aggregation and ensures colloidal stability. Yeasts produce a variety of biomolecules, including proteins, peptides, exopolysaccharides, and low-molecular-weight thiols (e.g., glutathione), which adsorb onto the nanoparticle surface and form a protective layer. Glutathione performs a dual function, acting both as a stabilizer and as a heavy metal detoxification agent. This biogenic coating creates steric hindrance that prevents CuNPs from approaching each other, ensuring their kinetic stability and preventing precipitation (Arriaza-Echanes et al., 2024).

A distinctive feature of copper nanoparticle biosynthesis using yeasts is also the formation of copper oxide forms. In many cases, metallic copper (Cu^0) is initially formed, which, due to its high reactivity, is rapidly oxidized by atmospheric oxygen to form Cu_2O or CuO. When marine yeasts such as *Rhodotorula mucilaginosa* are used, the process may involve preliminary hydrolysis of copper salts ($CuSO_4$) to form $Cu(OH)_2$, which is subsequently reduced by phenolic compounds to Cu_2O (Hassabo et al., 2022).

Use of biogenic copper nanoparticles for wastewater purification

Dye removal

Biogenic CuNPs demonstrate high efficiency in removing a wide range of synthetic dyes (Table 15) which are widely used in the textile, paper, and other industries. In particular, for the dye Congo red, a removal efficiency of up to 99.2% has been reported when using CuONPs (Kamakshi et al., 2024). CuNPs synthesized using bacteria provide approximately 97% degradation of Congo red (Noman et al., 2020a). Biogenic CuONPs show over 94% degradation efficiency for Amido black 10B (Khandelwal et al., 2024). High performance has also been observed for brilliant green and malachite green, where the removal efficiency using biogenic CuONPs can exceed 98% (Khandelwal et al., 2023). Methylene blue is effectively degraded both by CuSNPs synthesized using unicellular algae (Borah et al., 2022) and by CuNPs synthesized with the involvement of bacterial polysaccharides (Nkosi et al., 2025) and plant extracts (Nazir et al., 2023; Yu et al., 2025).

The high efficiency of biogenic copper nanoparticles in water purification processes is due to the combination of several mechanisms of action. One of the key mechanisms is the photocatalytic process, in which, under the influence of light radiation, reactive oxygen species such as hydroxyl and superoxide radicals are generated on the surface of the nanoparticles. These active species are capable of oxidizing complex organic dye molecules into simpler and less toxic compounds, including carbon dioxide and water (Khandelwal et al., 2023). Another important mechanism is catalytic reduction, which occurs in the presence of electron donors, where nanoparticles act as effective electron carriers and promote the breakdown of chromophoric groups in dyes, particularly azo bonds (Yu et al., 2025). Additionally, adsorption and flocculation processes play a significant role: functional groups (hydroxyl, carboxyl) on the surface of biogenic nanoparticles enable the binding of dye molecules and their subsequent removal from the aqueous environment through sedimentation (Nkosi et al., 2025).

