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Review Article

Nanoparticles as antimicrobial agent and its effect on the performance and production of animals and poultry

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Abstract

Antibiotic-resistant bacteria have become increasingly prevalent in recent years, leading to significant health issues. Researchers are looking for different antimicrobial compounds to prevent or control diseases brought on by microorganisms. To create antibacterial agents that work, various approaches are employed. Nanoparticles (NPs) are definitely promising materials in this regard. Bypassing the mechanisms of drug resistance in bacteria prevents the formation of biofilms and other critical processes associated with their potential for virulence. Nanoparticles have the ability to pass through bacterial cell walls and membranes and function by obstructing essential molecular functions. With the appropriate antibiotics, NPs may have a synergistic effect. to help stop the growing global bacterial resistance crisis. This article reports on antimicrobial nanoparticles, including their types and modes of action. Membrane disruption, enzyme inhibition, and the production of different reactive oxygen species are the main ways that metallic, polymeric, lipid, and carbon-based nanoparticles exhibit antimicrobial action. Additionally, minerals are essential for the nutrition of animal production systems. Minerals support animal development, reproduction, and digestion. These minerals are added 20–30 times more than what animals typically require because of the comparatively low bioavailability of minerals derived from their inorganic sources. As a result, these minerals may be excreted in excess in the feces, polluting the environment and upsetting the equilibrium of other minerals. Because of their

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larger surface area, higher surface activity, better catalytic efficiency, and improved adsorbing capacity, nanominerals improve bioavailability. The growth, productivity, and general health of animals can all be enhanced by nanominerals. The primary topics of this review are the methods used to produce nanoparticles, their various synthesis techniques (physical, chemical, and biological), their antibacterial properties, and their possible uses in the field of veterinary medicine.

Introduction

Nanoparticles (NPs) are particles in the 1-100 nm scale range. The physical and chemical characteristics of NPs are quite different from those found in bulk materials. While NPs could be created by using a variety of chemical and physical methods, biological synthesis provides a low-cost, non-toxic, and environmentally friendly green chemistry method. (**Çakıcı et al. 2019** and **Gurkok and Ozdal 2021**). Today, nanobiotechnology is an emerging subject in animal and veterinary sciences for a number of practical applications, such as medicinal, diagnostic, and nutritional. (**Amlan and Lalhriatpuii 2020** and **El-Maddawy et al. 2022**). The nano minerals showed important impacts, even in smaller amounts, than standard mineral sources. The nano minerals possess substantial stimulating growth, immunomodulatory, and antimicrobial activities than conventional counterparts. (**Sindhura et al. 2014**). The distinctive properties of nanoparticles, including size, shape, charge, high surface area ratio, and high reactivity, underpin their potential uses in a variety of sectors. This has piqued the interest of a large number of people (**Kim et al. 2007**). Nanoparticles of gold, silver, platinum, and other oxides have been widely exploited in the area of nanobiomedicine due to their specific features. (**Zhang et al. 2021**).

Bacteria may become resistant to both natural and synthetic antibiotics through a variety of methods, making them ineffective and requiring the creation of new substitutes. As an alternative to antibiotics, Nanoparticles (NPs) are being used more and more to target bacteria. Applications of NPs include antibacterial coatings for medical devices and implantable devices to stop infections and encourage healing of wounds, Systems for delivering antibiotics to treat illnesses, diagnosis of bacteria, and vaccines against bacteria to prevent infections. (**wang et al. 2017**). Consequently, using nano-

particles and antibiotics in combination could enhance their inhibitory effects and minimize the likelihood of organisms becoming resistant (**Sobhani et al. 2017**). Therefore, this review's aim is to elucidate the antimicrobial mechanisms of NPs and their impact on the health and growth performance of animals and poultry.

Nanoparticles (NPs) containing critical minerals, ranging in size from 1 to 100nm, might be employed as a substitute for traditional forms of elements in animal food. (**Kociova et al. 2020** and **Szuba-Trznadel et al. 2021**). It is thought that significantly lower quantities of nanoparticles than bulk minerals would be needed to supply animal needs for certain elements. (**Abdollahi et al. 2020** and **Ouyang et al. 2021**). Reducing the amount of minerals added to the animal diet could decrease the prices of feed. (**Vijayakumar and Balakrishnan 2014**). Furthermore, elements in nanoform can improve an animal's bioavailability. (**Youssef et al. 2019** and **Hidayat et al. 2021**), because of their tiny size, large surface area, excellent homogeneity, and physical reactivity (**Abdollahi et al. 2020**)

Properties of Nanoparticles

The surface-to-volume ratio considerably rises as the NPs' size declines. Wide NP surface areas improve interactions with bacteria and their antibacterial properties. According to research, the positively charged metal nanoparticles (NPs) exhibited enhanced antibacterial properties and bind more tightly to negatively charged bacterial surfaces. The spherical NPs were considered as a better antibacterial result by way of they allowed extra ions to be released as a result of their broad surface area (**Shanmuganathan et al. 2018**). Compared to spherical particles, rod-like particles were more effective in delivering silica nanoparticles (NO), releasing nitric oxide and producing

stronger antibacterial effects throughout the biofilm (Slomberg *et al.* 2013).

