

Review

Applications and impacts of nanotechnology in poultry nutrition

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Abstract

The rapid expansion of the world population, intensifying environmental concerns and increasing demand for healthy food have created significant challenges for humanity that require multifaceted solutions in various areas. The poultry sector is one of the fastest-growing industries worldwide, playing an important role in ensuring food security and meeting nutritional and economic needs. Advances in poultry nutrition with the help of emerging nanotechnology can offer promising avenues to address the aforementioned challenges. This review report reviews nanotechnology and reports on strategies to optimize the use of nutrients, micronutrients, bioactive compounds, and minerals in poultry production with the help of this technology. Nanoscale material manipulation provides an opportunity for researchers to exploit the unique properties and functions of nanoscale materials to stimulate immunity, improve production efficiency, and promote overall flock health. Therefore, the increasing application of nanotechnology is considered a vital opportunity for sustainable growth in the poultry industry, food security, and environmental protection. If we recognize and are aware of the proper use of this technology and eliminate implementation barriers, risks, and potential concerns, we can make good use of it in the future successful vision of the poultry industry and achieve the ideal goals of the poultry industry.

Keywords Flock health · Food security · Healthy food · Modulation immunity · Nanotechnology · Poultry

Abbreviations

UN	United Nations
FAO	Food and Agriculture Organization
NNI	National nanotechnology initiative
RES	Reticuloendothelial system
NPs	Polymer nanoparticles

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NLC	Nanostructured lipid carriers
BN	Biofunctionalized nanoparticles
BSA	Bovine serum albumin
ZnONPs	Zinc oxide nanoparticles
FCR	Feed conversion ratio
LDL	Low-density lipoprotein
HDL	High-density lipoprotein
GTF	Glucose tolerance factor
RNA	Ribonucleic acid
CrPic	Chromium picolinate nanoparticles
DCP	Dicalcium phosphate
NDCP	Nano dicalcium phosphate
EUSCA	European Union Scientific Committees and Agencies
WHO	World Health Organization
JMPR	Joint FAO/WHO meeting on pesticide residues
USFDA	United States Food and Drug Administration
ISO	International Standard Organization
OECD	Organization for Economic Co-operation and Development
IFST	Institute of Food Science and Technology
REACH	Registration, evaluation, authorization and restriction of chemicals
EC	European Commission
EU	European Union
EFSA	European Food Safety Authority
FDA	Food and Drug Administration

1 Introduction

Humanity faces imminent challenges across various domains, including social crises (such as a growing population and escalating demand for food), food crises (characterized by feedstuff shortages, hunger, and malnutrition), and environmental crises (encompassing global warming and climate change). Observations and evaluations highlight that these crises pose significant risks to global food security [1, 2]. Furthermore, according to United Nations (UN) estimates, approximately one-tenth of the global population currently suffers from hunger, and food production must increase by 50% by 2050 to meet the projected food demand [3].

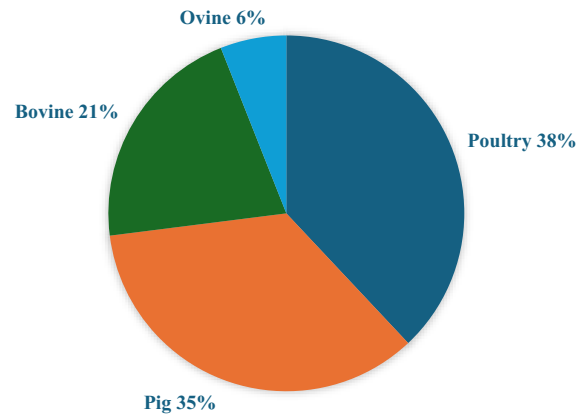
Considering the role of the poultry industry in providing protein needs and the effects of this industry in the food and agriculture cycle, the use of new, practical, and quick-yielding methods to improve the quality and quantity of the products of the poultry industry can be welcomed by the pioneers and experts of the poultry industry in the future [1–3]. The use of additives in poultry nutrition is not mandatory, but given that it preserves the diet formulation and simultaneously helps improve the bioavailability, performance, and health of the animal, it is always considered a popular and low-risk solution [4]. In addition, providing any solution to improve the performance and health of birds with traditional and modern methods in the form of manipulation of the formulation, feed processing, and the use of food additives containing vitamins and minerals and bioactive compounds by experts could be welcomed by the poultry industry [1, 5, 6].

In 2022, the FAO reported the world's meat production to be 360 million tons, and the share of poultry meat was nearly 38%, which showed an increase of about 10% compared to the year 2000 (Fig. 1) [7]. The first position of the share of poultry meat in production indicates the role of this industry in food security, and any scientific and practical measures to improve the quality and quantity of poultry products can increase the share of this industry in production and food security and improve the food security and make life safe, healthy and secure.

According to the NNI in America, the understanding and control of matter at the nanoscale, in the dimensions of 1–100 nm, is where unique phenomena are provided for new applications [4]. In the field of feed additives in poultry nutrition, studies show that nanotechnology can provide opportunities to improve the performance of additive molecules for the benefit of the productivity of poultry products [3]. Nanotechnology, as a prominent solution, has always been considered in solving the above-mentioned challenges. While it raises concerns about potential adverse effects in the

Fig. 1 Global share of poultry meat in the world. [7] in 2022, an increase of poultry production around 10% from 2000

GLOBAL SHARE OF MEAT PRODUCTION (%) IN 2022



future, it is recognized as the sixth revolutionary technology of the modern era, offering significant potential to meet human needs in the years to come [3].

The use of emerging nanotechnology with great potential in the field of food and medicine for humans and domestic animals is also considered one of the promising solutions for the poultry industry in the future [7]. In many fields of science and technology, the growth and application of nanotechnology has been able to provide smart solutions to solve all kinds of problems and challenges, and in the poultry industry, especially in the field of nutritional and non-nutritive additives taking advantage of the potential of nanotechnology is of interest to researchers, pioneers and experts [8].