Table 15

Use of biogenic copper nanoparticles for wastewater purification

Biological object for nanoparticles synthesis	Pollutant	Nanoparticles-mediated degradation	Reference
Acer palmatum (leaves)	Amido black 10B	86 % in 1.5 h	Sazak et al., 2023
Asterarcys quadricellulare (unicellular algae)	Brilliant green; Malachite green	98.02 % in 1 h; 96.04 % in 1 h	Khandelwal et al., 2023
Bacillus flexus FB-1 (bacteria)	Reactive black 5; phosphates; sulphates	88.16 % in 4 h; 49.49 %; 43.16 %	Batool et al., 2024
Celastrus paniculatus (leaves)	Methylene blue	90 % in 2 h	Mali et al., 2020
Chlorella ellipsoidea (unicellular algae)	Methylene blue	88.5 % in 1 h	Borah et al., 2022
Citrullus colocynthis (leaves)	Methylene blue	65 % in 2.6 h	Nazir et al., 2023
Coelastrella terrestris (unicellular algae)	Amido black 10B	94.19 % in 1.5 h	Khandelwal et al., 2024
Escherichia sp. SINT7 (bacteria)	Congo red	97.07 % in 5 h	Noman et al., 2020a
Malpighia glabra (fruit)	Phenol red	97 % in 9 min	Nguyen et al., 2024
Neurospora crassa (fungi)	Methyl red; Chrome (VI)	Over 90 % in 6 h; ~75 % in 5 h	Liu et al., 2021a
Pleurotus cystidiosus (mushroom)	Congo red; Malachite green; Remazole blue	99 %, 71.3 % and 49.2 % in 1.5 h	Kamakshi et al., 2024
Proteus mirabilis (bacteria)	Methyl orange; sulphates; phosphates; nitrates	93 %; 93 %; 88 %; 82 %	Nkosi et al., 2025
Chenopodium quinoa (seeds)	Cefixime	122.9 mg/g (absorption capacity)	Hassan et al., 2023
Sargassum cervicorne (brown algae)	Methyl orange	98.58 % in 8–10 h	Anwar et al., 2024
Stenotrophomonas maltophilia SCS1.1 (bacteria)	Chlorpyrifos, profenofos, imidacloprid	90.35 %; 87.24 %; 51.29 %	Kashyap et al., 2023
Zygnema sp. (filamentous green algae)	Reactive red	84.66 % in 1.25 h	Alsalamah et al., 2024

Removal of metal ions, pesticides, antibiotics, and other compounds

One of the key applications of biogenic CuNPs is the removal of metal ions (Table 15) from wastewater. Copper nanoparticles synthesized using the fungus *Neurospora crassa* are capable of removing up to 75% of toxic chromium (VI). The mechanism of this process includes both physical adsorption of chromium ions onto the nanoparticle surface and their chemical reduction to the less toxic chromium (III) form due to the action of active copper species on the nanoparticle surface (Liu et al., 2021a). Bacteria of the genus *Bacillus*, isolated from technogenically polluted environments, demonstrate the ability for complex wastewater purfication from metal ions. In particular, *Bacillus cereus* provides removal of up to 79.81% of copper, *Bacillus paramycoides* up to 86.74% of nickel, and *Bacillus wiedmannii* up to 91.96% of manganese, with simultaneous nanoparticle formation (Moeini et al., 2024). An important example of bioremediation is also the yeast *Yarrowia lipolytica*,

which is capable of extracellular synthesis of CuNPs directly during the treatment of ceramic industry wastewater, where copper ions accumulate both on the cell wall surface and within cellular vacuoles (El-Sayed, 2018).

CuONPs synthesized using the culture supernatant of *Stenotrophomonas maltophilia* SCS1.1 exhibit catalytic activity toward the degradation of common insecticides – chlorpyrifos, profenofos, and imidacloprid. The main mechanism in this case is the generation of reactive oxygen species on the nanoparticle surface, which induce oxidative degradation of pesticide molecules into less toxic compounds (Kashyap et al., 2023).

A promising direction is the use of CuNPs as nano-adsorbents for the removal of pharmaceutical pollutants from industrial wastewater. In particular, copper nanoparticles synthesized using an aqueous extract of quinoa seeds effectively adsorb antibiotics. For cefixime, the maximum adsorption capacity reaches 122.9 mg/g at pH 4, allowing nearly complete removal of this drug from real samples of pharmaceutical wastewater (Hassan et al., 2023).

The use of biogenic CuNPs leads to a significant reduction in the concentration of inorganic anions in water. Copper nanoparticles synthesized using bacteria reduce the concentration of sulfates and phosphates in textile industry wastewater (Batool et al., 2024). CuNPs enable the removal of up to 88% of phosphates, 80% of nitrates, and 63% of sulfates from coal mine effluents. In domestic wastewater, nitrate removal efficiency reaches 82% and total nitrogen removal 97%, indicating the significant potential of biogenic CuNPs in preventing eutrophication of aquatic ecosystems (Nkosi et al., 2025).