A nanoparticle is any particle smaller than 100 nanometers (nm). The Latin word nanus, which means dwarf, is where the term nano is derived. The nanoparticles' mechanical, optical, electrical, chemical, physical, and magnetic characteristics differ significantly from those found at a greater scale. (Buzea *et al.* 2007). The main difference between nanoparticles and larger ones is as follows:

1. Changed stability: Because joining adjacent atoms requires less energy and changes the fusion point of the given element, the atoms in nanoparticles are less stable than those in larger structures (Cao, 2004).
2. Quantum effects: The behavior of quantum nanostructures is comparable to that of an atom. When they are in the form of nanoparticles, their spatial arrangement enables them to possess characteristics that are not similar to the element, such as magnetism in metals like gold or platinum.
3. Surface area effect: When the material is divided into tiny particles, its surface area increases many times which increases the rate of the reaction (Buzea *et al.* 2007).

The goal of nanotechnology, an advanced technology, is to create materials with at least one dimension less than 100 nanometers (Buzea *et al.* 2007, Husen and Siddiqi 2014, Siddiqi and Husen 2016). Numerous industries, including agriculture, animal husbandry, and food systems, make extensive use of nanominerals. Compared to their conventional counterparts, these nano minerals exhibit notable growth-promoting, immunomodulatory, and antimicrobial properties. Additionally, they change the pattern of rumen fermentation when added to animal feed. In addition to this, nanominerals are used to improve poultry and cattle reproductive-performance. Animals need minerals for normal growth, to carry out different physiological and biochemical activities in their bodies, and to continue their race in the future (Park *et al.* 2004 and Suttle, 2010). Many animal feeds, particularly those for poultry, have very low levels of minerals, and even

when they are available in sufficient amounts, their bioavailability is very low. However, the animal needs more mineral supplements because, in addition to the minerals being used at the cellular level, large amounts of minerals are excreted into the environment, which raises the cost (Bao and Choct 2009 and Ghosh *et al.* 2016).

There are several routes for nanoparticles to enter the gastrointestinal tract (GIT). The smaller particles diameter, the faster it diffuses through the GIT mucus to reach the intestinal lining cells and is absorbed through the GIT barrier to enter the blood. There are several ways that uptake can happen, including passive diffusion through active transport systems, mucosal cells, and intercellular (O' Hagan, 1996). A smaller particle size penetrates deeper into the tissues and improves absorption. It has been shown that polystyrene nanoparticles of 100 nm or less may go to the liver and spleen through the lymphatic system. (Jani *et al.* 1990). Small particles that could be absorbed by the epithelium of the villi may reach the circulation directly and be mostly cleaned up by the liver and spleen. (Hillery *et al.* 1994). Parallel to absorption, physicochemical properties like solubility, charge, and size affect how mineral particles are distributed, broken down, and eliminated from the body. Additionally, it has been noted that the paracellular pathway for nanoparticle absorption uses less than 1% of the surface area of the mucosa.

Techniques used in nanoparticle production

Studying several nanoparticle synthesis techniques was crucial to produce acceptable nanomaterials with specific sizes, including physical, chemical, and biological methods.

Factors affecting nanoparticles synthesis (Demazeau, 2010):

- Particle size and shape
- Pore size
- Temperature
- Time
- Pressure
- Cost of preparation

Techniques for synthesis

A. Top-down technique (Siwach and Sen 2008)

The top-down technique was used initial macroscopic structures. This technique initiated with bigger particles that were move through a sequence of processes to become nanoparticles. The primary disadvantages of this technique were its enormous installation requirements and the hefty setup expense. Although this method worked well for laboratory research, it was not ideal for soft samples or large-scale production. The foundation of this technique was the grinding of materials. fig. 1

Method of top-down technique:

1. Chemical vapour deposition
2. Physical vapour deposition.
3. Ion implantation.
4. Electron beam lithography.
5. X-ray lithography.