In human nutrition, the direct use of nanotechnology for the purpose of quantitative and qualitative manipulations of edible ingredients is not acceptable to consumers, and human preferences and tendencies are more towards the use of natural products without special manipulations. Therefore, for livestock feeding, the unique opportunity will be provided for the use of nanotechnology to improve the quality and quantity of animal products, so that while meeting the needs, it does not create any competition, complications, and contradictions in the field of food and human nutrition [8]. Nanobiotechnology can provide techniques and tools to change the future of feed technology and affect the quality and quantity of feed production [9]. Despite the scientific progress in the modern era regarding this technology, its potential negative impacts cannot be overlooked. For instance, concerns have been raised about the high surface-to-volume ratio of nanoparticles, their ability to penetrate the nucleus and damage DNA, and their resemblance to cellular organelles in size, shape, affinity, and cellular interactions, all of which pose potential biological risks [3]. Moreover, no emerging technology should be introduced to society without thorough evaluation. Therefore, the recognition of potential benefits and associated risk factors must always be weighed fairly, considering all environmental, health, social, ethical, and economic aspects, so that the benefits of this technology outweigh its disadvantages [3].

In general, nanotechnology has the potential to maximize the nutritional effects of nutrients and to meet the physiological and metabolic needs of birds [10, 11]. In addition, a review of the scientific literature shows that other applications of nanoparticles in the poultry industry include the removal of pathogen residues, reduction of environmental pollutants, performance improvement, immune modulation, reduction of antibiotic consumption, and accurate and rapid diagnosis of poultry diseases and their effective and rapid treatment [12, 13]. In fact, nanotechnology can improve the performance of feed molecules by manipulating matter at the atomic and molecular levels, possibly the entire nutritional content of foods to optimize poultry health and performance and have positive effects such as improving the ability to digest and absorb nutrients, promoting growth and development [13–15].

According to studies, several regulatory agencies such as the scientific committees and agencies of the European Union, including EUSCA, FAO, WHO, JMPR, USFDA, ISO, OECD play an active and prominent role worldwide in providing guidelines and establishing policies and regulatory frameworks for the safe use of nanoproducts [3]. The IFST in the UK also controls the supply of nanoproducts, considering the size of particles and numerous tests. In the EU, the main regulatory authority REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) in the agri-food sector is sensitive and precise on nanoproducts and, based on the regulations of the EC, addresses safety standards and risk management issues related to agricultural nanotechnology [3]. Therefore, the control of the supply of nano products in the most important institutions and sectors worldwide indicates the sensitivity and importance of this technology in human life.

1.1 Scientific review and search approach

The search process in this review report was conducted by accessing electronic database resources, including the Directory of Open Access Journals (DOAJ), Google Scholar, Research Gate, Science Direct, and Scopus. The search keywords were: nanotechnology, poultry nutrition, immune system, immune system modulation, nano-feed additives and bioavailability.

1.2 Applications of nanotechnology in feed additives in poultry nutrition

Examining the progress of technology shows that the upcoming era can be introduced as the era of nanotechnology. The application of this technology in the fields of medicine, pharmacy, engineering, environment, and agriculture is of great importance [16, 17]. In today's modern research, this technology is of interest to experts and decision-makers with a forward-looking, strategic, and innovative attitude [18].

Furthermore, a review of scientific literature shows that absorption of nanoparticles in the gut occurs with passive diffusion in mucosal cells through active and intercellular transport mechanisms [11]. Nanoparticles and compounds attached to them pass more easily through capillary walls. Due to the existence of these biodegradable compounds in nanoparticles, there is no risk of environmental pollution or chemical accumulation, and subsequently, the biological interaction and durability of the compounds can be increased for effective absorption and delivery [13, 19]. In general, nanoparticles diffuse more easily than macro solid particles and behave like gas molecules in air or like large molecules in solutions. Compared to larger particles, nanoparticles are less exposed to precipitation and have a better effect on the target tissue. On the other hand, the smaller the diameter of nanoparticles, the faster they reach the blood through the lining cells in the digestive system [10, 11]. In addition, nanoparticles can increase surface area and prolong intestinal residence and persistence, subsequently increasing active intestinal cleansing mechanisms and tissue penetration [5]. After absorption in the gastrointestinal tract, nanoparticles can be transported to the target tissue and cells through the lymphatic system to the liver and spleen [11, 20].

However, population growth will lead to an increase in the demand for poultry products, and in parallel, the growth of this industry is inevitable. Therefore, as the industry grows, the growth of research to improve the condition of growth rate, feed efficiency, and health is a recurring strategy in this industry. Manipulation in the feed formulation along with the auxiliary use of food additives to achieve the ideal goals of the poultry industry is considered one of the reassuring solutions and in this regard, the emergence of the phenomenon of nanotechnology can be used for the industry is considered an exceptional opportunity [1, 5, 6]. Due to the high surface-to-volume ratio and high absorption in the body, nanoparticles play an effective role in the direct transfer of compounds to organs or vital systems of the body, and unlike antibiotic additives, they do not have rapid decomposition and microbial resistance [1, 5]. Despite the reports of various applications of nanotechnology and materials in various fields of modern sciences, the scientific literature on the potential effects of nanoparticles in poultry nutrition is not enough considering the extent and potential of the poultry industry, and scientific evidence and findings in the adoption of nanotechnology with concerns and challenges that make the necessity of detailed studies and research even more necessary. Therefore, it is necessary to provide a review of the available research results and the possible mechanisms on the performance and health of the herd, to prepare the ground for more efficient research and risk-free use of these food resources in the future [6, 21].

