Chapter 47

Application of Nanoparticles and Nanomaterials in Animal Health and Performance

Aneela Amin[1], Sadaf Faiz[1], Muhammad Asmat Ullah Saleem[2], Muhammad Usman[1], Muhammad Abdullah Arshad[1], Muhammad Asad Ali[1], Muhammad Bilal[1], Ali Haider[1] and Aisha Khatoon[1*]

[1]Department of Pathology, University of Agriculture, Faisalabad, Pakistan
[2]College of Veterinary Medicine Northeast Agricultural University, Harbin, China
*Corresponding author: aisha.khatoon@uaf.edu.pk

ABSTRACT

Nanotechnology is one of the fastest-growing industries in the world. It has a wide application in almost all fields from agriculture to food systems, thus crucial in overcoming future food scarcity in the world. This technology has all the characteristics, features, and potential to solve all the problems related to animal health and production. This chapter is mainly related to the production of different types of nanoparticles, their preparation methods, characterization, and potential use of nanoparticles in the veterinary field. In animal health, nanoparticles have a significant impact on diagnostics, therapeutic, vaccinology, and drug delivery as drugs delivered through this technology have maximum outputs in controlling the disease and improving the animal health and minimal toxicity. Nanoparticles also have a crucial role as a feed additive in animal production system as a very small amount of additive is used for maximum outputs. By reviewing all the miracles of nanotechnology in terms of cost and available resources in veterinary medicines, the main purpose of this chapter is to discuss briefly the uses of nanoparticles in the improvement of animal health and production and lastly, the main discussion will be on future potential and use of nanomaterials in the veterinary field.

KEYWORDS		
Nanoparticles, Diagnostics, Therapeutic, Immunization, Animal Health and Production	Received: 22-Jun-2024 Revised: 10-Jul-2024 Accepted: 21-Aug-2024	A Publication of Unique Scientific Publishers

Cite this Article as: Amin A, Faiz S, Saleem MAU, Usman M, Arshad MA, Ali MA, Bilal M, Haider A and Khatoon A, 2024. Application of nanoparticles and nanomaterials in animal health and performance. In: Ahmed R, Khan A, Abbas RZ, Farooqi SH and Asrar R (eds), Complementary and Alternative Medicine: Nanotechnology-II. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 413-420. https://doi.org/10.47278/book.CAM/2024.490

INTRODUCTION

Nanotechnology has become a part of our daily lives in recent years (Nasrollahzadeh et al., 2019). Therapeutic application of nanoparticles in veterinary field has played a significant role. This field of modern science focuses on the design, preparation of NPs, and alteration of particle structures ranging in size from 1-100 nm. Nanotechnology involves utilizing materials with at least one dimension at the nanometer scale to create products, tools, or structures with new or significantly improved properties (Kargoza et al., 2018). These nanomaterials have greater potential than traditional sources, allowing for reduced but effective quantities to be used. Nanoparticles have unique physiochemical properties including bioavailability, large surface area, controlled particle size, increased reactivity with pathogens, stability of the compound, controlled drug release property, and targeting to the specific site (Thakur and Thakur, 2022).

Nanomedicine is widely used in the livestock industry for diagnosis, monitoring, treatment, and prevention of disease. This field involves using nano-sized materials, such as biocompatible nanoparticles, within living organisms. The quantity and quality of dairy and poultry products are enhanced by using nanocomposites (Prasad et al., 2021).

Nanoparticles possess antimicrobial properties and can reduce antibiotic residues in livestock and poultry, making them potential candidates for combating antibiotic-resistant bacteria. For the early detection of livestock and poultry diseases nanoparticles prove to be a very cost-effective, unique, and rapid tool for accurate diagnosis of disease (Mekonnen, 2021). Nanomaterials has made a significant impact on veterinary medicine across various areas, integrating treatment, diagnostics, tissue engineering, vaccine production, and disinfectants. Nanoparticles have unique properties of targeting specific sites so, low dosage medicine is used that leads to a deceased withdrawal period of medicine (Ulucan-Karnak et al., 2023).