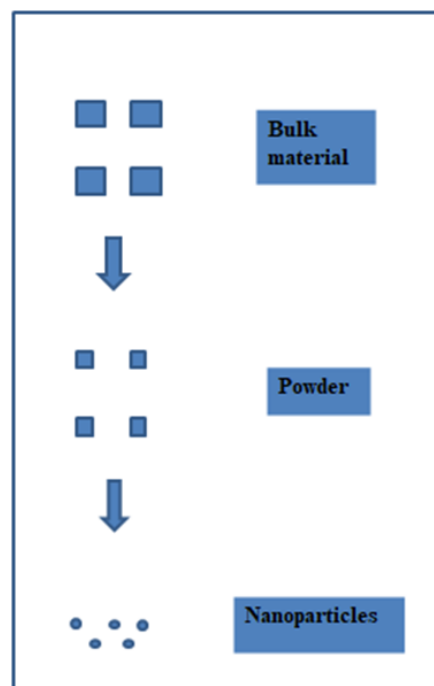


Fig. (1). Top-down method (Patil *et al.*, 2021)

B. Bottom-up technique (Rangarajan *et al.* 2014)

The bottom-up technique of production of nanomaterials involved reducing the material's constituent atoms size to the mostly small size, followed by the nanostructure's creation. During the subsequent progression, the simple units combined into larger stable structures through the physical forces acting on nanoscale. The principle of this technique based on of molecular recognition (self-assembly). Self-assembly was defined as the process of producing more and more of one's own type. For the commercial manufacturing of nanoparticles, several of these methods were either still being researched or were only recently being employed. fig. 2

Methods of a bottom-up technique (Hou *et al.* 2007):

1. Sol-gel synthesis
2. Colloidal precipitation
3. Hydrothermal synthesis
4. Organometallic chemical route
5. Electrodeposition

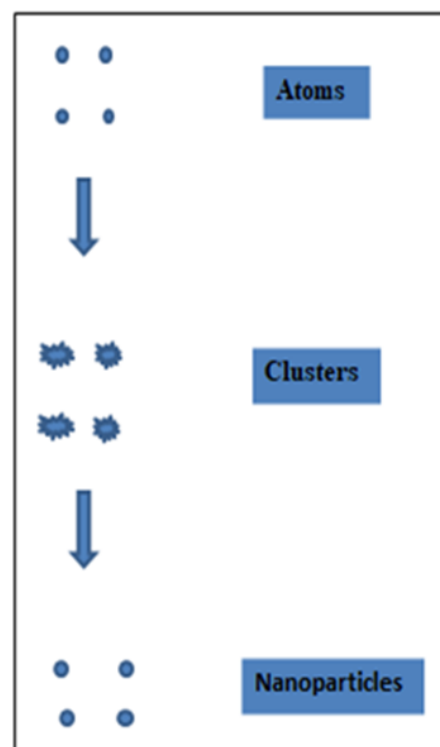


Fig. (2). Bottom-up method (Patil *et al.*, 2021)

Nanoparticle's synthesis Methods:

Three categories of methods for the nanoparticle's synthesis, table 1.

- A.Physical Methods
- B.Chemical Methods
- C.Biological Methods

Table (1). Nanoparticle's synthesis Methods:

Methods of synthesis of nanoparticles		
Physical Methods	Chemical Methods	Biological methods
Mechanical Method	Sol-gel Method	Synthesis Using Microorganisms
Pulse Laser Ablation	Sonochemical Synthesis	Synthesis Using Plant Extracts
Pulsed Wire Discharge	Co-precipitation Method	Synthesis Using Algae
Chemical Vapor Deposition	Inert Gas Condensation Method	
Laser Pyrolysis	Hydrothermal Synthesis	
Ionized Cluster Beam Deposition		

According to the requirement, the nanoparticle's synthesis methods were selected. Each method had some advantages and disadvantages; the synthesis method was choosing depended on the facilities available, for example the physical methods were appropriate for small-scale synthesis, while the chemical methods were choosing where the cost causes an anxiety and the biological methods were used in different consequence (**Krishnappa *et al.* 2018**).

Types of Nanoparticles

Various types of nanoparticles are often used in medicine and healthcare, especially when using antimicrobial chemotherapy. Applications for metal-based nanoparticles are numerous and include biotechnology to electronics, materials science, and medicine. These nanoparticles often display different physical and chemical characteristics due to their small size and high surface area-to-volume ratio. The many kinds of antimicrobial nanoparticles are detailed and enumerated below.

1. Metal-based AMNPs

Nanoscale particles made mostly of metal compounds or atoms are known as nanoparticles based on metal. The usual size of these nanoparticles is between 1 and 100 nanometers (nm), which is between tens to hundreds of atoms in size. In the investigation of antimicrobial nanotechnology, nanoparticles based

on metal including copper (Cu), zinc (Zn), and silver (Ag) are among the most investigated and used.

