Lactic acid bacteria for the synthesis of metals nanoparticles

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Abstract

Introduction. Metal nanoparticles (NPs) are widely used in various fields of scientific and practical activities. Biogenic metal nanoparticles attract attention with their unique properties and relative low cost of production, and lactic acid bacteria as biosafe producers.

Materials and methods. Morphological analysis of clusters of scientific knowledge about metal nanoparticles biosynthesis using lactic acid bacteria and antimicrobial properties of produced NPs.

Results and discussion. For biosynthesis of nanoparticles it is important the choice of: an ecofriendly biological agent; precursor metal salt; nontoxic material as a capping agent to stabilize the synthesized nanoparticles, and factors providing optimal conditions for the formation of nanoparticles, such as pH, temperature, pressure, time, agitation, biological reducing agent concentration, initial precursor salt concentration, and light. Lactic acid bacteria (LAB), which are belonging to the RG1 group of microorganisms (biologically safe) according to the European Union Directive, attract the attention as biosafe producers of various metal nanoparticles in a relatively inexpensive and accessible process of NPs biosynthesis. The last decade increasing interest in LAB use in the form of biomass, cell lysate, or cell-free supernatant (filtrate) has been observed. All metal nanoparticles exhibit high antimicrobial activity, and these properties against pathogenic bacterial strains are very important for NPS practical applications in treating bacterial infections, especially in conditions of widespread phenomenon of microorganism resistance to antibiotics. Especially important is the fact that metal nanoparticles have non-specific bacterial toxicity that makes it difficult to develop resistance by bacteria. NPs synthesized by lactic acid bacteria are effective against many antibiotic-resistant bacterial strains, including *Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus pyogenes, Klebsiella pneumoniae* and *Salmonella typhi*, as well as for different fungi and yeasts. The statistically proven absence of significant differences in the inhibitory effect of AgNPs synthesized by LABs on the growth of Gram-positive and Gram-negative bacteria was shown.

Conclusions. Lactic acid bacteria could serve as biosafe producers of different metal nanoparticles having strong antimicrobial abilities.

Introduction

Interest in nanotechnology, the branch of science and engineering devoted to the synthesis, manufacturing and application of tiny in size materials, has increased exponentially due to progress and technological innovation (Radulescu et al., 2023). Nanomaterials have special characteristics that differ from its bulk form with the same composition and thanks to them are found wide application in medicine, pharmaceutical, agriculture, food production, electronic devices, optical, catalysis, and environmental management. Nanoparticles (NPs) are the particles having size less than 1000 nm in at least one dimension (Gosh et al., 2021; Jeevanandam et al., 2018), meanwhile particles with size from 10 to 100 nm have even more valuable properties due to large surface-to-volume ratio and high surface energy, which make them more in demand. However, it should be noted that various physicochemical methods used for the synthesis of metal nanoparticles are expensive, need high thermal conditions, involve the use of toxic chemicals, generate excess by-products, and lead to pollution of the environment and the biosphere. Besides that, chemically produced nanoparticles have limited fields of application because of their toxicity (Singh and Singh, 2019). Thus, with modern advances in science and technology, an alternative method is biogenic synthesis, which has enormous potential as a sustainable, environmentally friendly and cost-effective method that does not require toxins, aggressive chemicals and the use of large amounts of energy, which is essential for physicochemical synthesis (Gupta and Seema, 2021). Different biological agents such as viruses, bacteria, actinomycetes, fungi, molds, microalgae, and plant extracts could be used for the biosynthesis of nanoparticles of a wide range of metals including silver, gold, platinum, palladium, copper, zinc, iron, titanium, magnesium, selenium, tellurium, cerium, and zirconium (Pandit et al., 2022). Microbial biosynthesis of nanoparticles involves metal capture, enzymatic reduction, and capping (Ghosh et al., 2021). Schematic for biological synthesis of nanoparticles, so called green nanotechnology, is shown in Figure 1 (adapted from Patra and Baek, 2014).

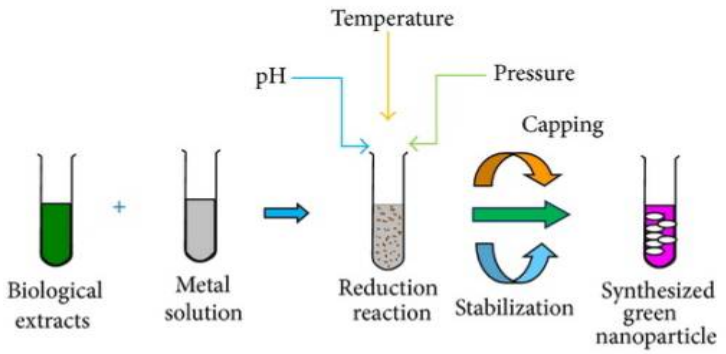

Figure 1. Biological synthesis of nanoparticles (Patra and Baek, 2014)

According to the given scheme, for biosynthesis of nanoparticles it is important: a) the choice of an ecofriendly biological agent; b) the choice of initial precursor metal salt; c) factors influenced on the process of biosynthesis (pH, temperature, pressure, time, agitation, biological reducing agent concentration, initial precursor salt concentration, light); and d) the choice of a nontoxic material as a capping agent to stabilize the synthesized nanoparticles (Javed et al., 2020; Miu and Dinischiotu, 2022; Patra and Baek, 2014).

When exploring the selection of biological agents capable of producing metal NPs, particular attention is drawn to lactic acid bacteria (LAB), which are belonging to the RG1

group of microorganisms (biologically safe) according to the European Union Directive (Directive 2000/54/EC, 2000) and considered Generally Recognized as Safe (GRAS) by the US Food and Drug Administration (Colautti et al., 2022; EFSA; 2016; Stabnikova et al., 2023).

Among lactic acid bacteria there are many representatives capable of synthesizing metal NPs; in particular, these bacterial strains belong to the genera *Lactobacillus*, *Lactococcus*, *Enterococcus, Streptococcus, Pediococcus* and *Leuconostoc.*

Biosynthesis of metal nanoparticles using lactic bacteria

Bacteria can synthesise metallic nanoparticles by either intracellular (endogenous) or extracellular (exogenous) mechanisms. Extracellular synthesis consists of enzyme secretion during bacteria cultivation and application of these reductase enzymes for metal bioreduction and formation of nanoparticles (Das et al., 2014; Singh and Singh, 2019). To obtain nanoparticles it is possible to use a cell-free supernatant containing microbial enzymes.