Nanoparticles (NPs) can effectively eliminate a variety of animal pathogens, including those responsible for persistent infections, intracellular pathogens, and blood parasites. Nanocomposites offers novel approaches to addressing significant challenges faced by veterinarians, such as tuberculosis, foot and mouth disease, brucellosis, and methicillin-resistant

Staphylococcus aureus (MRSA), as well as intracellular and blood pathogen infections (Osama et al., 2020). Consequently, researchers have been actively seeking new solutions, with metal NPs emerging as the most suitable agents. Ag NPs, Cu NPs, and AgCu-NPs on pathogen species were also assessed. There is also a great use of nanocomposites in the poultry sector. Copper, zinc, zinc oxide, selenium, chitosan, and chromium nanoparticles are being used at a larger scale in the poultry industry. These NPs used in diagnostic procedures, vaccine development, antimicrobials, disinfectants, immunomodulatory, and anti-mycotoxin agents (Hernández-Díaz et al., 2021). However, it is also worth emphasizing the term nanotoxicology because nanoparticles at high doses and administration for longer periods cause toxicity in animals. Considering the above information, this chapter intends to discuss the types, preparation methods, modes of action, and various applications of NPs as well as their safety and hazardous effects in the poultry and livestock industry.

Classification of Nanoparticles

Nanoparticles are classified into different types on the basis of their size, shape, application, surface modification, composition, and nature (Harish et al., 2023).

Based on Form

NPs have different types such as liposomes, fibers, dendrimers, nanotubes, carbon tubes, nanoclusters, and micelles based on form.

Based on Size

NPs have a size in the range between 1- 100nm. Particles of smaller size exhibit a large surface area.

Based on Shape

Different types of NPs based on shapes are there which include spheres, cubes, stars, tubes, plates wires, hooks, helices, plates, zigzags, and triangular.

Based on Application

Based on application nanoparticles have therapeutic and diagnostic properties. NPs also used in vaccine production and as feed additives in animals.

Based on Surface Modifications

Positive and negative charge nanoparticles are produced on the basis of surface modification.

Based on Composition

Nanomaterial may be synthesized only from one material (single material) and produced from at least two materials (composites or hybrid).

Based on Nature

NPs are organic, inorganic, and carbon NPs on the basis of nature. The details of these nanoparticles is described below.

(a) Organic NPs

Ferritin, liposomes, fibers, dendrimers, etc., are also known as organic NPs. Such NPs are nontoxic and biodegradable and certain particles like liposomes and the micelle have a hollow core known as nano-capsules and are prone to light and heat radiation, and one can efficiently use them for drug delivery. Along with their typical principles like size, structure, sugar morphology, etc. (Niknam et al., 2024) The organic NPs' field of application use depends on their drug-carrying power, stability, and delivery ways whether it is a trapped drug system or absorbed drug system. Organic NPs are used in the field of medicine since an efficient drug delivery system is safe to use, and also one can inject at a specific site (Ajith et al., 2023).

(b) Inorganic NPs

Metals and metal oxide are incorporated into inorganic type of nanomaterials and their significant characteristics are described below.

Metal-based

The nanoparticles based on metals are very commonly used and are prepared by different methods such as constructive and destructive. Common metals used in synthesizing nanoparticles include Ag, Au, Cu, Iron, Co, Al, and Hg (Shabatina et al., 2023). Almost all the metals may be transformed into nanoparticles. In addition to this coating of one type of nanoparticles to another may also be prepared and in this way, their efficacy may also be increased by several folds (Zang et al., 2023).

Metal Oxide based

In addition to the metal-based nanoparticles, their oxides can also equally be used for the preparation of nanoparticles (Carrapiço et al., 2023).

(c) Carbon-based Nanoparticles

In this type of nanoparticle, the main element from which the nanoparticles are prepared is carbon and this category can be classified as fullerenes, and carbon compounds like graphite, carbon tubes, carbon nanofibers, nanocarbon, and black carbon are of chief importance (Manimegalai et al., 2023).

Nanoparticles Synthesis

Particles that have a size of less than 100 nm in different dimensions are known as nanoparticles. Nanoparticles can be prepared in the lab by following different techniques like bottom-up techniques and top-down approaches in addition to nanoparticles in nature like in soil particles, ashes, and biomolecules (Nie et al., 2023).

Different factors are responsible for the synthesis of nanoparticles such as temperature, time, pressure, size and shape of particle, pore size of the material, and cost of the production of nanoparticles (Molaei et al., 2023)

Approaches for the Synthesis of Nanoparticles

Broadly two types of approaches are used in the synthesis of nanoparticles which are discussed as follows.

a) Top-down approach

The main purpose of these types of techniques is to decrease the size of larger size particles into smaller type particles and this can be achieved by a sequence of operations applied over them for the decrease in size (Table 1). This type of system uses large-scale machinery and a large amount of labor work. This type of system is very expensive and cannot be used on the industrial scale production of nanoparticles in a laboratory. The main principle of this type of method is to grinding of large-size materials (Abid et al., 2022).

b) Bottom-up Approach

The bottom-up technique can also be used for the preparation of nanoparticles in which the material size is reduced to the subatomic level with additional protocols to sensitize the NPs (Table 1). The basic principle of this method is uniting all the physical forces into a larger stable one and knowing the molecular recognition of materials used in the preparation of nanoparticles. These types of techniques are under-processed and innovative and have just started to be used at the commercial level for the production of nanoparticles (Jiang et al., 2022).