1.a. Silver (Ag)-based AMNPs

Silver nanoparticles are often produced by physical vapour deposition, chemical reduction, and biological processes. The principal route of action involves the production of silver ions that damage cell membranes, deactivate enzymes, and inhibit DNA/RNA synthesis, among other microbial cellular processes. They are known as having remarkable properties including potent antimicrobial activity and great electrical and thermal conductivity. They are very helpful in water purification systems, antimicrobial coatings, and wound dressings because of their antimicrobial characteristics. (**Gao *et al.* 2018**).

1.b. Zinc (Zn)-based AMNPs

For the synthesis of zinc nanoparticles, the sol-gel technique, green synthesis using plant extracts and chemical precipitation are used. This mostly has to do with the formation of reactive oxygen species (ROS), that cause microbial cells to exhibit oxidative stress. These particles are added to paint and utilized in cosmetics and sunscreens due to their antimicrobial and UV-blocking characteristics (Smijs and Pavel, 2011). They reduce microbial contamination in fertilizers and insecticides (**Gudkov *et al.* 2021**).

1.c. Copper (Cu)-based AMNPs

In addition to the widely used chemical reduction method, Cu nanoparticles are frequently synthesized using electrochemical reactions and thermal decomposition. Copper ions released by copper nanoparticles damage microbial cell membranes and prevent vital enzymes from functioning. (Ma *et al.* 2022). Cu nanoparticles are often used in packaging for food and as coatings for surfaces to decrease microbial contamination on high-touch surfaces. These nanoparticles are constantly being improved for increased effectiveness, less toxicity, and broader range (Ermini, and Voliani 2021).

2. Metal oxide AMNPs

They are atoms of oxygen and metal that combine to produce metal–oxygen compounds. They are made from a variety of metal components, such as non-metals like silicon and aluminum and transition metals, such as copper and iron, and titanium. (Mondal *et al.* 2024).

2.a. Zinc oxide nanoparticles

Zinc and oxygen atoms form zinc oxide nanoparticles (ZnO NPs), which are typically 1–100 nanometers in size. Their action is frequently linked to the production of reactive oxygen species (ROS), which induce oxidative stress in microorganisms. When exposed to light, zinc oxide nanoparticles may act as photocatalysts, which makes them beneficial for air and procedures for purifying water and air that depend on breakdown of organic contaminants. (De *et al.* 2010).

2.b. Titanium dioxide nanoparticles

UV light is frequently used with titanium dioxide nanoparticles to increase their antibacterial action. Additionally, these nanoparticles generate ROS, which destroy microbial cells. When exposed to ultraviolet (UV) radiation, TiO₂ nanoparticles show photocatalytic activity. This characteristic enables them to produce reactive oxygen species (ROS), including superoxide ions and hydroxyl radicals. (Liao *et al.* 2020). Because of their special surface properties, TiO₂ nanoparticles act as catalysts in chemical processes. (Pangprasit *et al.* 2023).

2.c. Magnesium oxide nanoparticles

It has been demonstrated that MgO nanoparticles may interrupt the growth of a variety of bacteria and fungus. They have the ability to interfere with cell membranes and metabolic functions of microorganisms, rendering them inactive. (Maji *et al.* 2020).

2.d. Iron oxide nanoparticles

They are small particles made mostly of oxygen (O) and iron (Fe) atoms. They can form a variety of iron oxide compounds, including maghemite, hematite (Fe₂O₃), and magnetite (Fe₃O₄). They have shown antimicrobial efficacy against a variety of bacteria including both Gram-negative and Gram-positive bacteria, in addition to several fungus species. They are widely applied in healthcare and biomedical uses. (de Toledo *et al.* 2018).

3. Polymer-based AMNPs

Nanoscale particles made mostly of polymers are known as polymer-based nanoparticles, which consist of large molecules called monomers, which are repeating subunits. The main constituents of polymer-based nanoparticles are either synthetic or natural polymers. Polyethylene, polyvinyl chloride (PVC), and polystyrene are examples of synthetic polymers that are frequently used. Alginate, cellulose, and chitin are examples of natural polymers. Common varieties of polymer-based nanoparticles include polystyrene polyethylene glycol (PEG) and poly (lactic-co-glycolic acid) (PLGA), PCL and polyethyleneimine (Idrees *et al.* 2020).

4. Carbon/graphene oxide-based nanoparticles

They are particles at the nanoscale in which atoms of carbon constitute a large part of these tiny particles. Because graphene oxide (GO) nanomaterials may physically disrupt cell membranes of microorganisms and act as a vehicle for other antimicrobial drugs, they exhibit encouraging antimicrobial activity (Ozdal, and Gurkok 2022).