In turn, the intracellular biosynthesis of NPs is based on the origin of the living organisms to extract metals from the surrounding media, enzymatically convert the metallic ions into elemental form, and accumulate them (Li et al., 2011; Miu and Dinischiotu, 2022). Positively charged metal ions are adsorbed on the negatively charged microbial cells, bioreduced, and form nanoclusters inside the cell (Marooufpour et al., 2019). Accumulation of nanoparticles in cells is confirmed by the appearance of a specific color of microbial biomass, which could be pinkish for gold NPs, red for selenium NPs, brownish for silver nanoparticles, and so on.

Biosynthesis of silver nanoparticles by lactic acid bacteria

The majority of lactic acid bacteria used for biosynthesis of silver nanoparticles belong to the genus *Lactobacillus* that are gram-positive having in their cell wall teichoic acids which give it an overall negative charge (Chapot-Chartier and Kulakauskas, 2014). In formation of negative charge on the surface of gram-positive bacteria, anionic polymers of the cell walls, especially peptidoglycan, are also involved. It is assumed that electrostatic interaction that occurs between positive charged ions and negatively charged original cells resulted in biosorption of metal ions on the surface of microorganism cells. Silver ions being trapped on the surface or inside of the microbial cells are reduced to respective metal atom Ag^+ due to action of reductase enzymes using functional groups of the cell that serve as an electron donor, and subsequently developing Ag nanoparticles (Yusof et al., 2020a). Examples of the biosynthesis of AgNPs with lactic acid bacteria are given in Table 1.

Biosynthesis of AgNPs by lactic acid bacteria can be carried out using cell-free supernatant (Awadelkareem et al., 2023), biomass (Yusofet al., 2020a) or cell lysate (Mousavi et al., 2020). Bacterial biomass is used less frequently for this purpose, since most metal ions are toxic to bacteria. Silver nitrate, $AgNO_3$, is usually used as a biosynthesis precursor with different concentration ranges from 0.1 to 100 mM, among which the most used concentration is 0.1 mM $AgNO_3$ (Dybkova et al., 2020; Mousavi et al., 2020; Popoola and Adebayo-Tayo, 2017; Sharma et al., 2022; Syame et al., 2020). The biosynthesis of AgNPs is carried out at temperatures from 22 to 37 ºC (Matei, 2020; Naseer et al., 2020; Rajesh et al., 2015; Sharma et al., 2022; Vijayakumar, 2023) usually for 24 hours (Awadelkareem et al., 2023; Rajesh et al., 2015; Sani et al., 2018; Sharma et al., 2022; Syame et al., 2020; Yusof et al., 2020a). However, in some cases the biotransformation of the precursor into NPs was going for 72 hours (Mousavi et al., 2020), 12 hours (Naseer et al., 2020); 5 days (Matei et al., 2020), and even 7 days (Viorica et al., 2018). The formed NPs have a spherical shape and different sizes in the range from 0.2 nm to 233 nm.

Table 1

Biosynthesis of silver nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus rhamnosus GG	Spherical, average size 233 nm	1 mM cell lysate, pH 7.0, 1 mM $AgNO_3$, 25 °C, 72 h, 150 rpm, in a dark	Mousavi et al., 2020
Lactobacillus acidophilus	Spherical, 4–50 m, average size 33 nm	Supernatant, 1 mM $AgNO_3$, 35°C, 24 h, in a dark	Rajesh et al., 2015
Lactobacillus sp. LCM5	Spherical, 3–35 nm average size13.8± 4.6 nm	Cell-free supernatant, 1 мМ $AgNO_3$, 28 °C, 5 days, 200 rpm	Matei et al., 2020
Lactobacillus crustorum F11	Spherical, average size 10±2.9 nm	Supernatant, 0.1 мМ $AgNO_3$, 30 °C, 24 h, in a dark	Sharma et al., 2022
Lactobacillus pentosus S6	Spherical, average size 50±2.9 nm		
Lactobacillus plantarum F22	Spherical, average size 20±2.9 nm		
Lactobacillus paraplantarum KM1	Spherical, average size 50±2.9 nm		
Lactobacillus plantarum TA4	Spherical, average size 14.0±4.7 nm	Biomass, 2 мМ $AgNO_3$, 37 °C, 24 h, 150 rpm, in a dark	Yusof et al., 2020a
Lactobacillus bulgaricus	Spherical, ranged from 30 to 100 nm	Biomass, 1 мМ $AgNO_3$, over night at room temperature	Naseer et al., 2020
Lactobacillus plantarum	*, 4-6 nm	Biomass, 0.1 M (Ag:NH_3=1:2), room temperature, 24 h, 120 rpm	Dybkova et al., 2020
Lactobacillus plantarum	Spherical or polyhedral, poly-dispersed, 5 to 40 nm	Cell-free supernatant, 2 мМ $AgNO_3$, pH 8.3, 37 °C, 24 h, 150 rpm, in a dark	Syame et al., 2020
Lactobacillus brevis			
Lactococcus lactis 56 KY484989	Sperical, 5-50 nm, average size 19±2 nm	Supernatant, 1 мМ $AgNO_3$, 26 °C, 7 days, agitation	Viorica et al., 2018
Lactobacillus delbrueckii subsp. *bulgaricus*	Sperical, 1.4–8.9 nm	Supernatant, 1 мМ $AgNO_3$, room temperature, 24 h, exposed to direct sunlight for 10 min	Sani et al., 2018
Lactobacillus casei LPW2	*, 0.2–10 nm	Supernatant, 10 мМ $AgNO_3$, room temperature, 24 h	Popoola and Adebayo-Tayo, 2017
Bifidobacterium bifidum NCDC 229	Sperical, *	Supernatant, 1 мМ $AgNO_3$, 37 °C, 24 h, 160 rpm, pH 6,0	Kumar et al., 2016
Lactobacillus plantarum	Sperical, average size 14.0±4.7 nm	Supernatant, 1 мМ $AgNO_3$, 37 °C, 24 h	Vijayakumar et al., 2023

*There was no information.

Biosynthesis of selenium nanoparticles by lactic acid bacteria

Selenium nanoparticles have higher bioavailability, higher antioxidant activity, and scavenging effect on free radicals than sodium selenite (Deng et al., 2023). An analysis of the literature shows that to obtain selenium nanoparticles using lactic acid bacteria, biomass of LAB usually is applied (Hu et al., 2023; Laslo et al., 2022; Wang et al., 2023). Among the factors influencing selenium biotransformation, the source of Se and its concentration in the medium are the most significant (Liao and Wang 2022; Stabnikova et al., 2023). As a biosynthesis precursor, sodium selenite (Na_2SeO_3), sodium hydroselenite ($NaHSeO_3$) and, much less frequently, selenium oxide (SeO_2) were used (Kheradmand, 2014; Spyridopoulou et al., 2021; Vicas, 2021). Maximum concentration of Na_2SeO_3 in medium for lactic acid bacteria cultivation is considered to be 5 mg/l, but further increase may inhibit growth of nanoparticle producer and even can cause mass death of microbial culture cells (Pescuma et al., 2017; Spyridopoulou et al., 2021; Stabnikova et al., 2023).