Table 1: Approaches for synthesis of nanoparticles

Methods in top-down approach	Methods in a bottom-up approach
• Physical vapor deposition.	• Sol-gel synthesis
• Ion implantation	• Colloidal precipitation
• Electron beam lithography	• Hydrothermal synthesis
• Chemical vapor deposition	• Organometallic chemical route
• X-ray lithography	• Electrodeposition

Methods of Synthesis of Nanoparticles

There are three kinds of approaches to produce nanoparticles (Table 2) (Joudeh and Linke, 2022).

1. Physical Methods
2. Chemical Methods
3. Biological Methods

Physical Methods

There are different methods used in the preparation of NPs, one of them is a physical method which uses evaporation and condensation by using a tube furnace at atmospheric pressure. The main purpose of this technique is to reduce particle size to the desired level and this can be achieved by employing radiation and speed in addition to certain chemicals. Limitations of this method are that a very small amount of product is achieved at the cost of high energy in addition to this contamination with different solvents used in this procedure may also be observed. Physical elements used in the reduction of particle size include mechanical pressure, high-energy waves, radiation, and thermal energy (Islam et al., 2022).

Chemical Methods

Chemical methods use different chemicals for the reduction of particle size. They mostly used the mixing of precursor and reducing agents while having the composition equal to the operating systems at which the reaction is carried out. The very small amount of surfactant is used for reciprocal aggregation.

The reducing reagents are mainly responsible for the sizing of the NPs i.e., stronger reagents produce the smaller size of particles and vice versa. Certain stabilizers such as acetates, amines, phosphines, thiols, and carbon monoxide generally monitor particle size preparation and reduce the clumping of these NPs. One of the common limitations of this type of chemical method is that this holds significant toxicity issues such as hazardous chemicals are the main players of this method (Pracht et al., 2020).

Biological Methods

Many chemicals like surfactants and reductants are toxic to humans and animals and proved to be dangerous for the environment. Efforts have been made to introduce a green synthesis process that is non-harmful and eco-friendly. Microbial synthesis of nanoparticles makes a connection between nanotechnology and microbial biotechnology. Biosynthesis of gold, silver, gold–silver nanocomposites, silica palladium, selenium, uraninite, platinum, tellurium, quantum dots, titanium, zirconia, and magnetite NPs by bacteria, viruses, yeast, fungi, and actinomycetes have been recorded. Utilizing naturally occurring non-toxic environmentally friendly reductants, microorganisms such as fungi, and algae, plant extracts containing plant active molecules, proteins, template supports like DNA (often referred to as "greener synthesis"), and other biological materials (such as ferritin) are used in biological methods for NP synthesis. A wide range of mineral NPs, including zinc, silver, palladium, selenium, gold, silver, cadmium, and titanium, have been created biologically utilizing various plant elements (Samrot et al., 2021).

Table 2: Methods for synthesis of nanoparticles

Physical method	Chemical method	Biological method
Mechanical Method	Sol-gel method	Synthesis using microorganisms
Pulse Laser Ablation	Sonochemical synthesis	Synthesis using plant extracts
Pulsed Wire Discharge Method	Co-precipitation method	Synthesis using algae
Chemical Vapor Deposition	The inert gas condensation method	
Laser Pyrolysis	Hydrothermal synthesis	
Ionized Cluster Beam Deposition		
(Dhand et al., 2015).		

Nanoparticle Characterization

Different techniques are used for the characterization of NPs**.** Size and shape affect the function and properties of nanoparticles (Zang et al., 2023).

- Particle size distribution
- Zeta potential
- Scanning electron microscopy
- Transmission electron microscope (TEM)
- X-ray diffraction (XRD)
- Infrared Spectroscopy (IR)
- Fourier Transform Infrared Spectroscopy (FTIR**)**

Modes of Actions of NPs

Size, charge, and solubility affect the mechanism of action of nanoparticles. For higher interaction with the pathogen's surface proper size and charge of NPs should be required.