5. Chemical classification of nanoparticles (Mageswari *et al.* 2016)

According to nanoparticles chemical properties, nanoparticles are classified in to:

5.a. Organic nanoparticles

Fat, sugar, and protein molecules are classified as organic nanoparticles. Organic nanoparticles can encapsulate nutrients and can transport them through the bloodstream, which is now referred to as the nanocapsule, which are added to feed as liposomes and also serve as antibacterial agents in stored feed. Nano-emulsion identify as another class of organic nanoparticles that is primarily utilized as a stabilizing agent to deliver active ingredients in a continuous phase or at the water/oil interface.

5.b. Inorganic nanoparticles

Inorganic nanoparticles are widely utilized in feed products, such as titanium dioxide, which serves as an ultraviolet barrier in feed packaging and as a feed colorant. Minerals such as silver, magnesium, and calcium are being used as antimicrobial agents, as water purifiers, and in feed storage. Nanoclays are one of inorganic nanoparticles use in the packaging of feed.

The antibacterial activity of nanoparticles, Fig. 3:

Antibiotic-resistant bacteria was become more prevalent recently, which led to major health issues. In order to manage or avoid bacterial diseases, researchers were looking for substitute antibacterial compounds. A growing variety of NP-based materials and NP variations had been employed as a new line of defense against multidrug resistance (MDR) and bacterial resistance (**Cavassin *et al.* 2015**)

Particularly, NPs were shown broad-spectrum antibacterial capabilities against Gram-positive together Gram-negative bacteria. Numerous metal nanoparticles (NPs), such as iron oxide (Fe₃O₄), zinc oxide (ZnO), copper (Cu), selenium (Se), nickel (Ni), gold (Au), silver (Ag), and titanium dioxide (TiO₂), were thoroughly investigated for their antibacterial properties (**Hemeg, 2017**). In this regard, it was revealed that Ag nanoparticles were exhibited antibacterial action against *Escherichia coli* and *Pseudomonas aeruginosa* that was depended on the concentration, and ZnO NPs inhibited *Staphylococcus aureus* (**Ramalingam *et al.* 2016**)

Mechanisms of NPs antibacterial proper-

ties:

It was still unclear how exactly NPs work to have antibacterial effects. The following were some of the main ways that cell death was caused:

1. Adhering of the bacterial cell and impairing of the respiration and the cell membrane permeability. For example: the direct contact of silver nanoparticles (AgNPs) with the bacterial cell wall and subsequent cytoplasmic penetration was linked to the fatal effect of AgNPs. The bacterial cell wall and membrane were exposed to NPs, which resulted in morphological abnormalities like cytoplasm shrinkage, membrane instability, the formation of many electron-dense pits, and membrane disruption. (**Sondi *et al.* 2004**).
2. Inducing of the toxicity through the discharge of free metal ions from NPs' surfaces.
3. Oxidative stress by generating reactive oxygen species (ROS), which were essential for several cellular signaling pathways and were created during normal oxygen consumption. During oxidative phosphorylation, oxygen served as the last acceptor of electrons carried by the electron transport system (ETS) and was subsequently reduced to the water molecule. Molecular oxygen absorbed some of these electrons, creating O₂⁻, which might subsequently be converted to H₂O₂ and •OH. However, metal ions released from the NPs' surface caused ROS eruptions in bacterial cells with disordered respiratory systems, which might greatly boost intracellular ROS generation. But after being exposed to NPs, ROS levels rose to a point where bacteria were unable to withstand the damaging alterations in essential biological components such the cell wall, cell membrane, DNA, and protein (**Baptista *et al.* 2018**). Consequently, chromosome DNA and protein damage, hole formation, lipid peroxidation, and ultimately cell death were caused by the accumulation of chemically highly reactive ROS and ROS-induced oxidative stress in the bacterial cell. Metal oxide nanoparticles (NPs) such as ZnO and TiO₂ were believed to have bactericidal

effects primarily through the reactive oxygen species (ROS) production (Leung *et al.* 2016), while it was thought that Ag and

Au mainly had bactericidal effects by releasing metal ions (Cui *et al.* 2012).