The accumulation of selenium depends on the time of microbial cultivation. Thus, the amount of accumulated Se increased with the incubation period for *Lactobacillus acidophilus* CRL 636 and *Lactobacillus reuteri* CRL 1101 (Pescumav et al., 2017). The formation of SeNPs during LAB cultivation can be monitored by the appearance of a dark red color of cultural medium. It was found that the time of its appearance varied among different strains, and the color change could occur at different stages of bacterial growth. In case of strain *Lactobacillus casei* growth in nutrient medium with an initial $NaHSeO_3$ content of 20 μg/ml, colour became red only at 96 h of cultivation, which corresponded to the late logarithmic/early stationary phase of bacterial growth (Spyridopoulou et al., 2021). However, change of the bright yellow colour of medium for *Lactobacillus paracasei* cultivation to red was observed on 32 h in the exponential phase of bacterial growth (El-Saadony et al., 2021a).

It should be noted that the properties of selenium nanoparticles depend on their size: with the decrease of particle size, the ratio of surface area to volume increases, as well as the bioavailability and biological activity against hydroxyl radicals and the protective effect against DNA oxidation (Deng et al., 2023). The size of selenium NPs decreases in the presence of O_2 as it promotes the oxidation of Se, resulting in the redox process becoming slower and smaller SeNPs being formed (Martínez et al., 2020; Spyridopoulou et al., 2021). Particle size also depends on the strain (Martínez et al., 2020). The range of possible sizes of SeNPs should be limited to 20 to 500 nm. Most LABs produce spherical selenium NPs, but hexagonal SeNPs synthesized by *Lactobacillus paracasei* HM1 are also reported (El-Saadony et al., 2021a). SeNPs can be individual or form aggregated conglomerates (Spyridopoulou et al., 2021). Examples of the biosynthesis of SeNPs with lactic acid bacteria are given in Table 2.

Table 2

Biosynthesis of selenium nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei ATCC 393	*, 50-80 nm	Luria-Bertani broth, 200 mg/l Na_2SeO_3, 37 °C, 24 h	Xu et al., 2018
Lactobacillus acidophilus CRL 636	Sperical, average size 176 nm	Broth De Man, Rogosa and Sharpe (MRS), 25 mg/l Na_2SeO_3, 37 °C, 24 h	Moreno-Martin et al., 2017
Lactobacillus reuteri CRL 1101	Sperical, average size 160±24 nm		
Lactobacillus delbrueckii subsp. bulgaricus CRL 65	Sperical, average size 130±23 nm		
Lactobacillus rhamnosus	Sperical, 20-60 nm	Luria-Bertani broth, 4 mM Na_2SeO_3, 35 °C, 48 h, 170 rpm	Rajasree and Gayathri, 2015
Lactobacillus acidophilus	Sperical, 40-60 nm		
Lactobacillus plantarum	Sperical, 60-80 nm		
Enterococcus faecalis	Sperical, 29–195 nm	Luria-Bertani broth, 33–514 mg/l Na_2SeO_3, 37 °C or 42 °C, 24 h and 48 h, 150 rpm	Shoeibi and Mashreghi, 2017
Lactobacillus paracasei HM1	Hexagonal monodisperse, average size 91±1.8 nm	Luria-Bertani broth, 692 mg/l Na_2SeO_3, 35 °C, 32 h, 160 rpm, pH 6.0	El-Saadony, et al., 2021a
Lactobacillus casei ATCC 393	*, 170-550 nm	Broth MRS, 20 mg/l $NaHSeO_3$, 37 °C, 96 h	Spyridopoulou et al., 2021
Lactobacillus casei LC4P1	Sperical, ≤ 80 nm	Broth MRS, 200 мг/л Na_2SeO_3, 37 °C, 48 год	Vicas et al., 2021
Lactobacillus plantarum ATCC 8014	Sperical, 25 – 250 nm	Broth MRS, 200 мг/л SeO_2, 37 °C, 120 h, stirring	Kheradmand et al., 2014
Lactobacillus johnsonii			
Lactobacillus. acidophilus CRL636	*, 25–370 nm	Broth MRS, 5 mg/l Na_2SeO_3, 37 °C, 24 h	Pescuma et al., 2017
Lactobacillus reuteri CRL1101			
Lactobacillus brevis	*	Broth MRS, 254 mM SeO_2, 37 °C, 72 h	Yazdi et al., 2013

Table 2 (*Continue*)

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus pentosus ADET MW861694	Sperical, average size 106.1 nm	Broth MRS, 5 mM Na_2SeO_3, 37 °C, 72 h	Adebayo-Tayo et al., 2021
Lactobacillus casei IMB B-7280	Sperical, different in size: small (30–50 nm) and large (150–250) nm	Broth MRS, 5 ppm Na_2SeO_3, 30 °C, 24 h, 220 rpm	ok et al.,
Lactobacillus gasseri 55	*	Corn medium, 8 mg/l Na_2SeO_3, 37 °C, 24–48 h	Ohirchuk and Kovalenko, 2016
Pediococcus acidilactici DSM20284	Sperical, average size 239 nm	Broth MRS, 100 mg/l Na_2SeO_3, 37 °C, 48 h, under shaking	Wang et al., 2023
Enterococcus durans A8-1	*	Broth MRS, 60 mg/l Na_2SeO_3, 37°C, 18 h, 200 rpm	Liu et al., 2022
Lactobacillus casei	Sperical, average size 200 nm	Broth MRS, 200 mg/l Na_2SeO_3, 37 °C, 48 h	Laslo et al., 2022
Lactobacillus acidophilus ML14	Sperical, average size 46 nm	Luria-Bertani broth, 6 mM Na_2SeO_3, 35 °C, 170 rpm, until the synthesis of NPs is completed	El-Saadony et al., 2021b
Pediococcus lolii	Sperical, average size 186.6 nm	Milk permeate, 200 ppm Na_2SeO_3, 37 °C, 24 h	Zommara et al., 2022
Lactobacillus brevis	Sperical, average size 188.7 nm		
Lactobacillus plantarum	Sperical, average size 125 nm		
Lactobacillus paracasei SCFF20	Sperical, polydisperse, 500.62 nm	Broth MRS, 100 mg/l Na_2SeO_3, 37 °C, 24 h, 120 rpm	Hu et al., 2023
Lactococcus lactis NZ9000	*	Broth MRS, 0.6 mM Na_2SeO_3, 30 °C, 24 h, 120 rpm	Chen et al., 2021

*There was no information.