- Nanoparticles have a high surface area that can increase their contact with pathogens.
- Due to their small size, they can easily penetrate through membranes of bacteria, viruses, and fungi.
- Nanoparticles trigger the production of excessive reactive oxygen species (ROS) which produces stress on the bacterial cells that leads to damage to DNA and RNA decreases membrane activity and produces peroxide (Pikula et al., 2020)

Applications of Nanoparticles in Veterinary Medicine

Nanotechnology presents veterinarians with similar opportunities as physicians, such as in therapy, diagnostics, tissue engineering, vaccine manufacturing, and the development of disinfectants. Nanotechnology is already being utilized in animal health, production, husbandry practices, reproduction, and nutrition of animals (Zhao et al., 2022). While nanoparticles have long been employed in human medicine for diagnosis and treatment, their use in veterinary medicine and animal processing is a recent development (Morena et al., 2022).

Nanoparticles used against different Infectious Diseases

Nanoparticles are used against various types of animal pathogens that cause chronic infections such as Hemiparasite, and intracellular pathogens. Nanomaterial helps veterinarians to deal with severe infectious diseases such as bovine TB, foot and mouth disease, brucellosis, and methicillin-resistant *Staphylococcus (S.) aureus*. Mastitis is a very serious issue in livestock production, pathogens that cause this disease have antibiotic resistance, therefore, researchers developed new solutions, to overcome these issues. In this regard, metal NPs gain attention (Morena et al., 2022). CuNPs, AgNPs, and composite of Cu and Ag nanoparticles against pathogens species (e.g., *S. aureus* and *E. coli*) that are involved in inflammation of the udder of mastitis cow (Yu et al., 2024). Nanoparticles of appropriate size and properties did not show any lethal effect on the mammary glands of the animals and decreased the viability of pathogens. Silver nanoparticles were used against multiple drug-resistant strains of *Pseudomonas* (P.) *aeruginosa* and *S. aureus* in goats infected with mastitis (Bruna et al., 2021).

Nanoparticles as an Alternative to Antibiotics

In the livestock industry, antibiotics are mainly used as growth promoters, but these antibiotics have greater microbial antibiotic resistance. Alternative to these antibiotics, nanoparticles are being used as antimicrobials to fulfill the demand of the livestock industry (Singh et al., 2020). Nanoteparticles plays a very important role in the veterinary field. Nanocomposites helped to establish antimicrobial agents that are non-toxic and decreased antibiotic resistance against various pathogens that cause chronic animal diseases, like *Brucella*, *Mycobacterium bovis, Streptococcus,* and *Rhodococcus equi* (Mubeen et al., 2021).

Nanoparticles used in Vaccine Preparation

Nanoparticles are widely used in vaccine production for veterinary use. Nanoparticles have immune-modulatory property that enhances the immune response. Nanoparticles increase peptide cross-linkage and activate antigen-presenting cells resulting in targeting the lymph nodes. NPs also act as adjuvant to make the slow release of antigens that enhance vaccine efficacy (Kheirollahpour et al., 2020). The IBV vaccine coated with chitosan nanoparticles was used alone or in combination with the live attenuated vaccine by ocular and nasal route in broiler birds causing both humoral and cell-mediated immune response and protecting the chicks against IBV (Renu et al., 2020). Nano-based vaccines such as recombinant B. anthracis, bovine para influenza type III vaccine, influenza vaccines, *Bordetella pertussis* vaccine, tetanus toxoid, and C. Recombinant Leishmania SOD vaccine loaded with chitosan nanoparticles are being used in veterinary practice. Gold nanoparticles-based vaccines are also being used against FMD (Maina et al., 2020)

Nanoparticles in Animal Nutrition

In animal nutrition, nanoparticles play a very important role in processing nanominerals that are being used in veterinary practices. These nanowires decrease intestinal mineral antagonism, excretion, and environmental decontamination. Feeding of nanoparticles increases the intentional digestive capability, and immune status of animals (Prasad et al., 2022). Scientists managed to process food, meat, and milk that contains high levels of minerals contents to enhance the flavor, taste, appearance, and long-term storage of food. Nanoparticles are used as a feed additive in micro and macro-nanoparticle forms to increase their digestibility in animals. Contaminated-free meat and meat products are synthesized by use of nanomaterial. Micro and macro nanoparticles are inexpensive, used in low amounts, and act as growth-promoting and immune stimulators. These nanomaterials also manipulate pathogens present in the feed and the fermentation process in the rumen is improved by nanoparticles (Osama et al., 2020). ZnO NPs are one of the most used nano minerals to enhance the growth and immune response of the animals. Nano zinc is also used in cows suffering from mastitis and leads to decreased somatic cell counts. Mycotoxicosis is a very serious issue in both humans and animals (Reda et al., 2021). SiO2 and MgO nanoparticles are the best nanoantimycotoxin against toxins and inactivate them. Chitosan nanoparticles also get attention in this regard to use against aflatoxin (Jogee et al., 2020).