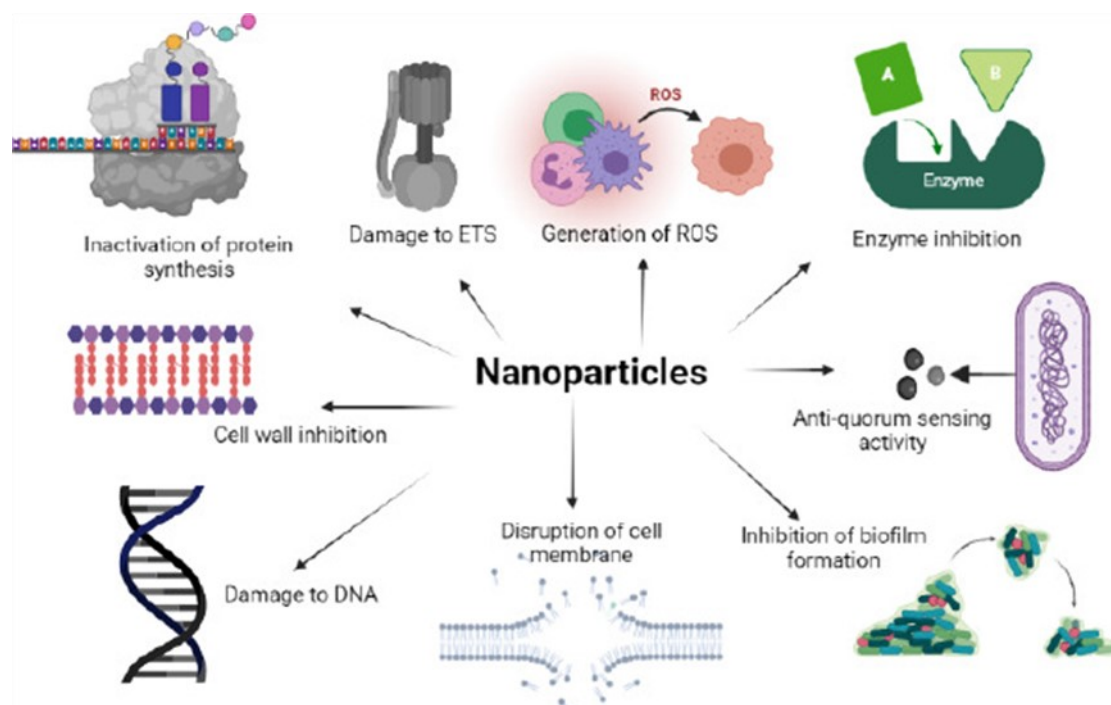


Fig. (3). Antibacterial mechanisms of NPs (Ozidal and Gurkok 2022)

Antibacterial roles of Nanoparticles (NPs), fig 3:

1- Synergistic effects of NPs with antibiotics

In systems of NP-drug conjugates, NPs were coupled with other antimicrobial agents and tailored, their effectiveness against resistant microbes increases. The chemical characteristics of nanoparticles allowed for both enzyme safety and long-term binding to the antibiotic target site. Consequently, higher antibiotic requirements were avoided. Conjugates of antibiotic nanoparticles were essential for preventing infections caused by multidrug-resistant pathogenic microorganisms. Therefore, combining NPs with antibiotics was observed as a way to prevent the bacterial resistance occurrence (Zhao *et al.* 2013).

Abed and Mohammed (2021) demonstrated that AgNPs coupled with bacitracin, ciprofloxacin, tetracycline, and cefixime shown synergistic efficacy against *P. aeruginosa*, *E. coli*, *S. aureus*, and *Candida albicans*. Abo-Shama *et al.* (2020) also demonstrated that when compared antibiotic using alone to the synergistic

action of antibiotics (azithromycin, cefotaxime, cefuroxime, fosfomycin, and chloramphenicol) against *E. coli* was safely enhanced in AgNPs presence. Another study of Zhang *et al.* (2018) found that CuO NPs and cephalexin antibiotic together had a synergistic effect against *E. coli*

2- Anti-quorum sensing and anti-biofilm properties of NPs

Another focus of NPs' antibacterial action was bacterial signal transduction. Quorum sensing (QS) obstruction was one effective alternate tactic for combating bacterial infections. In many pathogenic bacteria, QS, a cell density-dependent regulation process that relied on the releasing of extracellular small signal molecules called autoinducers, controlled the expression of virulence proteins (Qais *et al.* 2020). The QS system, which bacteria created, was shown to be in charge of biofilm formation, cell-to-cell communication, and the production of several virulence agents (Maruthupandy *et al.* 2020).

Additionally, it was demonstrated that NPs ef-

ficiently eliminate pre-existing biofilms and stopped new one's formation. In nature, biofilms-definite, well-organized multicellular microbial communities-were one of the ways that microorganisms survived. Free-floating microbes verified their presence on a surface, started to proliferate, and eventually settled there. They were arranged in dense groups within the extracellular polymeric materials (EPS) that they molded (**Rather *et al.* 2021**).