Biosynthesis of gold nanoparticles by lactic acid bacteria

There is limited information related to the synthesis of AuNPs by lactic acid bacteria. Analyzed available materials, it should be noted that auric acid, $HAuCl_4$, of varying concentrations ranging from 1 to 10 mM is usually used as a biosynthesis precursor (Markus et al., 2016; Miran and Ali, 2024), and the biosynthesis itself is achieved using the

supernatant (Miran and Ali, 2024; Repotente, 2022) or biomass (Markus et al., 2016) of lactic acid bacteria, and the process of AuNPs biosynthesis is conducted at room temperature under agitation. It was shown that AuNPs could be synthesized by reducing chloroauric acid using lactic acid isolated from the probiotic strain *Lactobacillus acidophilus* (Repotente et al., 2022). In study of Kato et al. (2019) it was shown that synthesis of AuNPs in *L. casei* was induced by the cooperation of lacto-N-triose, lactic acid and glycolipids. Meanwhile, Markus et al. (2016) found that protein and functional groups (carboxylate) on *Lactobacillus kimchicus* DCY51 were responsible for the reduction of gold nanoparticles. Gold nanoparticles have spherical shape and size from 5 to 140 nm. Examples of the biosynthesis of AuNPs with lactic acid bacteria are given in Table 3.

Table 3

Biosynthesis of gold nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus kimchicus DCY51	Sperical, moderately polydisperse, 5–30 nm	Biomass, 1 мМ $HAuCl_4$, 30 °C, 12 h, 150 rpm	Markus et al., 2016
Lactobacillus acidophilus	Sperical, 6–12 nm	Supernatant, 7 mM $HAuCl_4$, 1.25 mg/ml calcium lactat, 48 h	Repotente et al., 2022
Lactobacillus paracasei	Sperical, average size 65.3 nm	Supernatant, 0.01M $HAuCl_4$, 25 °C, 24 h, pH 8.0, stirring for 2 h	Miran and Ali, 2024
Lactobacillus casei	Sperical, average size 68.2 nm		
Lactobacillus plantarum	Sperical, average size 139.67 nm		
Lactobacillus fermentum	Sperical, average size 127.29 nm		
Lactobacillus casei	7–56 nm, the size of the highest frequency was ≈ 30 nm	Biomass, 2g/l, 0.5 mM, auric acid (0.5 mM $K[AuCl_4]$), 24 h	Kikuchi et al., 2016

Biosynthesis of iron oxide nanoparticles by lactic acid bacteria

To obtain Fe_3O_4 NPs using lactic acid bacteria, a cytoplasmic extract is proposed to be used. Solution of ferrous sulfate, 0.001 M, served as a precursor for biosynthesis, and the biotransformation process occurs at 37 C for 3 weeks in the presence of 5% carbon dioxide. The formed Fe_3O_4 NPs had a spherical shape and size ranging from 10 to 15 nm. The first sign of the formation of iron oxide NPs was a change in the color of the iron sulfate solution from colorless to black (Torabian, 2018; Fani, 2018). Examples of the biosynthesis of Fe_3O_4 NPs using lactic acid bacteria are given in Table 4.

Table 4

Biosynthesis of iron oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei PTCC 1608	Sperical, 10–15 nm	Cytoplasmic extract, 0.001 M solution of ferrous sulfate, 37 °C, 3 weeks, 5 % CO_2, pH 6.5	Torabian et al., 2018
Lactobacillus fermentum PTCC 1638	Sperical, 10–15 nm	Cytoplasmic extract, 0.001 M solution of ferrous sulfate, 37 °C, 3 weeks, 5 % CO_2, pH 6.5	Fani et al., 2018

Biosynthesis of zinc oxide nanoparticles by lactic acid bacteria

Biosynthesis of ZnO NPs is carried out using biomass (Yusof et al., 2020b) or culture liquid (Al-Zahrani et al., 2018; Selvarajan and Mohanasrinivasan, 2013; Yusof et al., 2020b). It was shown the possibility to obtain ZnO NPs using the cell-biomass or cell-free supernatant of zinc-tolerant *Lactobacillus plantarum* TA4 (Yusof et al., 2020b) added with solution of zinc nitrate, $Zn(NO_3)_2 \cdot 6H_2O$, containing dissolved ions of Zn^{2+}. Biotransformation using bacterial biomass was conducted at 37 °C for 24 h under agitation at 150 rpm, and at room temperature overnight using supernatant. Electronic microscope study showed that ZnO NPs biosynthesized with cell biomass had an irregular shape with average size of 191.8 nm, but a flower-like pattern was observed for ZnO NPs obtained using supernatant having average size of 291.1 nm. Proteins, carboxyl, and hydroxyl groups were detected on the surface of both types of NPs, which act as reducing and stabilizing agents. The authors suggested that reduction of Zn^{2+} to ZnO NPs was due to activity of proteins present in supernatant and biomass suspension in concentrations of 2.79±0.11 mg/mL and 1.94±0.20 mg/mL, respectively, as well as because of functional group present on the bacterial cell (Yusof et al., 2020b). Examples of the biosynthesis of ZnO NPs using lactic acid bacteria are given in Table 5.

Table 5

Biosynthesis of zinc oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus plantarum TA4	An irregular shape, average size 191.8 nm	Biomass, $Zn(NO_3)_2 \cdot 6H_2O$ solution with Zn^{2+}, 37 °C, 24 h, 150 rpm	Yusof et al., 2020b
Lactobacillus plantarum TA4	A flower-like pattern, average size 291.1 nm	Supernatant, $Zn(NO_3)_2 \cdot 6H_2O$ solution with Zn^{2+}, room temperature, overnight	
Lactobacillus plantarum VITES07	Sperical, average size 7 nm	Supernatat, 0.1 M $ZnSO_4 \cdot H_2O$, 37 °C, 12 h, pH 6,0	Selvarajan and Mohanasrinivasan, 2013
Lactobacillus johnsonii	Sperical, 4–9 nm	Supernatant, 0.1 g/ml ZnO, 37 °C, 24 h	Al-Zahrani et al., 2018

Biosynthesis of titanium oxide nanoparticles nanoparticles by lactic acid bacteria

To obtain TiO_2 NPs, supernatant (culture liquid) of lactic acid bacteria are mainly used, and 0.025 M solution of TiO_2 is used as a precursor. Biotransformation occurs at temperatures 25 - 37 °C for 12 – 48 hours (Al-Zahrani et al., 2018; Hasan et al., 2023; Ibrahem et al., 2019; Jha et al., 2009). Formed nanoparticles mostly have spherical shape with size ranging from 4 to 90 nm. It was reported that synthesized TiO_2 nanoparticles remained stable without change in color after storage for three months at 4ºC (Ibrahem et al., 2019). Examples of the biosynthesis of ZnO NPs using lactic acid bacteria are given in Table 6.