Nanoparticle in Animal Reproduction

In animal reproduction, nanomaterials are used as cryo-preservatives for embryos, sperm, oocytes, and gonadal tissues. To facilitate fertilization from a single dose to conceive more than one female, nanoparticles are used to potentiate fertilization efficiency. By using nano-purification of the semen, damaged sperm can be differentiated from healthy, undamaged sperm (Ajdary et al., 2021). A nano-purified bull's spermatozoa showed conception levels equal to un-purified semen without any negative effects. Several applications of nanocomposites have been developed for diagnosing and treating reproductive problems, detecting estrus, freezing sperm, and interfering with the calving process. Further, many issues related to the reproductive health of the animals such as retained placenta can be cured by the use of nanoparticles. Additionally, nanoparticles have a great effect on protecting and managing the release of reproduction hormones like steroid and gonadotropic hormones. Nano-sensors are also used in reproduction with a cell probe. These probes are used for the diagnosis of reproductive disorders, illness, metabolic and hormonal issues, and the detection of heat in animals. Metallic nanoparticles like cadmium lead to toxicity in animals so sterilized nanoparticles can be used in appropriate doses (Fard et al., 2023).

Application of Nanoparticles in Drug Delivery Systems

In the field of pharmacology, nanoparticles are used ideal in drug delivery that protect animals from bacterial, viral, and parasitic infection but are also helpful in wound healing and decrease pain. NPs deliver drugs to specific sites of tissue and organs. These frameworks may affect the rate at which drugs or other substances are absorbed, digested, and released from the body. They may also allow for the monitoring of drug dynamics, the acquisition of a therapeutic effect, the assurance of bioavailability and stability, the extension of the duration of movement, the reduction of the frequency of doses necessary to maintain therapeutic responses, and the mitigation of toxicity (Onugwu et al., 2023).

Nanoparticles and Pet Care

Nanoparticles are also used in pet care. These are used as surface refreshing and disinfects due to their unique physiochemical properties. Different nanoparticles like silver nanoparticles added in the shampoo for tropical use in the pet (Yavuz et al., 2023).

Applications of NPs in the Poultry Industry

Nanoparticles also gained attention in the field of poultry. Copper, zinc, zinc oxide, chitosan and chromium and selenium nanoparticles are being used at a larger scale. These NPs used in diagnostic procedures, and vaccine development as immunomodulatory agents, antimicrobials, disinfectants, and anti-mycotoxin agents (Younas et al., 2023). The administration of chitosan nanoparticle-based vaccine against salmonellosis in birds enhanced the level of T helper cell 1 and 2 cytokines, mRNA expression and increases the levels of antibodies (IgYand IgA) (Renu et al., 2020). DNA-based vaccine encapsulated with $AgSiO_2$ used against ND in chickens that results in protective mucosal immunity. Vaccines prepared aluminum NPs have been shown to produce high and long-lasting antibody titers after a single immunization. AgNPs are used to reduce microbial load, proper disinfection of eggs and hatcheries, and protection for longer periods as antibacterial and antiviral during the incubation of eggs (Salesa et al., 2023). NPs are used as feed additives in poultry and administration of NPs in poultry is via oral, inhalation, injection, and topical. Feed additives contain minerals (micro and macro) in nano forms (nano zinc, nano copper, nano selenium) that act as growth promoters in poultry. NPs specially the metallic act as antibacterial against different diseases in poultry like Aeromonas, Flavobacterium, Escherichia, Klebsiella spp Bacillus, *Staphylococcus aureus*, *Pseudomonas aeruginosa,* and *Salmonella Enteritidis*. Gold nanoparticles and green synthesized Ag exhibit antiviral properties and may be used as a delivery system for immunomodulatory drugs. ZnO NPs have the potential to be used as antiviral agent against different antiviral infections in poultry like H1N1 influenza virus infection Gold NPs used as anti-parasitic agent in different parasitic diseases (Fatima et al., 2024). Ag NPs and chitosan showed measurable harm, growth retardation, and cytotoxic effects against a variety of parasites, including plasmodium, Giardia, helminths, Toxoplasma and Leishmania. Different NPs used as antifungal agent against different various strains of Aspergillus and Candida spp. Chitosan NPs have the great adsorption capability against different mycotoxin such as AF, OTA, DON and FUM when compared with antifungal drugs like nystatin (Pawariya et al., 2023).