Improvement of general wastewater quality indicators

The application of CuNPs and CuONPs significantly affects key physicochemical parameters of wastewater quality. In particular, chemical oxygen demand (COD), which is an indicator of the level of organic pollution, is substantially reduced when biogenic nanoparticles are used. It has been established that CuONPs synthesized using an aqueous extract of freshwater unicellular algae *Coelastrella terrestris* are capable of reducing COD levels by more than 80% (Khandelwal et al., 2024). CuNPs obtained using the bacteria *Bacillus flexus* FB-1 and *Escherichia* sp. SINT7 ensure a reduction of this parameter within the range of 40–70% (Batool et al., 2024; Noman et al., 2020a). In the case of CuNPs synthesized using bacterial polysaccharides, the efficiency of COD reduction can exceed 90%. A similar trend is observed for biological oxygen demand (BOD), where the use of biogenic CuNPs leads to a reduction of 75–91% (Nkosi et al., 2025).

An important effect is also the normalization of the acid-base balance of wastewater. Treatment with biosynthesized nanoparticles contributes to reducing alkalinity and bringing pH values closer to neutral, which is critically important for the subsequent discharge of water into natural reservoirs. At the same time, a significant increase in dissolved oxygen levels is observed, associated with the degradation of organic pollutants and improved aeration properties of water. This creates favorable conditions for the restoration of aquatic ecosystems (Khandelwal et al., 2024).

In addition, the use of biogenic CuNPs leads to a reduction in both dissolved and suspended impurities in wastewater. The level of total dissolved solids (TDS) decreases by 57–89%, while total suspended solids (TSS) are reduced by 55–78%. A decrease in electrical conductivity by 55–81% confirms the effective removal of dissolved salt ions. A reduction in total water hardness by 45–61% and a decrease in chloride concentration by 44–61% are also observed, indicating reduced mineralization and improved overall wastewater quality (Noman et al., 2020a).

Use of biogenic copper nanoparticles for agriculture

Impact on bacterial and fungal infections agents

Copper nanoparticles perform broad spectrum of antimicrobial activity against numerous phytopathogens (Table 16).

Table 16

Copper nanoparticles activity against phytopathogens

Copper nanoparticles synthesis platform	Pathogen test culture	Nanoparticles antimicrobial activity indicator	Reference
Aspergillus carbonarius (fungi)	*Fusarium oxysporum*	Growth reduction zone 16 mm at 150 mM CuNPs	Al-Qaissi et al., 2024
Aspergillus niger AH1 (fungi)	*Ralstonia solanacearum*	Growth reduction zone 30 mm at 200 µg/mL CuSeNPs; MIC 12.5 µg/mL	Attia et al., 2025
Azadirachta indica, *Lantana camara*, *Senna spectabilis*, *Tectona grandis* (leaves)	*Corynespora cassiicola*	Mycelium growth reduction 75 % at 1000 ppm CuONPs	Yadava et al., 2025
Chaetomium globosum; *Trichoderma virens* (гриби)	*Xanthomonas euvesicatoria*	Growth reduction zone at 50 µg/mL CuNPs 22–22.6 mm	Dorjee et al., 2024
Citrus aurantium (fruit peel)	*Alternaria alternata*	Radial growth reduction 73,7 % at 2.5 mg/mL CuONPs	Albrahim et al., 2025
Heliotropium bacciferum (leaves)	*Rhizoctonia solani*; *Fusarium oxysporum*	Mycelium growth reduction at 100 µg/mL CuONPs 81.48 % for *R. solani* and 71.11 % for *F. oxysporum*	Hamdy et al., 2024
Mangifera indica (leaves)	*Rhizopus oryzae*	Mycelium growth reduction at 100 µg/mL CuONPs	Shah et al., 2024
Oedogonium sp. (freshwater algae)	*Xanthomonas citri*	Growth reduction zone 35.2 mm at 1200 ppm CuNPs; MIC 2000 µg/mL	Waqif et al., 2024
Phoma glomerata MTCC-2210 (fungi)	*Aspergillus niger*; *Aspergillus flavus*	Growth reduction zone at 1 mg/mL CuONPs: 19 mm for *A. niger*, 23 mm for *A. flavus*; MIC: 180–220 µg/mL	Ingle et al., 2024
Pseudomonas aeruginosa MO1 (bacteria)	*Colletotrichum capsici*; *Rhizoctonia solani*	At 30 µg/mL CuONPs growth reduction zone 25.16 mm for *C. capsici* and 16.1 mm for *R. solani*	Tejaswi et al., 2025
Pterocarpus santalinus (leaves)	*Aspergillus niger*	Mycelium growth reduction zone 23 mm at 120 µg/mL CuONPs	Babulla et al., 2024
Serratia sp. ZTB29 (bacteria)	*Alternaria* sp.	Mycelium growth reduction 91 % at 200 µg/mL CuONPs	Singh et al., 2023
Stenotrophomonas maltophilia SCS1.1 (bacteria)	*Penicillium digitatum*; *Fusarium oxysporum*	Mycelium growth reduction zone at 100 ppm CuONPs 100% for *P. digitatum*, 95.19 % for *F. oxysporum*	Kashyap et al., 2023
Xenorhabdus sp. NP2 (bacteria)	*Fusarium* sp.	Growth reduction zone 19 mm at 100 µg/mL CuNPs	Bharathi et al., 2022
Ziziphus spina-christi (leaves)	*Fusarium solani*	Mycelium growth reduction zone 91.17 % at 250 µg/mL CuONPs	El-Abeid et al., 2024