Table 6

Biosynthesis of titanium oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus johnsonii	Uneven, agglomerated, 4–9 nm	Cultural liquid, 0.025 M solution TiO_2, 37 °C, 24 h	Al-Zahrani et al., 2018
Leuconostoc mesenteroides subsp. *mesenteroides*	Sperical, average size 53.4–59.4 nm	Cultural liquid, 0.025 M solution TiO_2, 30 °C, 24 h	Hasan et al., 2023
Leuconostoc mesenteroides subsp. *cremoris*			
Leuconostoc pseudomesenteroides			
Lactobacillus spp.	Spherical, 8–35 nm, average size 30 nm	Biomass, 0.025M $TiO\cdot(OH)_2$ solution, room temperature 12–48 h	Jha et al., 2009
Lactobacillus rhamnosus	Sperical, 3–10 nm, average size 5.7±1.9 nm	Supernatant, 5M $Ti[OCH(CH_3)_2]4$, pH 8, 24 h	Abdel-Maksoud et al., 2023
Lactobacillus crispatus	Sperical or oval, average size 87.9 nm	Supernatant, 0.025 M solution TiO_2, 37 °C, 24 h, stitting	Ibrahem et al., 2019

Biosynthesis of copper and magnesium oxides nanoparticles by lactic acid bacteria

The CuO NPs were biosynthesized using biomass *Lactobacillus casei* subsp. *casei* as biological agent, 1 mM solution of copper sulphate as a precursor, at pH 6.0 at 37ºC for 48 hours until the medium turned from yellow to dark brown showing the formation of CuO NPs, spherical in shape magnesium oxide nanoparticles without any agglomeration (Kouhkan et al., 2020).

Biomass of the strain *Lactococcus* spp. was used for biosynthesis of magnesium oxide nanoparticles, while 0.1 M solution of magnesium nitrate, $Mg(NO_3)_2\cdot 6H_2O$, was used as a precursor (Suba et al., 2022). Examples of the biosynthesis of copper and magnesium metal oxide nanoparticles using lactic acid bacteria are given in Table 7.

Table 7

Biosynthesis of copper and magnesium oxides nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei subsp. *casei*	Sperical, uniform, average size 200 nm	Biomass, 1 mM solution of $CuSO_4$, pH 6.0, 37 °C, 48 h	Kouhkan et al., 2020
Lactoccocus spp.	Spherical, evenly dispersed, average size 32 nm	Biomass, 0.1 M solution of $Mg(NO_3)_2 \cdot 6H_2O$, 40 °C, 10 h	Suba et al., 2022

Antimicrobial activity of metal nanoparticles synthesized by lactic acid bacteria

Antibiotic resistance is one of the most serious threats to human health. It was estimated that more than 1.27 million people in the world died in 2019 because of antibiotic resistance (WHO, 2023). Six nosocomial pathogens designated by the acronym ESKAPE (*Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter species*) represent the great threat to humans because they possess high virulence being multidrug resistant (Mulani et al., 2019). Development of new antimicrobial agents as an alternative to antibiotics will be a possible solution of widespread antibiotic resistance. That is why the identified bactericidal properties of metal nanoparticles against pathogenic bacterial strains are very important for their practical applications in treating bacterial infections. Particularly important is the fact that metal nanoparticles have non-specific bacterial toxicity that makes it difficult to develop resistance by bacteria (Sánchez-López et al., 2020).

To achieve an antibacterial effect, nanoparticles need to come into contact with bacterial cell. Contact of a nanoparticle with a cell occurs due to electrostatic attraction, van der Waals forces, as well as receptor-ligand and hydrophobic interactions (Wang et al., 2017). Interaction of NPs with cell wall involves loss of cell wall and cell membrane integrity followed by NPs direct interference with several metabolic pathways required for bacteria viability. After that NPs cross the bacterial membrane and interact with the bacterial cell structures such as DNA, lysosomes, ribosomes, and enzymes generating oxidative stress via reactive oxygen species (ROS), changing cell membrane permeability, inhibiting of enzyme activity, damaging bacterial protein and DNA (Sharmin et al., 2021; Wang et al., 2017) (Figure 2).

Thus, by synthesizing AgNPs from the supernatant of *Lactobacillus acidophilu*s, Rajesh and co-authors (2015) developed environmentally friendly antibacterial components and proved their antibacterial properties when used against *Klebsiella pneumoniae*, causing cytolysis and destroying the bacterial cell membrane. It is known that the size of nanoparticles is a key parameter determining antimicrobial activity. Smaller particles possess higher surface-to-volume ratio, and large surface area of NPs is necessary for attachment to microbial cell and rapid penetration into cells. For most NPs it is found that their smaller size correlates with a greater biological activity and stronger antimicrobial effect (Shoeibi and Mashreghi, 2017). It was shown for laser Ag NPs that nanoparticles with an average size of 19 nm were more effective against *Escherichia coli* than fraction with size ranges from 19 to 47 nm. Comparative study on influence silver nanoparticles with size 5, 20 and 50 nm on human cells also showed the correlation of smaller size on NPs and its toxicity effect (Korshed et al., 2019)

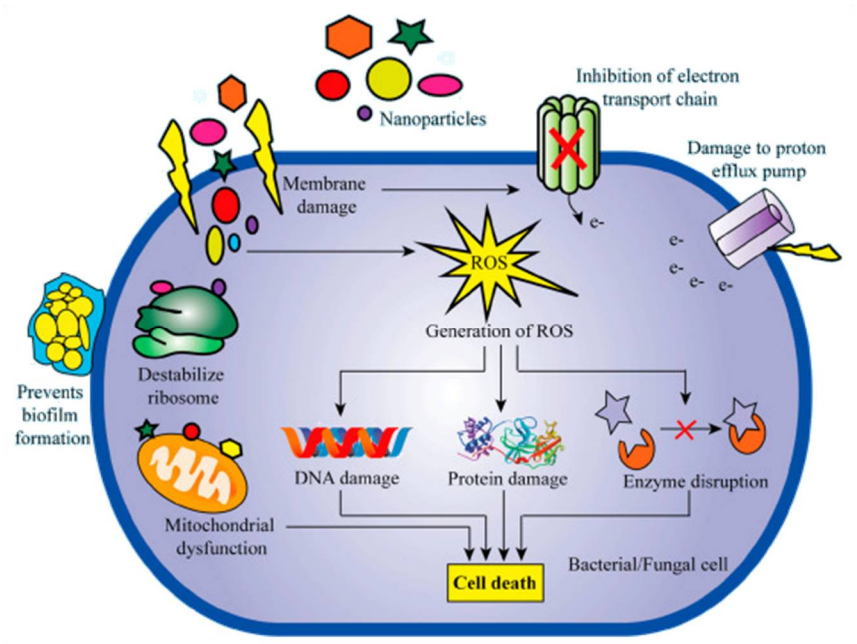

Figure 2. Schematic represents antimicrobial (bacteria and/or fungi) mechanisms of various nanoparticles (Sharmin et al., 2021)