Research findings show that for a series of special minerals such as zinc, selenium, copper, manganese, silver, and iron, the use of nanotechnology in nutrition is more useful and reliable, and worries are less [1, 21]. However, it has been determined that nanotechnology can make a significant contribution in the field of nutrition, focusing on items such as production, processing, storage, transportation, traceability, security, and food safety [7]. Research shows that in the case of intravenous injection of nanoparticle compounds into the circulatory system, bioavailability of up to 100% can be experienced for a series of compounds that have high macro excretion. For example, minerals in the nano state quickly reach tissues such as liver, spleen, and other target tissues by blood circulation and highly perfused RES [20]. However, with nanotechnology, it is possible to provide food needs in smaller amounts, and following this incident, it will help to reduce the discharge of pollutants and help the environment as well and in parallel, for the poultry industry, it ensured the improvement of production performance, flock health and food safety [21].

Fig. 2 Classification of feed additives for poultry nutrition, based on nanotechnology

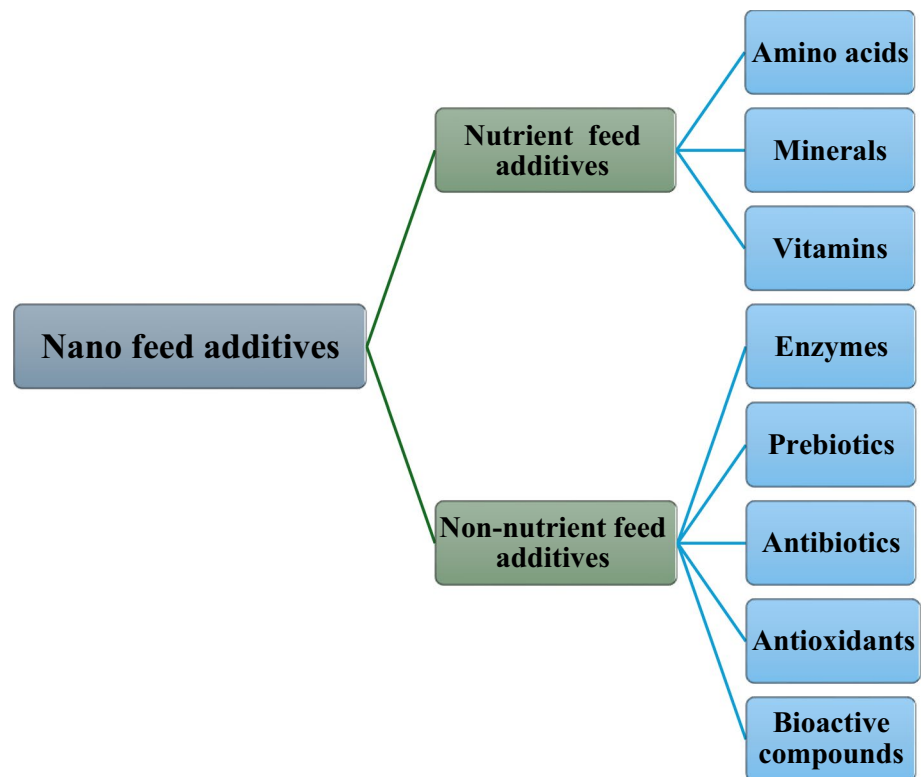
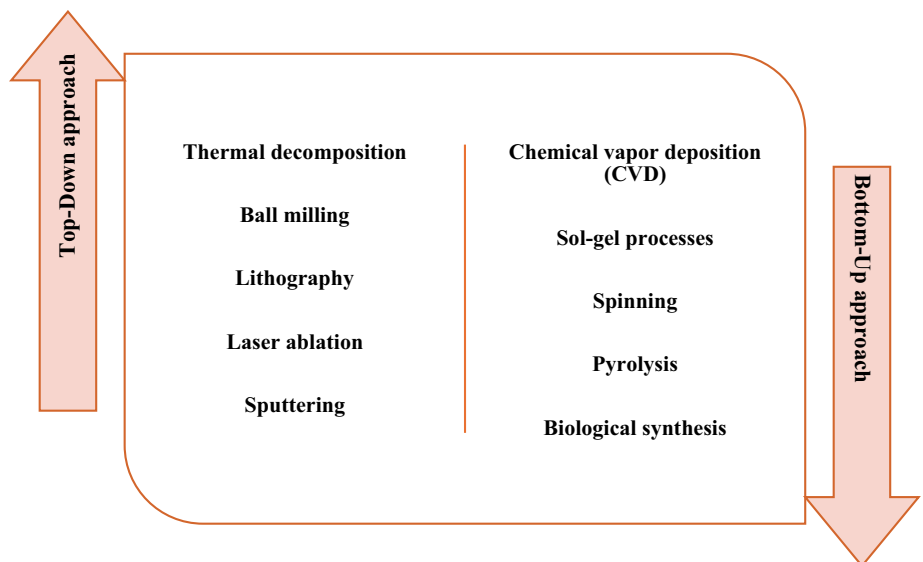


Fig. 3 Strategies to synthesize nanoparticles as feed additives for poultry nutrition



2 Nano feed additives in poultry nutrition

Feed additives used in poultry feeding can be divided into nutrient additives and non-nutrient additives, which are shown in each set of well-known and popular compounds (Fig. 2) [14, 22].