Biosynthesized CuNPs exhibit complex multimodal antimicrobial mechanisms, which significantly reduce the likelihood of development of the resistance in microorganisms. One of the initial stages of antimicrobial action is their interaction with the cell wall of phytopathogens.

Due to electrostatic attraction between positively charged nanoparticles and negatively charged components of the cell wall, adsorption onto the cell surface occurs. Their small size and high surface-area-to-volume ratio facilitate the penetration of CuNPs through cellular barriers, leading to mechanical damage of membrane structures. As nanoparticles accumulate, defects such as pores and localized disruptions are formed, accompanied by loss of membrane selective permeability, decreased membrane potential, and loss of intracellular contents, ultimately resulting in microbial cell death (Shah et al., 2024).

A key mechanism of CuNP cytotoxicity is the induction of oxidative stress. Biosynthesized nanoparticles are capable of catalyzing the formation of reactive oxygen species (ROS), including hydrogen peroxide and hydroxyl radicals. Excessive ROS accumulation disrupts the cellular antioxidant system and causes lipid peroxidation of membranes. This leads to further damage to cellular structures and enhances the overall cytotoxic effect (Tejaswi et al., 2025).

An important component of antimicrobial action is the gradual release of copper ions (Cu^{+} and Cu^{2+}) from the nanoparticle surface. These ions penetrate the cell and disrupt ionic homeostasis by interacting with key biomolecules and interfering with metabolic processes. In particular, they can replace other metal ions in the active sites of enzymes, leading to their functional inactivation. At the intracellular level, CuNPs and copper ions cause significant damage to genetic material and proteins. Interaction with DNA and RNA disrupts their spatial organization, induces strand breaks, and causes mutational changes, thereby blocking replication and transcription processes (Dorjee et al., 2024).

In addition to general mechanisms, CuNPs demonstrate specific activity against fungal pathogens. They are capable of inhibiting chitin synthase activity – a key enzyme in fungal cell wall chitin biosynthesis – leading to cell wall weakening and increased sensitivity to external factors (Hamdy et al., 2024). Interaction of nanoparticles with membrane ergosterol has also been established, resulting in pore formation and disruption of osmotic balance (Tahir et al., 2022). Furthermore, CuNPs affect fungal morphogenesis by causing hyphal deformation and suppressing sporulation processes, thereby limiting their reproduction and spread (Ammar et al., 2019).

Insecticidal activity

Biogenic CuNPs demonstrate pronounced insecticidal activity against various groups of insects, including storage pests, lepidopterans, as well as representatives of social insects and dipterans. For example, CuNPs synthesized using aqueous leaf extracts of *Acacia cornigera* and *Annona purpurea* ensure high mortality of *Tribolium castaneum* (red flour beetle), reaching levels of 90% and 76.6%, respectively (Solorzano Toala et al., 2024). CuNPs obtained using the bacterium *Pseudomonas fluorescens* MAL2 also exhibit significant toxicity toward *Tribolium castaneum* (LC50 = 36.89 ppm) (El-Saadony et al., 2020).