Nanoparticle Related Safety and Hazardous Concern

In animals and poultry, safe delivery of nanoparticles depends upon intercellular, biological interaction and function of the nanoparticles. Previous studies revealed that NPs are eco-friendly, and non-toxic but recent studies showed that NPs have adverse effects on animals. Concentration, size, and charge affect the toxicity of NPs. Accumulation of NPs in organs like the liver and kidney and effects on the immune systems are seen due to prolonged exposure to nanoparticles. Nanoparticles are water soluble, so their aggregation is harmful to some beneficial bacteria therefore their concentration should be monitored before being in to feed of animals (Chen et al., 2023).

Conclusion

Nanotechnology is one of the fastest-growing industries in the world and has a wide application in almost all fields from agriculture to food systems. By the use of nanomaterial in food and feed the production performance of livestock and poultry can be enhanced. One of the fine aspects of nanotechnology is the use of nanomaterials in vaccine development against new emerging diseases. It is a need of time to use nanoparticles for the well-being of humanity in terms of modernization of diagnostics, development of new tools for early disease detection, and increase production both in agriculture and animal so we can overcome future problems ailing humanity.

REFERENCES

Abid, N., Khan, A. M., Shujait, S., Chaudhary, K., Ikram, M., Imran, M., and Maqbool, M. (2022). Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. *Advances in Colloid and Interface Science*, *300,* 102597.

Ajdary, M., Keyhanfar, F., Moosavi, M. A., Shabani, R., Mehdizadeh, M., and Varma, R. S. (2021). Potential toxicity of nanoparticles on the reproductive system animal models: A review. *Journal of Reproductive Immunology*, *148*, 103384.

Ajith, S., Almomani, F., Elhissi, A., and Husseini, G. (2023). Nanoparticle-based materials in anticancer drug delivery: Current and future prospects. *Heliyon*.

Bruna, T., Maldonado-Bravo, F., Jara, P., and Caro, N. (2021). Silver nanoparticles and their antibacterial applications. *International Journal of Molecular Sciences*, *22*(13), 7202.

Chen, J., Guo, Y., Zhang, X., Liu, J., Gong, P., Su, Z., and Li, G. (2023). Emerging nanoparticles in food: sources, application, and safety. *Journal of Agricultural and Food Chemistry*, *71*(8), 3564-3582.

Carrapiço, A., Martins, M. R., Caldeira, A. T., Mirão, J., and Dias, L. (2023). Biosynthesis of metal and metal oxide nanoparticles using microbial cultures: Mechanisms, antimicrobial activity and applications to cultural heritage. *Microorganisms*, *11*(2), 378.

Dhand, C., Dwivedi, N., Loh, X. J., Ying, A. N. J., Verma, N. K., Beuerman, R. W., and Ramakrishna, S. (2015). Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview. *Rsc Advances*, *5*(127), 105003-105037.

Fard, N. J. H., Mohammadi, M. J., and Jahedi, F. (2023). Effects of nano and microplastics on the reproduction system: In vitro and in vivo studies review. *Food and Chemical Toxicology*, 113938.

Fatima, A., Zaheer, T., Pal, K., Abbas, R. Z., Akhtar, T., Ali, S., and Mahmood, M. S. (2024). Zinc oxide nanoparticles significant role in poultry and novel toxicological mechanisms. *Biological Trace Element Research*, *202*(1), 268-290.

Harish, V., Ansari, M. M., Tewari, D., Yadav, A. B., Sharma, N., Bawarig, S., and Barhoum, A. (2023). Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *Journal of the Taiwan Institute of Chemical Engineers*, *149*, 105010.

Hernández-Díaz, J. A., Garza-García, J. J., Zamudio-Ojeda, A., León-Morales, J. M., López-Velázquez, J. C., and García-Morales, S. (2021). Plant-mediated synthesis of nanoparticles and their antimicrobial activity against phytopathogens. *Journal of the Science of Food and Agriculture*, *101*(4), 1270-1287.

Islam, F., Shohag, S., Uddin, M. J., Islam, M. R., Nafady, M. H., Akter, A., and Cavalu, S. (2022). Exploring the journey of zinc oxide nanoparticles (ZnO-NPs) toward biomedical applications. *Materials*, *15*(6), 2160.