In general, to synthesize nanoparticles as feed additives in poultry nutrition, two main strategies and approaches are used, including “top-down approach” and “bottom-up approach” (Fig. 3). The selection of each method and technique depends on the synthesis conditions, facilities and hardware equipment, and control mechanisms that can be used in different fields [23]. In the first case and the top-down approach (left-blue diagram), raw materials

Fig. 4 Nanoparticle synthesis approaches: physical, chemical, and biological methods

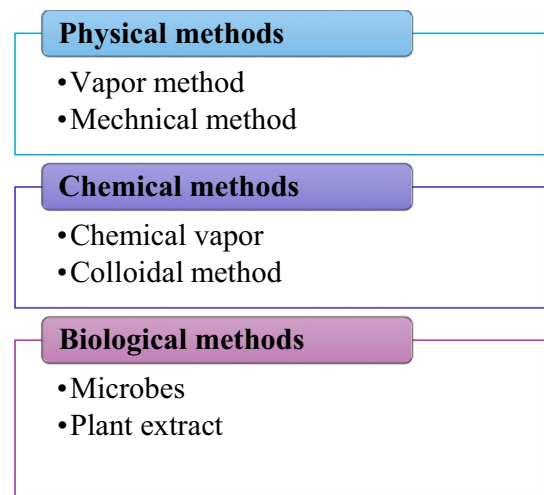
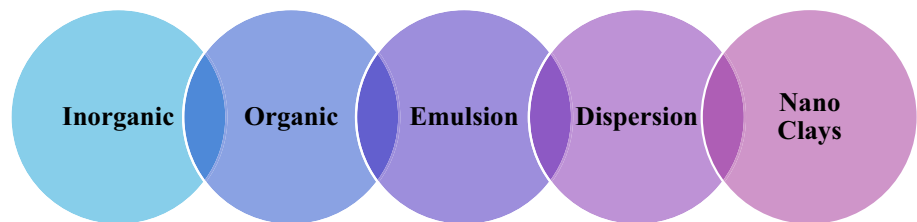


Fig. 5 Classification of nanoparticles based on their chemical properties



are converted into larger structures and then synthesized into nanoparticles. In the second case and the bottom-up approach (left-orange diagram), first, nanoparticles are made at the molecular or atomic level and then they are assembled together [14]. In addition, recently, methods such as reactive precipitation, microemulsion, Sono chemical and supercritical chemical processes have also attracted the attention of experts in the synthesis of nanoparticles [14, 24].

Nanoparticles are applied across various fields of food and medicine, utilizing three main synthesis approaches: physical methods (e.g., high-energy ball milling and steam deposition), chemical methods (e.g., colloid formation), and biological methods (Fig. 4) [14].

After the synthesis with the mentioned approaches and methods, the produced nanoparticles include several classifications in terms of their nature and structural content, which respectively include inorganic (such as nano-mineral materials), organic (including nano-molecules of proteins, fats and sugars), emulsions, dispersions and nano polymers such as nano clay (Fig. 5) [25].

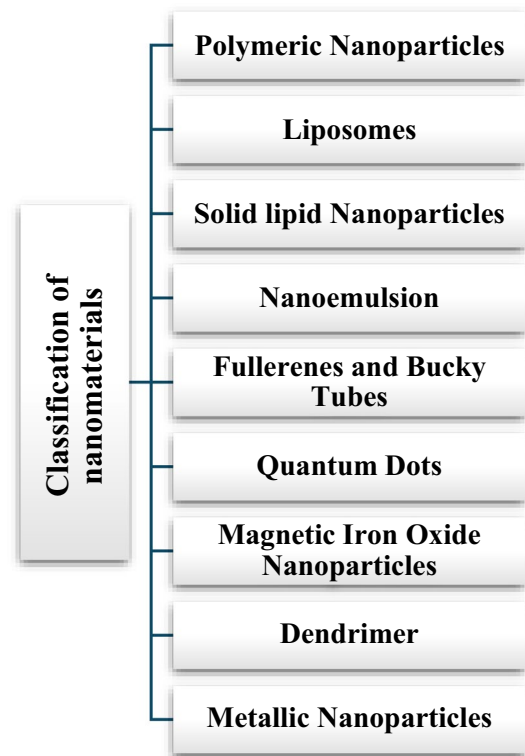
A review of the scientific literature shows that inorganic nanoparticles in the field of feed additive manufacturing have been welcomed and received more attention in applied research. This form is used for packing and storing feed. The organic form of nanoparticles is also used to produce encapsulation of vitamins and a series of nutrients to improve nutritional value and reduce bad taste factors, etc. [26]. In the form of nanoemulsions, the active ingredients are enclosed and stabilized with feed elements and are used for a series of food/feed and pharmaceutical compounds [13].

In recent years, the production of products with nanotechnology has caused experts to introduce more diverse and complex structures for carriers in nano dimensions and provide innovative classifications in the structure of nanomaterials (Fig. 6) [6].

2.1 Polymer nanoparticles

The potential of encapsulating valuable active compounds in food/feed and drugs is of interest, which absorbs and keeps the compounds in the range of 1–1000 nm. There are two polymer nanoparticles in the form of polyethylene glycol and polymers based on polysaccharides, such as inulin and chitosan. The value of these nanoparticles is in protecting the active compounds in the physiological pathway and the controlled delivery of the drug or bioactive compound to the target tissue. In poultry viral diseases such as Newcastle, antibodies with this mentioned structure can be helpful and effective in the treatment and health of the bird [6, 27].

Fig. 6 Classification of nano-materials used to obtain novel products



2.2 Nanoliposomes

Nanoliposomes are obtained by placing lipid molecules in an aqueous solution, so that the lipophilic phospholipid molecules have their hydrophobic groups placed on the inside of the sphere and their hydrophilic groups on the outside of the sphere and a double-layered spherical membrane is formed [17, 28]. Therefore, this way of orientation will allow the loading of hydrophilic compounds in the core and hydrophobic compounds in the shell of liposomes. Encapsulation with the relevant technique is more important for increasing the effectiveness of pharmaceutical and bioactive compounds and reducing side effects, and its industrial production has received attention due to its desirable quality. In the poultry industry, this structure has been proposed in the form of immunoliposomes for the purpose of immunizing with conjugated foreign antigens and binding to antibodies to destroy dangerous cells in the body [29, 30].