High efficacy of CuNPs has also been established against lepidopteran pests. Nanoparticles synthesized using the liquid culture supernatant of *Xenorhabdus* sp. NP2 cause up to 80% mortality in larvae of *Spodoptera litura* (cotton leafworm) (Bharathi et al., 2022).

There are also reports on the effectiveness of CuNPs against termites and mosquitoes. For instance, nanoparticles synthesized using leaf extract of *Grewia asiatica* cause high mortality of *Heterotermes indicola* (termites) at a concentration of 100 ppm and also exhibit pronounced toxicity toward larvae of *Aedes aegypti* (mosquitoes), highlighting their potential use as biodegradable insecticides (Tahir et al., 2022).

Remediation and enhancement of plant resistance to abiotic stress

Biosynthesized CuNPs are considered an effective tool for mitigating abiotic stress in plants, particularly under conditions of soil salinity and heavy metal pollution. One of the key applications of biogenic CuNPs is reducing the negative impact of salt stress. In particular,

nanoparticles synthesized using the liquid culture of *Klebsiella pneumoniae* NST2 have demonstrated the ability to significantly improve the physiological state of maize plants under saline conditions. The protective mechanism is based on the ability of nanoparticles to interact with sodium and chloride ions in the external environment, thereby limiting their uptake and accumulation in plant tissues (Noman et al., 2021).

Equally important is the use of biogenic CuNPs to reduce the toxic effects of heavy metals, particularly chromium. It has been shown that nanoparticle treatment increases wheat tolerance to high concentrations of chromium in soil. This is attributed to the ability of CuNPs to immobilize chromium ions by converting them into forms less available for uptake. As a result, the translocation of chromium ions from the root system to aboveground organs and grains is reduced, thereby limiting their toxic effects on cellular structures and metabolic processes (Noman et al., 2020b).

Nanofertilizers

The application of biogenic copper nanoparticles has a positive effect on the morphological parameters of plant development. In particular, treatment of tomatoes with CuONPs synthesized using an aqueous leaf extract of *Ziziphus spina-christi* leads to an increase in the seedling vigor index, higher fresh and dry biomass, and a significant increase in plant height – up to 65.33 cm compared to 37 cm in the control. Stimulation of tomato root system development also was observed, promoting more efficient uptake of water and mineral nutrients (El-Abeid et al., 2024).

Biosynthesized CuNPs stimulate growth processes in maize under saline soil conditions. Specifically, root length increases by 43.5% and shoot length by 44%, along with enhanced fresh and dry biomass compared to untreated plants (Noman et al., 2021). Low doses of CuNPs (0.06 mg/mL) stimulate wheat root growth by 173% and shoot growth by 216% (Essa et al., 2021). Treatment of eggplant with CuSeNPs leads to increased levels of photosynthetic pigments and activation of systemic resistance mechanisms, positively affecting plant growth and development (Attia et al., 2025).

At the physiological and biochemical levels, biosynthesized CuNPs activate key processes that determine plant growth and stress tolerance. Their application is associated with increased levels of photosynthetic pigments (chlorophyll a, chlorophyll b) and carotenoids, linked to the activation of photosystems I and II, as well as regulation of gene expression encoding enzymes of the photosynthetic apparatus (El-Abeid et al., 2024; Oraibi et al., 2023). Biogenic CuNPs also stimulate the antioxidant system by increasing the activity of enzymes such as peroxidase, polyphenol oxidase, and catalase, thereby reducing oxidative stress and enhancing plant resistance to both biotic and abiotic factors (Attia et al., 2025; Noman et al., 2021).

The effectiveness of CuNP application shows a pronounced dose-dependent pattern. The use of nanoparticles at concentrations of 25–50 mg/kg of soil provides a stimulatory effect, ensuring optimal copper supply as an essential micronutrient and improving plant nutrition. However, exceeding optimal doses above 100 mg/kg of soil may lead to phytotoxic effects, manifested by growth inhibition, reduced levels of photosynthetic pigments, and the development of oxidative cellular damage (Essa et al., 2021).