Jiang, Z., Li, L., Huang, H., He, W., and Ming, W. (2022). Progress in laser ablation and biological synthesis processes:"Top-Down" and "Bottom-Up" approaches for the green synthesis of Au/Ag nanoparticles. *International Journal of Molecular Sciences*, *23*(23), 14658.

Jogee, P., and Rai, M. (2020). Application of nanoparticles in inhibition of mycotoxin-producing fungi. *Nanomycotoxicology*, 18 (1), 239-250.

Joudeh, N., and Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *Journal of Nanobiotechnology*, *20*(1), 262.

Kargozar, S., and Mozafari, M. (2018). Nanotechnology and Nanomedicine: Start small, think big. *Materials Today: Proceedings*, *5*(7), 15492-15500.

Kheirollahpour, M., Mehrabi, M., Dounighi, N. M., Mohammadi, M., and Masoudi, A. (2020). Nanoparticles and vaccine development. *Pharmaceutical Nanotechnology*, *8*(1), 6-21.

Maina, T. W., Grego, E. A., Boggiatto, P. M., Sacco, R. E., Narasimhan, B., and McGill, J. L. (2020). Applications of nanovaccines for disease prevention in cattle. *Frontiers in Bioengineering and Biotechnology*, *8*, 608050.

Mekonnen, G. (2021). Review of the application of nanotechnology in animal health and production. *Journal Nanomedicine Nanotechnology*, *12*, 559.

Molaei, S., Hamidpour, M., Shirani, H., and Sabet, M. (2023). Investigation of factors affecting removal of arsenic from polluted water using iron-based particles: Taguchi optimization design. *Revista Internacional de Contaminación Ambiental*, *39*.

Manimegalai, P., Selvam, K., Loganathan, S., Kirubakaran, D., Shivakumar, M. S., Govindasamy, M., and Bahajjaj, A. A. A. (2023). Green synthesis of zinc oxide (ZnO) nanoparticles using aqueous leaf extract of Hardwickia binata: their characterizations and biological applications. *Biomass Conversion and Biorefinery*, 1-16.

Morena, A. G., Bassegoda, A., Natan, M., Jacobi, G., Banin, E., and Tzanov, T. (2022). Antibacterial properties and mechanisms of action of sonoenzymatically synthesized lignin-based nanoparticles. *ACS Applied Materials and Interfaces*, *14*(33), 37270-37279.

Mubeen, B., Ansar, A. N., Rasool, R., Ullah, I., Imam, S. S., Alshehri, S., and Kazmi, I. (2021). Nanotechnology as a novel approach in combating microbes providing an alternative to antibiotics. *Antibiotics*, *10*(12), 1473.

Nasrollahzadeh, M., Sajadi, S. M., Sajjadi, M., and Issaabadi, Z. (2019). Applications of nanotechnology in daily life. *Interface Science and Technology*, *28*, 113-143.

Nie, P., Zhao, Y., and Xu, H. (2023). Synthesis, applications, toxicity and toxicity mechanisms of silver nanoparticles: A review. *Ecotoxicology and Environmental Safety*, *253*, 114636.

Niknam, Z., Zadeh, F. H., Toosi, S., Shoreh, N. K. H., Rasmi, Y., and Saleem, I. (2024). Organic-based nanomaterials for regenerative medicine. In *Handbook of Nanomaterials, Volume 2* (pp. 359-400). Elsevier.

Onugwu, A. L., Nwagwu, C. S., Onugwu, O. S., Echezona, A. C., Agbo, C. P., Ihim, S. A., and Khutoryanskiy, V. V. (2023). Nanotechnology based drug delivery systems for the treatment of anterior segment eye diseases. *Journal of Controlled Release*, *354*, 465-488.

Osama, E., El-Sheikh, S. M., Khairy, M. H., and Galal, A. A. (2020). Nanoparticles and their potential applications in veterinary medicine. *Journal of Advanced Veterinary Research*, *10*(4), 268-273.

Pawariya, V., De, S., and Dutta, J. (2023). Chitosan-based Schiff bases: Promising materials for biomedical and industrial applications. *Carbohydrate Polymers*, 121395.

Pikula, K., Mintcheva, N., Kulinich, S. A., Zakharenko, A., Markina, Z., Chaika, V., and Golokhvast, K. (2020). Aquatic toxicity and mode of action of CdS and ZnS nanoparticles in four microalgae species. *Environmental Research*, *186*, 109513.

Pracht, P., Bohle, F., and Grimme, S. (2020). Automated exploration of the low-energy chemical space with fast quantum chemical methods. *Physical Chemistry Chemical Physics*, *22*(14), 7169-7192.