Several NP types for example, NiO, Ag, Au, Se, Te, Si, and AgCl-TiO₂ obstructed the mechanism of QS and inhibited the formation of biofilms. As an example, methicillin-resistant *S. aureus* biofilm formation was inhibited by ZnO and TiO₂ NPs (**Jesline *et al.* 2015**). AgNPs produced through *Solibacillus isronensis* demonstrated antibiofilm action against *E. coli* and *P. aeruginosa* (**Singh *et al.* 2020**).

3- Nanoparticles penetration ability to the bacterial cell wall and membrane

NPs gathered on the cell wall and membrane of bacteria, beginning morphological alterations, including cytoplasmic shrinkage, membrane separation, and the development of many electron-dense pits, finally rupture of the membrane, for example: NP accumulation in *E. Coli*'s cell wall formed pits that released membrane proteins and lipopolysaccharide molecules, causing the outer membrane to become less intact and ultimately leading to cell death (**Sondi *et al.* 2004**). NPs that targeted the cell membrane also reduced intracellular ATP levels, impeded oxidative phosphorylation, and degraded proton motive force and membrane potential. One example of this was the spherical AgNPs that were used against *E. coli* (**Lok *et al.* 2006**).

4- Disrupting important molecular mechanisms.

Free metal ions also interacted with the phosphate, carbonyl, amino, and sulfhydryl (thiol) groups of the cellular macromolecules, such as proteins, lipids, and DNA, once they were within the cell (**Tang and Zheng 2018**). In contrast to phosphate groups, unbound Ag ions were shown to preferentially connect with bacterial nucleic acids through nucleosides, which broke down chromosomal DNA or stopped

DNA replication. **Cui *et al.* (2012)** demonstrated that AuNPs exhibited antibacterial qualities against *E. coli* through lowering ATP levels besides collapsing membrane potential by blocking ATPase activity and preventing the ribosomal component from binding to tRNA.

Effect of Minerals Nano Particles on the Performance of Animals

Compared to their normal-sized counterparts, the nanoparticles' bioavailability is probably going to increase several times. There are, however, few papers outlining the impact of dietary supplements containing nanoparticles on animal performance. According to (**Zaboli *et al.* 2013**), children that received supplements of 20–40 ppm nano zinc oxide showed no change in feed consumption. However, (**Ahmadi *et al.* 2013**) found that supplementing broiler with 30-120 ppm of zinc nanoparticles enhanced their daily feed consumption considerably when compared to the control. (**Tong *et al.* 2012**) discovered that adding 500 ppm. Daily feed intake was enhanced by nano ZnO. Several biological functions, including digestion, metabolism, and nutrition intake, may be impacted by the capacity to improve protein stability by interacting with nanomaterials. Zinc nanoparticle supplementation at a 60 ppm level significantly increased the activity of digestive enzymes (lipase, amylase, and protease) in freshwater prawn post larvae (**Muralisankar *et al.* 2014**). According to (**Rohner *et al.* 2007**), Fe nanoparticles' relative bioavailability and in vitro solubility were both noticeably higher than those of its regular form, making them more beneficial. While the digestibility of dry matter, organic matter, ether extract, neutral detergent fiber, and acid detergent fiber was similar, (**Uniyal *et al.* 2017**) found that the group fed organic and commercial nano zinc had a considerably greater crude protein digestibility than the other groups. In comparison to control given 60 ppm zinc oxide, (**Zhao *et al.* 2014**) found that supplementing broiler with nano zinc at 20, 60, and 100 ppm levels greatly improved feed efficiency. According to (**Shi *et al.* 2011**), adding nano-Se to the basal diet at levels of 0.3, 3, and 6 ppm reduced ruminal pH and linearly raised the concentration of total VFA (ranging from

73.6 to 77.7 mM) as the amount of nano-Se rose.

Effect on growth performance

According to (Zaboli *et al.* 2013), children that received supplements of 20–40 ppm nano zinc oxide showed no change in average daily gain. (Wang *et al.* 2012) found that adding 0–400 ppb Cr-loaded Chitosan nanoparticles (Cr-CNP) to finishing pigs did not effect on their growth performance. However, compared to the control group, guinea pigs fed a 20 ppm commercial nano zinc (30 nm) diet shown a significantly higher rate of development (Uniyal *et al.* 2017). In comparison to control birds given 60 ppm zinc oxide, broiler chicks supplemented with nano zinc at doses of 20, 60, and 100 ppm acquired significantly greater weight (Zhao *et al.* 2014). Zinc nanoparticles (60 ppm) significantly improved the development and survival rates of freshwater prawn post larval (Muralisankar *et al.* 2014). In a similar vein, guinea pigs treated with 150 ppb of nano selenium for 70 days showed a much higher average daily increase than those given organic and inorganic selenium (Bunglavan *et al.* 2013). According to (Gonzales-Eguia *et al.* 2009), piglets' growth rate was considerably increased when they received 50 ppm of nano Cu supplementation. After adding 150–450 ppb of nano Cr to the rats' meal for eight weeks, it was discovered that the rats' growth rate and food efficiency were unchanged in contrast to the group under control (Zha *et al.* 2009).