Application of biosynthesized copper nanoparticles in the food industry

Active antimicrobial packaging

Active antimicrobial packaging based on biosynthesized CuNPs is considered one of the most promising innovations in the modern food industry, aimed at enhancing microbiological safety and extending the shelf life of food products. To create such packaging materials, nanoparticles are incorporated into various polymer matrices, primarily biodegradable and environmentally friendly ones. Among the most commonly used biopolymers are chitosan and agarose, which, due to their inherent antimicrobial properties and high biocompatibility, form

effective composite systems. For example, films based on chitosan, agarose, CuNPs, and CuONPs are effective against a wide range of pathogenic microorganisms, including *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus cereus*, *Staphylococcus aureus*, and *Staphylococcus epidermidis* (Abd El Rahman et al., 2025).

Polylactic acid (PLA) is also an important carrier for CuNPs due to its biodegradability and good mechanical properties. Copper nanoparticle-modified PLA composite films effectively inhibit microbial growth in fresh food products, particularly poultry meat, fish, and dairy products (Santos et al., 2024). Similarly, hypromellose is used to create flexible packaging materials embedded with copper nanowires, characterized by controlled release of Cu^{2+} ions and consequently reduced cytotoxicity (Bagchi et al., 2022).

The combination of cellulose acetate with polycaprolactone in the presence of CuNPs enables the production of superhydrophobic films with improved moisture barrier properties and high mechanical strength. Such materials are especially promising for packaging high-moisture products, where the risk of microbial spoilage is particularly significant (El-Naggar et al., 2022).

Biogenic CuNPs can also be applied to the surface of cellulose paper, cardboard, or textile materials used for packaging fruits, vegetables, and other food products. Antimicrobial activity of such packaging has been demonstrated against bacteria such as *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, as well as the yeast *Candida albicans* (Aziz et al., 2024).

The antimicrobial mechanism of biosynthesized CuNPs is multifactorial and operates through several interconnected pathways. The first stage involves interaction of nanoparticles with the bacterial cell surface, leading to its deformation (Rajamma et al., 2020). Subsequently, CuNPs penetrate the cell and release Cu^{+}/Cu^{2+} ions, which interact with biomolecules. Copper ions bind to specific sites of nucleic acids, causing their denaturation (Baral et al., 2025). Copper also interacts with thiol, carboxyl, and amino groups of amino acids, leading to protein denaturation and enzyme inactivation (Shah et al., 2024).

A crucial role is played by the induction of oxidative stress through the generation of reactive oxygen species, including superoxide anions, hydrogen peroxide, and hydroxyl radicals. These compounds initiate lipid peroxidation, damage proteins and nucleic acids, and disrupt cellular functions (Idrees et al., 2025). Copper additionally catalyzes Fenton-like reactions, enhancing the formation of highly reactive radicals (Yu et al., 2025). Moreover, biosynthesized CuNPs and CuONPs affect key metabolic processes in microbial cells. In particular, they can inhibit the enzyme dihydrofolate reductase (DHFR), which is essential for nucleotide synthesis and cell proliferation. CuONPs also exhibit high affinity for DNA gyrase (GyrB), blocking its ATPase activity and thereby halting DNA replication and bacterial growth (Sazak et al., 2023).

An important aspect of implementing active antimicrobial packaging is its safety and environmental friendliness. Studies on the migration of copper ions from polymer matrices into model food media have shown that the level of copper release remains below the permissible limits (5 mg/kg) established by regulatory standards. This indicates that such materials comply with food safety requirements (Santos et al., 2024; Scattareggia Marchese et al., 2022). The integration of CuNPs does not hinder the biodegradation of polymer matrices. PLA-based biocomposites demonstrate a high degree of degradation under composting conditions, reaching near-complete degradation within 14–30 days. This highlights the suitability of such materials in the context of sustainable packaging solutions and the circular economy (Santos et al., 2024).

Preservation of freshness and quality of fruits and vegetables

Postharvest losses of fruits and vegetables can reach 20–50%, which requires the implementation of innovative technologies capable of effectively suppressing pathogen development while maintaining the physiological and biochemical characteristics of products. Postharvest treatment of mango fruits by immersion in a CuONP solution extends their shelf life from 10 to 18 days. Such treatment helps preserve pulp firmness, reduces weight loss, and maintains higher levels of ascorbic acid and titratable acidity, indicating a slowdown in ripening and senescence processes (Joshi et al., 2025).