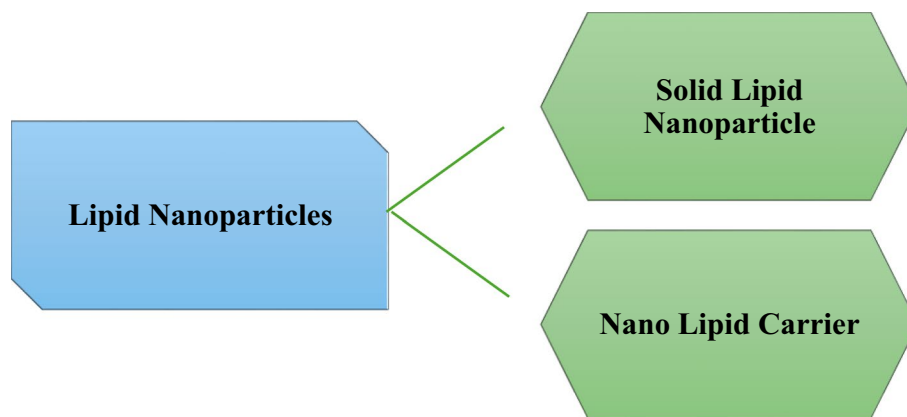
2.3 Lipid nanoparticles

Lipid nanoparticles have colloidal structures and include two main groups, namely solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC), with sizes ranging from 50 to 1000 nm (Fig. 7) [6].

In the encapsulation process, lipid nanoparticles have better efficiency compared to other nanocarriers, lipophilic compounds are better coated, and less toxic organic solvents are used. In addition, it has acceptable stability against moisture, light, chemical decomposition, and oxidizing agents due to less penetration of oxygen into metals, and it is possible to produce and sterilize them on a large industrial scale [31, 32].

Due to the similarity with emulsions or nanoemulsions, the existence of particles covered with dispersed emulsifiers is inside the aqueous medium. Another unique feature of lipid nanocarriers is the targeted release of substances into the body using active (composition of antibodies) and passive (particle size) mechanisms [32, 33]. Microencapsulation of plant bioactive compounds through lipid carriers has led to the improvement of their effectiveness, and this will be possible by facilitating their intercellular release and increasing their presence time in the cell [34].

Fig. 7 Types of lipid nanoparticles according to their sizes



2.4 Solid lipid nanoparticles

Solid lipid nanoparticles have a hydrophobic solid core that contains very pure triglycerides, a mixture of glyceride complexes or waxes, surrounded by stabilizing surfactants or a phospholipid monolayer. In addition, the solid core is the substrate of the drug or active compound, and its hydrophobic end is a phospholipid that is placed in the fat tissue [35]. The main advantage of these carriers compared to polymer nanoparticles is high biocompatibility and reduction of chronic and acute toxicity [36]. In addition, the cost of producing solid nanoparticles is lower compared to liposomes, and the problems of storage and leakage of their materials are far less [37]. The average particle size in solid lipid nanoparticle carriers is between 47 and 1777 nm, and they are among the most suitable carriers for food/feed and pharmaceutical compounds [38]. Medicines and bioactive compounds in the lipid part, as well as protecting against environmental damage and increasing the effectiveness time of the compound on the target tissue, are desirable features of these nanocarriers [39].

2.5 Nanostructured lipid carriers (NLC)

The structure of NLC is a different mixture of solid fat and liquid oil, which lipid and oil are immiscible with each other and cause the trapping and accumulation of more drug molecules and active compounds. This type of structure is for the purpose of controlling and releasing active compounds and vitamins, as well as increasing the permeability of the digestive tract wall for food/feed and pharmaceutical agents [40, 41]. The research conducted in connection with the application of NLC in the food industry can be the production of nanostructured lipid carriers containing quercetin [42], the production of beta-carotene nanostructured lipid carriers using grape seed oil and squalene, optimization of NLC formulation containing lutein [43], and production of lipid nanocarriers containing vitamin A palmitate [40].

2.6 Nano emulsion

Nano emulsions exist in two forms: oil-in-water and water-in-oil. Oil droplets are covered by a thin layer of surfactant against water. The use of nano emulsions in medicinal compounds is of interest due to their bactericidal and virucidal power. Oil droplets in nano emulsions can stick to bacterial and viral coatings and exert their therapeutic effects on cells and microscopic structures. In addition, it has been determined that nano emulsions deliver antigenic compounds to the target tissue [6].

2.7 Fullerenes and bucky tubes

Fullerene carbon nanoparticles are in the form of a small ball that can effectively communicate with all types of cells and pathogens. Bucky tubes, as nanotubes, have round and hollow structures that are used as biosensors to identify

immunoglobulins and due to the needle structure of these tubes, they can enter inside and penetrate cells and help treat disease [44]. However, fullerenes are very pure and have good durability over time [6].

2.8 Quantum dots

This type of nanomaterial has a mineral center and a shell around the liquid coating that can be combined with different biomolecules [45]. Among the applications of quantum dots, we can mention safety detection and presence detection. In these compounds, small molecules between 2 and 10 nm are formed, which when exposed to light, have semi-conducting properties and can be ideal in the field of electronics and light [46].

2.9 Magnetic iron oxide nanoparticles

This composition consists of an iron core and a fluorescent layer of silica that surrounds the outer layer. The outer shell is made of polymer, which helps to regulate the particles. The main feature of this group is directing the blood flow to the target cell through a magnetic field, which is an effective method for delivering valuable bioactive compounds or drugs and treating diseases [6].