Naseer et al. (2020) synthesized AgNPs from *Lactobacillus bulgaricus* and evaluated their antibacterial efficacy against *Staphylococcus aureus*, *S. epidermidis*, and *Salmonella typhi*. They showed that Gram-negative bacteria were more sensitive than Gram-positive bacteria to inhibition effect of silver nanoparticles. Some authors explained this phenomena that cell wall of Gram-negative bacteria have thinner wall and nanoparticles could penetrate easily inside the cell, damage cell membrane showing higher antimicrobial activity. Besides that, the cell wall of Gram-negative bacteria contains the lipopolysaccharides creating a greater negative charge of their cell wall in comparison with Gram-positive bacteria causing stronger adhesion of positively charged NPs on their surface (Bonnet et al., 2015). However, antimicrobial activity of SeNPs synthesized by lactic acid bacteria *Enterococcus faecalis* was shown against *Staphylococcus aureus* (Gram-positive) and was not shown against *Esherichia coli* (Gram-negative) (Shoeibi and Mashreghi, 2017). Syame with co-authors (2020) showed that inhibition zones of AgNPs synthesized using supernatant of *L. plantarum* were 16-18 mm against Gram positive bacteria, and 16-22 mm against Gram-negative; meanwhile AgNPs synthesized using supernatant of *L. brevis* were 16–21 mm against Gram-positive, and 13–22 mm against Gram-negative.

Antimicrobial activity of different metal nanoparticles synthesized by various lactic acid bacteria is shown in Table 8.

Table 8

Antimicrobial activity of nanoparticles synthesized by lactic acid bacteria

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus acidophilus	*Klebsiella pneumoniae*	Gram-	AgNPs, sperical, 4–50 nm,	16	60	Rajesh et al., 2015
Lactobacillus sp.	*Aspergillus flavus* *Aspergillus ochraceus* *Penicillium expansum* *Chromobacterium violaceum*	Fungi Fungi Fungi Gram-	AgNPs, sperical, 3–35 nm, average size 13.8 ±4.6 nm	12.4 ±0.6 12.9 ±0.8 15.9 ±1.0 18.0 ±0.7	*	Matei et al., 2020
Lactobacillus crustorum	*Staphylococcus aureus* *Listeria monocytogenes* *Bacillus cereus* *Fusarium oxysporum*	Gram+ Gram+ Gram+ Fungi	AgNPs, sperical, 10 nm	20.0 ±0.6 14.0 ±1.0 12.0 ±7.1 23.0 ±0.4	*	Sharma et al., 2022
Lactobacillus bulgaricus	*Staphylococcus aureus* *Staphylococcus epidermis* *Salmonella typhi*	Gram+ Gram+ Gram-	AgNPs, sperical, 30–100 nm	15 17 17	*	Naseer et al., 2020
Lactobacillus rhamnosus	*Chromobacterium v iolaceum* *Pseudomonas aeruginosa* *Serratia marcescens*	Gram- Gram- Gram-	AgNPs, sperical, average size 6.3 nm	13 10 7	13.3 26.5 53.1	Awadelkar eem et al., 2023
Lactobacillus plantarum	*Staphylococcus aureus* *Enterococcus faecalis* *Staphylococcus epidermis* *Staphylococcus aureus* *Clostridium perfringens* *Escherichia coli* *Klebsiella pneumoniae* *Pseudomonas aeruginosa* *Neisseria gonorrhoeae*	Gram+ Gram+ Gram+ Gram+ Gram+ Gram- Gram- Gram- Gram-	AgNPs, sperical, multifaceted, polydisperse, 5–40 nm	18 17 16 16 17 22 15 18 15	*	Syame et al., 2020

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus brevis	*Staphylococcus aureus*	Gram+	AgNPs, sperical, multifaceted, polydisperse, 5–40 nm	16	*	Syame et al., 2020
	Enterococcus faecalis	Gram+		21		
	Staphylococcus epidermis	Gram+		14		
	Staphylococcus aureus	Gram+		14		
	Clostridium perfringens	Gram+		17		
	Klebsiella pneumoniae	Gram-		15		
	Pseudomonas aeruginosa	Gram-		13		
	Escherichia coli	Gram-		22		
	Neisseria gonorrhoeae	Gram-		16		
Lactococcus lactis	*Pseudomonas aeruginosa*	Gram-	AgNPs, sperical, 5–50 nm, average size 19±2 nm	14 ±0.12	6.3	Viorica et al., 2018
	Staphylococcus aureus	Gram+		14 ±0.02	3.1	
	Staphylococcus epidermis	Gram+		16 ±0.05	3.1	
	Proteus mirabilis	Gram-		11 ±0.07	3.1	
Lactobacillus casei	*Bacillus sp.*	Gram+	AgNPs, *, 0.2–10 nm	24	*	Popoola and Adebayo-Tayo, 2017
	Streptococcus pyogenes	Gram+		22		
	Staphylococcus aureus	Gram+		15		
	Klebsiella sp.	Gram-		16		
	Pseudomonas aeruginosa	Gram-		13		
Enterococcus faecalis	*Staphylococcus aureus*	Gram+	SeNPs, sperical, 29–195 nm	8	*	Shoeibi and Mashreghi, 2016
Lactobacillus paracasei	*Candida albicans*	Yeast	SeNPs, hexagonal monodisperse, 91±1.8 nm	29 ±0.1	55	El-Saadony et al., 2021a
	Candida parapsilosis	Yeast		27 ±0.5	60	
	Candida krusei	Yeast		25 ±0.3	70	
	Candida glabrata	Yeast		23 ±0.4	65	
	Candida tropicalis	Yeast		24 ±0.5	70	
	Fusarium oxysporum	Fungi		26 ±0.2	50	
	Fusarium solani	Fungi		29 ±0.3	45	