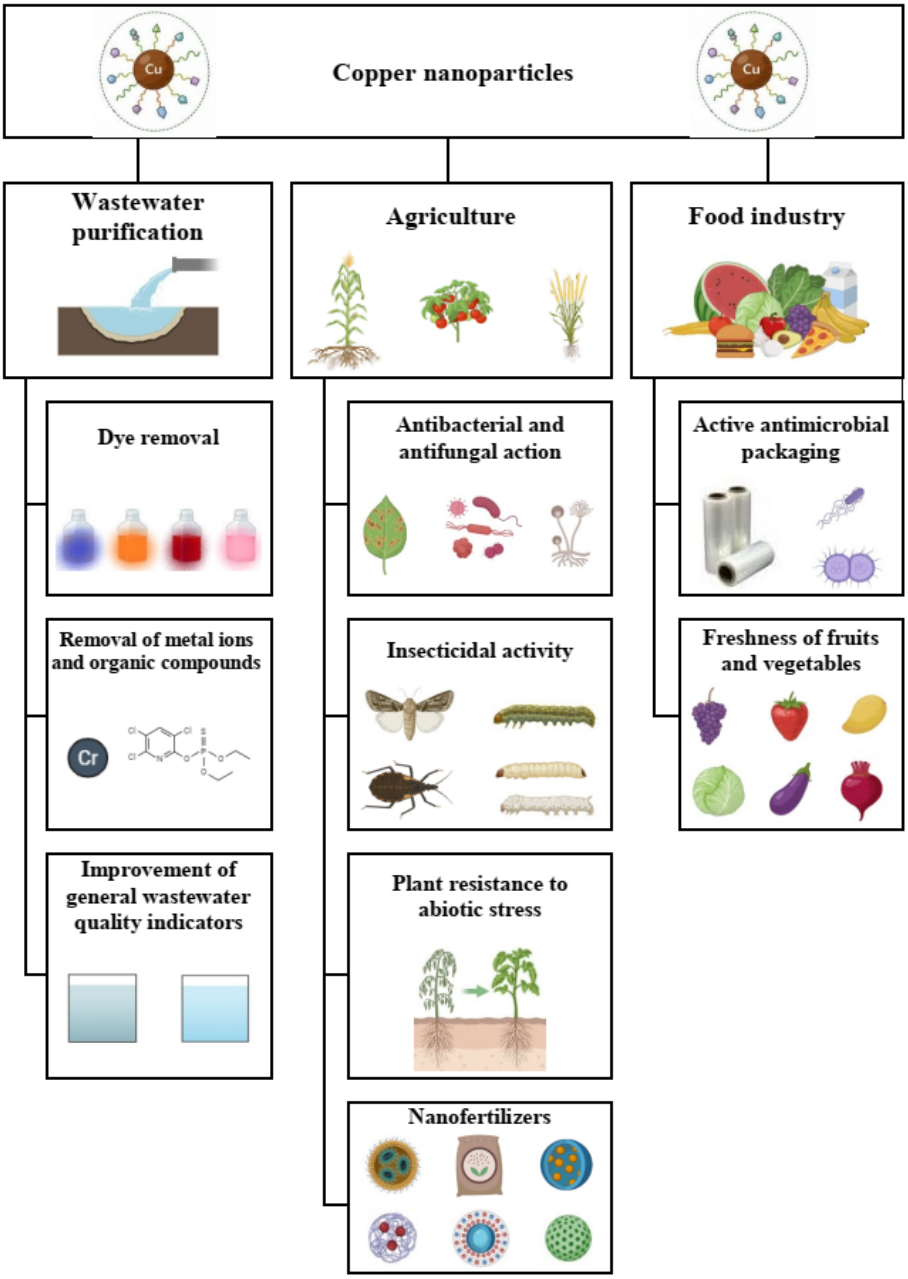

Figure 3. Practical application of CuNPs
(elements from BioRender.com have been used for scheme)

Conclusions

An important advantage of biosynthesized CuNPs is their pronounced antimicrobial activity against a wide range of pathogens. In the case of persimmon, CuONPs demonstrated strong antifungal activity against *Rhizopus oryzae*. The use of nanoparticles at a concentration of 100 μg/mL leads to inhibition of mycelial growth on the fruit surface and a reduction in infection levels compared to untreated fruits (Shah et al., 2024). It was shown that CuONPs inhibit the development of *Fusarium solani* – the pathogen of Fusarium root rot in tomatoes (El-Abeid et al., 2024) – and *Aspergillus niger*, responsible for black rot in onions (Babulla et al., 2024). Biosynthesized CuNPs completely inhibit the growth of *Phytophthora parasitica* and *Fusarium oxysporum*, pathogens that cause vegetable spoilage (Ammar et al., 2019).