2.9.1 Dendrimer

Dendrimers include three-dimensional and nano-sized polymers that are characterized by compact spherical structure in aqueous solutions. Polymers of dendrimer nanomaterials are smaller than body cells, so adverse resistance reactions are prevented during injection. Investigations show that polymer dendrimers can be combined with many water-soluble and insoluble restorative substances through chemical and physical bonds and loading drugs into empty centers through accumulation and covalent bonding. Following this event, it leads to an increase in the strength and therapeutic effectiveness of vital drugs [6].

2.9.2 Metal nanoparticles

Metal nanoparticles have a metal core and a protective coating. Known and used metals include silver, platinum, and manganese. Chemical functional groups can synthesize these substances and then conjugate them with drugs, ligands, and antibodies, which can be effective for the treatment of diseases and the effectiveness of drugs [6].

3 General mechanism of nanoparticles in the bird

In poultry nutrition, nanoparticles can be consumed by ingestion or inhalation. The mechanism of action of nanoparticles has many biochemical and physiological complications, but in general, the size of the particles is the most important factor in their performance [47]. Research shows that particles smaller than 100 nm can reach tissues, and particles smaller than 300 nm can spread in the blood [48]. For example, clinical trials have shown that the lifetime of trypsin and peroxidase enzymes can be dramatically increased (from several hours to several weeks) by attaching them to magnetic iron nanoparticles [49]. Creating nano technology and nano particles protein enzymes more stable, improving their effect on digestion, metabolism, and absorption of nutrients [11]. Overall, smaller particles are more absorbable and can enter the body system more deeply. Other factors, such as the solubility and particle charges, affect the performance, absorption, and removal of nanoparticles [50]. The absorption, distribution, decomposition, and excretion of nanoparticles in the bird's body will depend on the physicochemical characteristics of nanoparticles in terms of solubility, charge, and size [13].

4 Application of nanoparticles in the field of poultry production

The range of applications of nanotechnology and nanoparticles in the poultry industry is diverse, but considering the position and potential of this industry, the use of this technology could be improved. The use of nanotechnology for vital minerals such as copper, zinc, selenium, silver, gold, and chromium has attracted the most research and interest. In addition, the use of this technology for nanoparticles in the fields of vaccine preparation, immune stimulants, diagnostic

agents, disinfectants, antimicrobial compounds (antiviral, antibacterial, antiparasitic, antifungal) and antimycotoxin agents are of interest [51]. In the field of the food industry and packaging of poultry products, nano biosensors are used for food processing and preservation to detect the quality of food, which can intelligently help to improve quality control [6].

To control the absorption of macronutrients and micronutrients, nanotechnology improves the feed efficiency and the dynamic feed intake, deals with and control diseases, targets delivery and increases drug effectiveness [9]. Moreover, this technology can improve and enrich the contents of eggs, including producing full protein eggs and eggs without cholesterol, improving and enriching meat contents, reducing the loss of protein and energy, and reducing the price of poultry products in the poultry industry to help [52].

In the poultry feed industry, nanotechnology is used for (1) increasing the quality of feed by stabilizing nutrients and bioactive substances in feed matrices; (2) increasing the bioavailability of nutrients and micronutrients as well as bioactive substances with the aim of targeted delivery; (3) minor changes in the texture of feed to improve the sensory factors of feed such as color and taste, innovation in feed packaging, increasing the shelf life of feed; and (4) development of biosensors to detect pollutants and pathogens, improving feed safety and increasing the antimicrobial properties of feed are used and applied [9].

To eliminate intestinal pathogens in poultry, the BN are among the other applications of nanotechnology in the poultry industry. For example, *Campylobacter* is a harmless microbe in the bird's body, when it enters the human body in the form of poultry products, it will lead to muscle cramps and bloody diarrhea [9, 53]. Therefore, with nanotechnology and the use of nanoparticles in poultry feed, nanoparticles can be attached to *Campylobacter*, and after this event, the removal of this microbe from the body by chickens can be strengthened. As a result of this approach, the use and feeding of poultry products will be safe for human consumption. In general, biofunctionalized nanoparticles can bind pathogens together and prevent them from binding to the host and finally remove them from the digestive system and subsequently ensure safe and healthy poultry nutrition. A series of research shows that vitamins and their precursors, like carotenoids, are insoluble in water, but when they are formulated as nanoparticles, they can be dissolved in cold water and their bioavailability is improved [8, 10]. In feed processing, nanoparticles always have a higher surface area and consequently have a more effective absorption of nutrients. By encapsulating valuable compounds, nanotechnology can prevent the loss of nutrients, micronutrients, and bioactive substances during feed processing [54]. Basically, feed additives have been very important to improve poultry growth performance, but there have been challenges such as reduced nutrient absorption due to interaction with natural nutrients and the possibility of endotoxin production in the compounds, and any attempt to overcome these challenges with the help of feed additives in the small intestine to reduce nutrient loss and increase absorption efficiency can be very effective and beneficial [14, 55]. In fact, the encapsulation process involves covering or trapping a substance (feed additives or nutrients) inside another substance to protect it from the surrounding environment, which is of interest in poultry nutrition research and feed processing. With this process, it is possible to strengthen the feed's resistance to spoilage, heat, and light, as well as to protect it against the destruction of digestive enzymes. In addition, with the encapsulation technique with nanotechnology, delivery of the nutrient or bioactive substance to specific target sites is guaranteed and released in a controlled manner [56–58].

5 Application of nanotechnology in poultry feeds

In general, in the field of nutrition research, nanotechnology can be promising to obtain accurate information about the place of action of a nutrient or bioactive substance in poultry cells or tissue. Ultra-sensitive diagnosis and understanding of metabolic and biomolecular interactions of nutrients can be quite effective for improving nutritional and bio-providing assessments. In nutritional programs, the digestive tract system is the most important and preferred delivery route for nutrients, micronutrients, bioactive substances, and pharmaceutical compounds, so the fate of nanoparticles in this route should be properly understood to meet expectations fulfilled without any concern [9, 52]. However, nanotechnology in poultry nutrition is of interest to improve the production performance and improve the safety status [11].