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus rhamnosus	*Candida albicans* *Aspergillus niger*	Yeast Fungi	SeNPs, sperical, 20-60 nm	10 9	*	Rajasree and Gayathri, 2015
Lactobacillus acidophilus	*Candida albicans*	Yeast	SeNPs, sperical, 40-60 nm	4	*	
Lactobacillus plantarum	*Candida albicans* *Aspergillus niger*	Yeast Fungi	SeNPs, sperical, 60-80 nm	8 9	*	
Lactobacillus plantarum	*Candida albicans*	Yeast	SeNPs, sperical, 25–250 nm	28 ±0.5	*	Kheradmand, et al., 2014
Lactobacillus johnsonii	*Candida albicans*	Yeast		26 ±0.5	*	
Lactobacillus pentosus	*Escherichia coli* *Salmonella arizonae* *Salmonella tphimurium* *Staphylococcus aureus*	Gram- Gram- Gram- Gram+	SeNPs, sperical, average size 106.1 nm	11.5 13.2 9.0 10.1	*	Adebayo-Tayo et al., 2021
Pediococcus acidilactici	*Escherichia coli* *Klebsiella pneumoniae* *Staphylococcus aureus* *Bacillus subtilis*	Gram- Gram- Gram+ Gram+	SeNPs, sperical, 239 nm	17.5 ±0.8 13.4 ±0.9 27.9 ±1.2 16.2 ±1.1	*	Wang et al., 2023
Lactobacillus acidophilus	*Fusarium graminearum* *Fusarium cerealis* *Fusarium poae* *Fusarium avenaceum* *Fusarium culmorum* *Fusarium sporotrichioides*	Fungi Fungi Fungi Fungi Fungi Fungi	SeNPs, sperical, 46 nm	29 ±0.3 33 ±0.4 32 ±0.2 31 ±0.5 28 ±0.5 32 ±0.5	35 20 25 30 40 20	El-Saadony et al., 2021b
Lactobacillus plantarum	*Escherichia coli* *Salmonella sp.* *Staphylococcus aureus* *Staphylococcus epidermis*	Gram- Gram- Gram+ Gram+	ZnO NPs, *, average size 124.2 nm	19.3 ±0.6 16.7 ±1.2 19.0 ±1.0 17.7 ±0.6	*	Yusof et al., 2020b

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, µg/ml	Reference
Lactobacillus rhamnosus	*Aspergillus favus* *Aspergillus versicolor* *Penicillium citrinum* *Aspergillus chinensis* *Aspergillus ustus* *Penicillium chrysogenum*	Fungi Fungi Fungi Fungi Fungi Fungi	Sperical, 3–10 nm, average size 5.7 ±1.9 nm 300 µg/ml	17.7 ±0.6 20.3 ±1.5 18.7 ±0.6 20.3 ±0.5 18.3 ±0.6 17.7 ±1.2	*	Abdel-Maksoud et al., 2023
Lactobacillus casei subsp. casei	*Staphylococcus aureus* *Pseudomonas aeruginosa*	Gram+ Gram-	CoO NPs, spherical, average size 200 nm	12 10	250 50	Kouhkan et al., 2020
Lactoccocus spp.	*Clostridium perfringens* *Clostridioides difficile* *Esherihia coli* *Salmonella typhi* *Candida albicans* *Aspergillus flavus*	Gram+ Gram+ Gram- Gram- Yeast Fungi	MgO NPs, spherical, average size 32 nm	26 ±0.5 24 ±1.4 23 ±2.3 22 ±0.1 21 ±1.5 20 ±2.3	*	Suba et al., 2022

*There was no informationi; MIC, Minimum inhibitory concentration

The data presented in Table 8 convincingly demonstrated the effectiveness of LAB-derived AgNPs against many antibiotic-resistant bacterial strains, including *Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus pyogenes, Klebsiella pneumoniae* and *Salmonella typhi* (Naseer et al., 2020; Popoola and Adebayo-Tayo, 2017; Rajesh et al., 2015; Sharma et al., 2022; Syame et al., 2020; Viorica et al., 2018).

According to data shown in Table 8 inhibition zone caused by AgNPs calculated for different lactic acid bacteria and different Gram-negative test cultures was 15.00±3.76 mm (N_1=17) with coefficient of variation 14.1%; meanwhile for Gram-positive test cultures it was 16.72±3.09 mm (N_2=18) with coefficient of variations 9.5%. Calculated coefficient of Student equals to 0.1971, meanwhile Student's t table at degree of freedom N_1+N_2-2=33 and significance level 0.05 is 2.0341. So, the differences are not significant. Thus, there appears to be no real difference in the inhibitory effect of silver nanoparticles synthesized by lactic acid bacteria on Gram-positive or Gram-negative bacteria.

In the study of Sharma et al. (2022) results of the biosynthesis of safe and inexpensive AgNPs by different probiotic strains such as *Lactobacillus plantarum* F22, *L. paraplantarum* KM1, *L. pentosus* S6, and *L. crustorum* F11 are presented. The effectiveness the obtained AgNPs to inhibit the growth of various bacterial and fungal pathogens, namely *Bacillus cereus, Listeria monocytogenes*, antibiotic-resistant *Staphylococcus aureus*, *Pythium aphanidermatum, Pythium parasitica* та *Fusarium oxysporum* has been shown. Among them, AgNPs, synthesized by *Lactobacillus crustorum* F11, showed strong inhibition against all pathogens, with maximum activity against *Staphylococcus aureus* and *Fusarium oxysporum* with inhibition zones 20±0.61 mm and 23±0.37, respectively (Sharma et al., 2012).

Ability of metal nanoparticles to suppress different strains of bacteria, yeasts, and molds, as it is shown in Table 8, could find application in medicine, veterinary, pharmaceuticals, plant pathogen control, cosmetics, and manufacturing of food packing materials.

Practical use of metal nanoparticles

An analysis of modern literature confirms the fact of significant progress in nanotechnology over the past two decades, which is reflected in the intensive growth of scientific research and the discovery of numerous methods for the development and use of metal NPs in various industries, in particular in medicine, pharmacy, biology, food and textile industries, agriculture and electronics (Rana et al., 2020).

AgNPs play a special role in modern anticancer therapy and are being explored for detection and diagnosis of malignant tumors (Pothipor, 2019), controlled and external drug delivery systems (Karuppaiah et al., 2020; Nigam et al., 2017). Nanosilver-based compounds are used as antimicrobial agents because they have the ability to penetrate biological membranes and exert local or systemic effects, thus being used for a variety of treatments, including dental and digestive pathologies, wound healing and burns (Mohler et al., 2018; Sim et al., 2018). Nanosilver-based compositions have proven effective therapeutic effects against several pathologies caused by clinically significant viruses, such as severe acute respiratory syndrome, SARS-CoV-2 (Balagna et al., 2020; Tremiliosi et al., 2020), papillomavirus (Rajawat and Malik, 2019), rotavirus (Adebayo-Tayo et al., 2019; Zhang et al., 2017) and other enteric viruses (Castro-Mayorga et al., 2017; Sofy et al., 2019).