Prasad, R. D., Charmode, N., Shrivastav, O. P., Prasad, S. R., Moghe, A., Sarvalkar, P. D., and Prasad, N. R. (2021). A review on concept of nanotechnology in veterinary medicine. *ES Food and Agroforestry*, *4*, 28-60.

Prasad, R. D., Sahoo, A. K., Shrivastav, O. P., Charmode, N., Kamat, R., Kajave, N. G., and Prasad, N. R. (2022). A review on aspects of nanotechnology in food science and animal nutrition. *ES Food and Agroforestry*, *8*, 12-46.

Reda, F. M., El-Saadony, M. T., El-Rayes, T. K., Attia, A. I., El-Sayed, S. A., Ahmed, S. Y., and Alagawany, M. (2021). Use of biological nano zinc as a feed additive in quail nutrition: biosynthesis, antimicrobial activity and its effect on growth, feed utilisation, blood metabolites and intestinal microbiota. *Italian Journal of Animal Science*, *20*(1), 324-335.

Renu, S., and Renukaradhya, G. J. (2020). Chitosan nanoparticle based mucosal vaccines delivered against infectious diseases of poultry and pigs. *Frontiers in Bioengineering and Biotechnology*, *8*, 558349.

Salesa, B., Ferrús-Manzano, P., Tuñón-Molina, A., Cano-Vicent, A., Assis, M., Andrés, J., and Serrano-Aroca, Á. (2023). Study of biological properties of gold nanoparticles: Low toxicity, no proliferative activity, no ability to induce cell gene expression and no antiviral activity. *Chemico-Biological Interactions*, *382*, 110646.

Samrot, A. V., Sahithya, C. S., Selvarani, J., Purayil, S. K., and Ponnaiah, P. (2021). A review on synthesis, characterization and potential biological applications of superparamagnetic iron oxide nanoparticles. *Current Research in Green and Sustainable Chemistry*, *4*, 100042.

Shabatina, T. I., Vernaya, O. I., Shimanovskiy, N. L., and Melnikov, M. Y. (2023). Metal and metal oxides nanoparticles and nanosystems in anticancer and antiviral theragnostic agents. *Pharmaceutics*, *15*(4), 1181.

Singh, A., Gautam, P. K., Verma, A., Singh, V., Shivapriya, P. M., Shivalkar, S., and Samanta, S. K. (2020). Green synthesis of metallic nanoparticles as effective alternatives to treat antibiotics resistant bacterial infections: A review. *Biotechnology Reports*, *25*, e00427.

Thakur, P., and Thakur, A. (2022). Introduction to nanotechnology. *Synthesis and Applications of Nanoparticles*, 1-17.

Ulucan-Karnak, F., Kuru, C. İ., Türkcan, C., and Kulabhusan, P. K. (2023). Potential application of nanobiotechnology for creating various diagnostic approaches for diseases in livestock. In *Nanobiotechnology for the Livestock Industry* (pp. 157-174). Elsevier.

Yavuz, G., Yilmaz, E., Halvaci, E., Catal, C., İrem, T. Ü. R. K., Maran, F. N., ... and Fatih, Ş. E. N. (2023). Nanotechnology In Medical Applications: Recent Developments In Devices And Materials. *Journal of Scientific Reports-C*, (005), 1-32.

Younas, Z., Mashwani, Z. U. R., Ahmad, I., Khan, M., Zaman, S., Sawati, L., and Sohail. (2023). Mechanistic approaches to the application of nano-zinc in the poultry and biomedical industries: A comprehensive review of future perspectives and challenges. *Molecules*, *28*(3), 1064.

Yu, R., Chen, H., He, J., Zhang, Z., Zhou, J., Zheng, Q., and Zhang, X. (2024). Engineering antimicrobial metal–phenolic network nanoparticles with high biocompatibility for wound healing. *Advanced Materials*, *36*(6), 2307680.

Zhao, R., Xiang, J., Wang, B., Chen, L., and Tan, S. (2022). Recent advances in the development of noble metal NPs for cancer therapy. *Bioinorganic Chemistry and Applications*, *2022*.

Zang, Y., Zhang, Y., Wei, R., Xue, H., and Jiang, J. (2023). Difunctional molecularly imprinted polymers and heterostructured CdS nanoparticle-sensitized ZnO nanorod arrays for antibody-free photoelectrochemical alpha-fetoprotein sensor. *Journal of Electroanalytical Chemistry*, *944*, 117631