Among the key advantages of biosynthesized CuNPs is their environmental friendliness, as plant-based waste materials, such as pineapple peels, can be used for their synthesis, contributing to reduced environmental impact (Mitra et al., 2024). In addition, studies indicate a low level of copper ion migration into fruit pulp, which does not exceed established food safety limits (Joshi et al., 2025; Santos et al., 2024). At the same time, copper nanoparticles exhibit antioxidant properties, providing additional protection of bioactive compounds in fruits against oxidative degradation (Abd El Rahman et al., 2025; Shah et al., 2024).

Considering all the data, biosynthesized CuNPs can be applied for wastewater treatment, as antimicrobial and insecticidal agents in agriculture, as a part of nanoferilizers, for the soil remediation and as a part of active antimicrobial package materials. Moreover, CuNPs are potential solution for fruits and vegetables treatment for the extension of shelf-life (Figure 3).

At the same time, despite significant advances in the biosynthesis of copper nanoparticles, further studies are required to facilitate the transition of these technologies from laboratory-scale investigations to industrial applications. Particular attention should be given to improving the reproducibility and scalability of biosynthesis processes, as well as to the standardization of synthesis conditions and the long-term stability of the obtained nanoparticles.

The biosynthesis of copper nanoparticles using biological systems represents a promising direction in modern nanobiotechnology, consistent with the principles of sustainable development and green chemistry. A generalization of current scientific data indicates that a wide range of biological systems (plants, spices, condiments, food products and food waste, algae, fungi, and microorganisms) can be employed for the reduction of copper ions and the stabilization of the resulting nanoparticles.

It was demonstrated that biologically active compounds (polyphenols, flavonoids, proteins, amino acids, polysaccharides, and enzymes) play a key role in biosynthesis processes, functioning both as reducing and stabilizing agents. The mechanisms of nanoparticle formation are complex and multistage, involving processes of complexation, bioreduction, nucleation, growth, and stabilization. At the same time, the path of these processes largely depends on the nature of the biological system and its metabolic profile.

It has been established that the type of biological system and synthesis conditions (the nature and concentration of the precursor, pH of the medium, temperature, and process duration) determine the morphology, size, colloidal stability, and functional properties of the nanoparticles. This creates opportunities for the controlled synthesis of nanomaterials with tailored characteristics. However, unified approaches for predicting these parameters are currently lacking.

Despite significant progress in the field of nanoparticle biosynthesis, a number of unresolved challenges remain. In particular, the systematization of data regarding the comparative efficiency of different biological systems remains limited; the molecular and enzymatic mechanisms of copper ion bioreduction are insufficiently understood; and standardized approaches to scaling up biosynthesis processes are lacking. Additionally, the relationship between synthesis conditions and the functional properties of nanoparticles in the context of their practical applications requires

further in-depth investigation. It should also be noted that studies on the biosynthesis of copper nanoparticles using yeasts remain limited, highlighting the perspectives of this research direction.

The practical significance of biogenic copper nanoparticles lies in their broad potential applications as antimicrobial agents, catalysts, and photocatalysts, as well as in water purification and bioremediation processes. Particularly promising is the integration of nanoparticle biosynthesis with waste treatment and the remediation of polluted environments, in line with the concept of a circular bioeconomy. Further development of this field requires the integration of approaches from microbiology, biotechnology, biochemistry, materials science, and engineering in order to develop efficient, controllable, and scalable technologies for the biosynthesis of copper nanoparticles. Special attention should be given to the development of standardized synthesis methods, a deeper understanding of the underlying mechanisms, and the expansion of their practical applications across various areas of biotechnology.

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