SeNPs can be used for a wide range of targets. In particular, SeNPs have been found to have great potential in the treatment of diabetes and Alzheimer's disease, oxidative stress, inflammatory diseases such as rheumatoid arthritis, anti-tumor therapy, and serve as a protector against toxic substances, including heavy metals (Ferro, 2021; Khurana, 2015; Rehman et al., 2021). The possible development of dressings based on SeNPs to accelerate the healing of infected wounds has also been reported (Fang, 2023), the development of food additives for humans and veterinary needs (Malyugina et al., 2021), systems for detecting viruses, such as test strips for detecting anti-SARS-CoV-2 IgM and IgG in human serum and blood (Chen et al., 2022; Wang et al., 2020). Currently, the production of cosmeceuticals and nanocosmeceuticals for the care of skin, hair, nails and lips and protection against wrinkles, photoaging, hyperpigmentation, dandruff and hair damage with SeNPs is popular.

AuNPs. Based on a clinical study, gold nanoparticles have been shown to be useful for screening gastrointestinal tumors (Nejati et al., 2022). AuNPs are used for drug delivery, where light irradiation can trigger drug release at the target site (Tian et al., 2016). AuNPs

may also be useful for virus detection programs (Draz and Shafiee, 2018) as they have demonstrated antiviral activity against several viruses, such as hepatitis B virus, human papillomavirus, human rhinovirus, and even SARS-CoV-2 (Mehranfar and Izadyar, 2020).

Fe_3O_4 NPs explore biomedical approaches including magnetic resonance imaging, drug delivery, and hyperthermia therapy (Dadfar et al., 2019). Thus, Fe_3O_4 NPs are successfully used to coat optical instruments for solar energy (Tiquia-Arashiro and Rodrigues, 2016), in clinics as contrast agents for magnetic resonance imaging. Iron oxide nanoparticles have the dual ability to act as magnetic and photothermal agents in cancer therapy (Espinosa et al., 2016).

TiO_2 NPs and **ZnO NPs** have chemical stability, environmental properties and non-toxicity, and can be produced relatively cheaply. They are used in a variety of photochemistry applications, ranging from large-scale products to more complex programs. For example, in the case of environmental remediation, they have been used in water photoelectrolysis and dye-sensitive solar cells (El-Dafrawy et al., 2016). TiO_2NPs and ZnONPs also find application as UV filters in cosmetic products such as moisturizers, hair care products, makeup accessories, and sunscreens (Hameed et al., 2019).

CoO NPs as many other metal nanoparticles, such as AgNPs, MgO and TiO_2 NPs, are found application in dentistry due to their biophysicochemical functionalization, antimicrobial activity, and biocompatibility (Xu et al., 2022); in agriculture for protecting crops against pests and diseases and for delivery and controlled release of agrochemicals (pesticides and fertilizers) (Fincheira et al., 2023); in textile production, in wastewater treatment as a disinfectant, and can be used in solar energy conversion devices and electrochemical sensors (Woźniak-Budych et al., 2023).

MgO NPs are finding increasing attention for their application in medical and optical devices, drug delivery, antibacterial materials, toxic waste remediation, and manufacturing of petrochemical products. Due to their antibacterial, antifungal, anticancer, antidiabetic, and antioxidant abilities, biogenic MgONPs can be effectively used in biomedicine (Thakur et al., 2022).

Therefore, metal nanoparticles are widely used in various fields of human activity. Some areas of use of metal nanoparticles synthesized by lactic acid bacteria are presented in Table 9.

Table 9

Practical application of metal nanoparticles synthesied by lactic acid bacterium

NPs	Microorganisms	Practical application	Reference
AgNPs	*Lactobacillus plantarum* TA4 *Lactobacillus rhamnosus* MTCC-1423 *Lactobacillus crustorum* F11	Dressing components (Acticoat™, SilvaSorb™ Gel), catheter coating (SilverSoaker™ Catheter, Silverline® Drainage Catheters), targeted drug delivery vehicles, antimicrobial and antiviral agents	Awadelkareem et al., 2023; Gherasim et al., 2020; Yusof et al., 2020a

NPs	Microorganisms	Practical application	Reference
SeNPs	*Lactobacillus casei* ATCC 393 *Lactobacillus paracasei* HM1 *Lactobacillus paracasei* SCFF20	Packaging materials for food products, components of cosmetics, dietary supplements, food products, veterinary drugs, antioxidant, anti-inflammatory, antimicrobial agents	El-Saadony, 2021a; Hu, 2023; Xu, 2018
AuNPs	*Lactobacillus kimchicus* DCY51 *Lactobacillus acidophilus* USTCMS 1053 *Lactobacillus paracasei*	Anticancer therapy, targeted drug delivery, MRI contrast agents, antiviral agents	Markus, 2016; Miran and Ali, 2024; Repotente, 2022
Fe_3O_4 NPs	*Lactobacillus casei* PTCC 1608 *Lactobacillus fermentum* PTCC 1638	Coating optical instruments for solar energy	Fani et al., 2018; Torabian et al., 2018
ZnO NPs	*Lactobacillus plantarum* TA4 *Lactobacillus johnsonii*	Anticancer drugs, components of cosmetic products, targeted drug delivery vehicles, antimicrobial agents	Al-Zahrani et al., 2018 ; Yusof et al., 2020b
TiO_2 NPs	*Leuconostoc mesenteroides* subsp. *mesenteroides*	In photochemistry, components of cosmetics, antimicrobial agents	Hasan et al., 2023

Conclusions

Having carried out a detailed analysis of scientific literature for the period 2013-2024, it can be stated that there is a current permanently increasing interest in research and development in the field of production of metal nanoparticles by lactic acid bacteria using their biomass, cell lysate or free-cell supernatant. Lactic acid bacteria attract the attention of researchers as biosafe producers that make it possible to use for production of various metal nanoparticles in a relatively cheap process.

An assessment of data on the inhibitory effect of AgNPs synthesized by LABs on the growth of Gram-positive and Gram-negative bacteria showed the absence of significant differences in the sizes of inhibition zones of various representatives of both groups.

During the biosynthesis, intracellular or external accumulation of nanoparticles occurs, which in turn have different sizes, shapes and properties. Antimicrobial abilities of nanoparticles synthesized by lactic acid bacteria can find applications in many areas of human activity.

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