Several studies show that nanoparticles in poultry feed have an effective role in reducing harmful bacteria and increasing beneficial bacteria in the microbiome of chickens, which can improve performance and the health of the poultry. The reduction of bacterial toxin production, the increase in the production of vitamins and growth factors, and the improvement of nutrient absorption were also reported [13, 14]. The findings show that the micro-coating of compounds through nanotechnology has increased the solubility of fat-soluble additives in the feed, and in parallel, while improving the taste, it has been able to reduce the need for fat, sugar, salt, and preservatives [12]. Nanoparticles can increase the absorption

of nutrients by reducing the antagonistic effects of divalent cations [14]. Research shows that the effectiveness of nano minerals in dealing with dangerous poultry pathogens has provided opportunities to reduce the use of antibiotics, and subsequently, nano knowledge is used to develop healthy, efficient and safe poultry product exploitation [9].

Other findings show that the use of nanomaterials in the feed industry can be used to increase antimicrobial effects as well as biosensors and diagnostic markers. Nanoparticles having a larger specific surface area compared to normal-size particles have higher surface efficiency, stronger catalytic efficiency, and more adsorption ability. In addition, numerous researches have proven that nanoparticles have better strength, improved solubility, increased conductivity, optical properties, thermal dynamics, and catalytic efficiency due to their unique physical, chemical, and biological properties [59, 60]. As mentioned, increasing the level of nano-sized particles can significantly affect the digestibility and absorption of nutrients, the immune system, growth and development [61, 62]. However, nanotechnology is also considered in the feed processing process to deliver nutrients to the target organs through methods such as encapsulation, chelation, packaging and nanotubes without negatively affecting the taste and color of the feed [13].

6 Nano feed additives

Research into nano-sized feed additives in poultry nutrition is seen as a transformative and promising approach that can enhance productivity, promote agricultural sustainability, and improve food security, offering substantial benefits to the poultry industry [14]. In recent years, the research and development of nanostructures that were produced with rational approaches are the most impressive synthetic materials in terms of unique chemical, physical and biological properties that can revolutionize the poultry industry [63]. Mineral nano-additives with nano-emulsion technologies were able to be low-cost additives, and growth stimulants with immune-modulating properties in poultry nutrition and have always been an indicator of use and attention [64]. These small and powerful materials were able to show a vital and efficient role in improving poultry health and producing quality products. On the other hand, with the approach of creating a vital balance between technological innovations and sustainable and environmentally friendly food production systems, it is possible to respond to the ever-increasing global demand for food and contribute to food security in the future. Nano feed additives can be added in the form of micelles or protein capsules or other natural substances to food or feedstuff in poultry nutrition. Micelles are small spheres containing oil or fat, which are covered with a thin layer of bipolar molecules, and one end of which is soluble in fat and the other in water. The mentioned micelles are suspended in suspended water or water in oil-encapsulated micelles. Nano emulsions are thermodynamically more stable compared to normal emulsions in different conditions, and the reason for that is their small size and monodispersed, which are easily diluted in water without changing the droplet size distribution. It should be noted that the surfactant used to formulate nano emulsions plays an important role in the stability of the final product of the final emulsion in nano additives [11]. In many studies, nano-mineral materials have been mentioned as low-dose antibiotic substitutes that can improve growth in poultry and simultaneously reduce residues and pollutants and produce animal products without pollution. The recommendations are that inorganic nanoparticles should be designed smaller than 100 nm to meet the effects and expectations mentioned to improve production efficiency in poultry [12]. In poultry nutrition, minerals in high doses are referred to as mineral salts, which have the potential to improve the growth performance and health of the flock to some extent, but there are concerns about possible environmental problems of this form of resources minerals can be worrisome [14]. A series of nano additives are processed in protein micelles, capsules, and natural feed materials [13].

In addition to mineral nano-additives, reports show that essential oils, flavorings, and antioxidants can also be used as valuable nano-additives in poultry nutrition [65]. In addition, liposomal nanovesicles are also used and considered for the purpose of transferring a series of nutrients, enzymes, and antibacterial agents in the form of feed additives [13]. However, the variety of applications in the field of nanotechnology and especially in the feed additives sector in poultry nutrition indicates the good potential of this technology in the poultry industry, some of the latest findings and reports will be briefly mentioned.

7 The role of nano additives on the immune system

It has been generally proven that nanomaterials can induce humoral or cellular immune responses. Nanoparticles (NPs) can have positive or negative effects on the health of the host body, like a double-edged sword, depending on their physical structure. In general, the main task of the immune system is to recognize and eliminate foreign

agents. The tendency of nanoparticles to induce innate or acquired immune responses to evaluate their immune system stimulation potential is a research approach in many nano additive studies [4–6, 63].

According to studies, most nanoparticles induce innate immune responses in lymphocytes, dendritic cells, monocytes, mast cells, neutrophils, macrophages and natural killer cells as well as pattern recognition receptors such as Toll-like receptors (TLRs). In addition, interaction of nanomaterials with the adaptive immune system leads to modulation of Th1/Th2 responses and stimulation of cytokine production. It is also hypothesized that during vaccination, the effect of nanomaterials on B cells leads to increased immunity [3, 5, 8, 27]. In many cases of immune suppression, additional stimulation beyond the presence of antigen is necessary for effective antibody production, and when a B cell recognizes and binds to its corresponding antigen, a cascade of events is initiated that leads to the maturation and differentiation of the cell into plasma cells and produces antibodies. In this process, the role of nanoparticles as a trigger for the formation of a cascade can be very influential. This interaction can be modified by changing specific properties of nanoparticles such as particle size, shape, hydrophobicity, stiffness and surface components.