Applications of nanoparticles as feed additives on animal and poultry performance and health

Metal/metal oxide nanoparticles of various types have already been studied as potential feed additives. The most frequently examined nanoparticles are copper, silver, and zinc, and among animal species, poultry are the most commonly used (Mohapatra *et al.* 2014 a, b; Abd El-Hack *et al.* 2017). To determine the effects of the studied nanoparticles on cell cultures (Leng *et al.* 2020) or animal models, including mice (Zhang *et al.* 2008; Kesmati *et al.* 2016), fish (Gutierrez *et al.* 2021), or rats (Tomaszewska *et al.* 2017; Mazaheri *et al.*

2019) a number of researchers conduct preliminary nano-toxicological studies. This is the initial stage of evaluating metal nanoparticles as potential additions for animal feed. It is possible to extend the results acquired for these species to other living things (Pilaquinga *et al.* 2021). A number of factors appear to be significant when employing nanoparticles in animal nutrition. Metal/metal oxide nanoparticles can be added to drinking water or feed directly as feed additives. Particles may be administered in ovo as a type of nano-nutrition to poultry to give the embryos additional nutrients (Pineda *et al.* 2012; Mroczek-Sosnowska *et al.* 2014, 2015b, 2017). In addition to increasing animal productivity and performance, such as the production of meat, milk, and eggs, the quality of the products derived from an animal can also be improved by adding metal/metal oxide nanoparticles to its diet (Mekonnen, 2021). Better nutrient absorption in the stomach may benefit animal target tissues, perhaps leading to more potent biological effects. (Bunglavan *et al.* 2014; Vijayakumar and Balakrishnan 2014; Youssef *et al.* 2019; Amlan and Lalhriatpuii 2020). Nanoparticles of minerals can penetrate body cells and go through the stomach wall more rapidly than regular inorganic salts, which have larger particle sizes (Bunglavan *et al.* 2014). Additionally, oxidative stress can be decreased and serum oxidant status can be improved by supplementing with nano-minerals.

Conclusion

People worldwide suffer from a number of microbial infections in addition to other deadly diseases that are caused either directly or indirectly by dangerous microbes. Although potential treatments and medications have been developed, it is thought to be challenging to completely solve the issue. Nanoparticles' charge, surface area, shape and size all affect their activities. They are even being utilized to combat several infectious disorders that may be directly linked to harmful microorganisms. It is clear from the current research that nanoparticles (NPs) are effective against a variety of microbial diseases. Since NPs are tiny and have a charged surface, they can readily enter pathogenic cells and interfere with cellular compo-

nents including DNA and proteins, which causes programmed cell death. Furthermore, combining antibiotic treatment with nanotherapy is currently seen to be a systematic way to combat germ resistance. Nanotechnological intervention enables the development of new therapeutic medication candidates to decrease the drug resistance profile, biofilm formation, and QS-regulated virulence profile. Thus, it is concluded that this brief overview strengthens the corpus of information now accessible on NPs and encourages further research to ascertain the potential use of NPs in the management of various microbial diseases. However, in order to supply the need for food, the rapid and unchecked growth of the human population necessitates increased agricultural productivity. There is tremendous pressure on the animal nutrition industry to boost output to meet the growing need for animal-based protein. The current review demonstrated the potential of metal-containing nanoparticles produced through chemical, physical, or biological processes as advantageous feed additives. The performance of livestock and poultry is improved when elements like zinc, copper, gold, silver, chromium, calcium or selenium are added to their diet in nano-form. As a substitute for antibiotic growth promoters, they are suggested. The improvement in intestinal health is a result of nanoparticles' inhibition of pathogens. Nanoparticles' small size is one of their key benefits; it allows for the administration of smaller doses in the animal's diet as an alternative to bulk inorganic salts. In addition, it is feasible to stop these metals from building up excessively in waste, which lessens the harm to the environment. According to current research, adding nanomineral supplements enhanced several animal groups' development, immunity, antioxidant status, and digestive efficiency, among other aspects of their performance.

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