Regarding the role of nanoparticles in non-specific immunomodulation, cytokine transport and physical localization will occur, and this site will act as a reservoir for sustained release. On the other hand, toxicity caused by nanoparticles and negative effects on the immune system in the form of oxidative stress, inflammation, genetic damage, cell division and suppression of cell death are potential concerns [6, 8, 10].

Another mechanism by which nanomaterials affect the immune system is by helping the efficiency of the bird's digestive system. A review of the scientific literature has shown that the effectiveness and efficiency of the intestine in poultry are highly dependent on the diet. The intestinal mucosa is characterized by finger-like protrusions called villi that increase the absorption surface. If the length of the villi is directly proportional to the absorption of digested materials, the inner mucosa and the length of the villi play a vital role in the absorption process. Several studies have reported the importance of nanocomposites in improving the intestinal environment in poultry, such that nanoparticles play an effective and constructive role in maintaining the integrity of the intestinal epithelium and increasing the number of goblet cells. Since the acidic mucous secretions of these cells have a protective role in the intestinal mucosa against many pathogens and facilitate the movement of digested nutrients as a result of reducing the viscosity of the materials, which leads to an increase in the immune response and stimulation of this system in birds [5, 6, 8, 30]. Despite the significant and promising evidence of the role of nanoparticles on the immune system and enhancing the mechanism of improvement of this system, there are still concerns about the negative effects of these materials on immunity. Because the interaction of nanoparticles with the immune system and their effects are not fully understood, strategies for modulating the immune system using nanomaterials to treat immunological disorders face challenges [8, 10, 27, 30].

Overall, further mechanistic research is needed on the immunomodulatory effects of particles as either immunostimulatory or immunosuppressants. Although the cytotoxicity of nanoparticles is effective in detecting acute host injury, it is not sensitive enough to detect the effects of immunodeficiency. The predominant processes of nanoparticle-mediated toxicity include oxidative stress, inflammation, DNA damage, and inhibition of cell division and death [3, 5, 6, 8, 10]. Research has shown that the cytotoxicity of nanoparticles is usually directly related to the production of ROS, which is the basis of oxidative stress and many activities including induction of protein phosphorylation, activation of several transcription factors, and apoptosis of cells. The induced oxidative stress enhances cellular signaling pathways and subsequently increases the production of proinflammatory cytokines. Also, some nanoparticles activate inflammatory cells such as macrophages and neutrophils and increase ROS production. Several nanoparticles, such as titanium dioxide (TiO₂), zinc oxide (ZnO), cerium oxide (CeO₂), and silver nanoparticles, due to their surface properties, can deposit on the cell surface or even inside intracellular organelles and stimulate oxidative stress signaling cascades, leading to oxidative damage to the cell [3, 6, 8, 27, 35]. A review of the scientific literature has shown that the main variables in ROS induced by nanoparticles include (i) the active redox cycle on the surface of the nanoparticles due to the transition metal-based nanoparticles, (ii) surface functional groups, and (iii) nanoparticle-cell interactions. Because cellular responses to nanoparticles are accompanied by ROS production and can be stimulated by the oxidant properties of the particles themselves. Free radical intermediates exist on the reactive surfaces of particles and are quite stable. However, there are effects of the nanoparticles' functionalities on the formation of redox-active groups. When the immune system encounters a foreign body such as nanoparticles, the first cells to respond are phagocytic cells. Almost all of the immune system-stimulating responses induced by nanoparticles are accompanied by the release of pro-inflammatory cytokine mediators [3, 5, 8, 27, 35].

8 Role of nano additives in bioavailability

Revolutionary nanotechnology has been able to create promising and challenging developments in the fields of food systems, diagnostics, therapeutics, pharmaceuticals, agriculture and nutraceuticals. It is very important in relation to the role of nanoparticles in providing solutions for enhancing the bioavailability of nutrients, micronutrients and bioactive [27, 30, 35]. Nanotechnology is modernizing the entire food chain system from production to processing, storage and consumption. Due to the remarkable thermodynamic properties of nanoparticles, food additives containing bioactive compounds can increase the efficiency of access and absorption, and research and researchers' findings support the increase in the bioavailability of micronutrients. The efficacy, stability, and utilization of micronutrients can be improved with the help of food-grade nanoparticles through their encapsulation properties. Scientific reports show that nanotechnology can enhance thermal stability, water solubility, and improve the properties of bioactive particles in spices and medicinal plants by increasing their water solubility and antioxidant properties, so that the active ingredients are homogeneously dissolved and subsequently improve the bioavailability. In general, the degradation of micronutrients in a food product significantly depends on the physicochemical and molecular properties, as well as the composition of the food and storage conditions. Micronutrients may be subject to physical, chemical, and enzymatic instability in a food product. Changes in molecular structure lead to significant changes in the physicochemical and nutritional properties of the bioactive component. Common causes of chemical degradation of micronutrients by enzymes present in food products. Bioavailability is a key point in ensuring the bioefficacy of oral drugs or bioactive food components. This is influenced by the chemical degradation of bioactive elements during processing, production, storage and transportation as well as their manifestation in the gastrointestinal tract (GIT) [3, 27, 35, 58].

However, the use of nanotechnology in the field of poultry nutrition has advantages and disadvantages (Table 1), which, according to the important strategies of the poultry industry in the future perspective, should be accepted with a smart and scientific approach to use this technology in order to optimally utilize the benefits of this technology and its products [3, 5, 27, 30].

According to studies, international organizations such as FAO, FDA and EFSA have adopted specific guidelines and positions regarding the use of nanotechnology in the field of nutrition.

Smart packaging and helping to increase the absorption and bioavailability of nutrients and control toxicity are among the general strategies of the FAO regarding nanotechnology in the field of nutrition. At the FDA, the organization's focus is on food safety and nanotechnology-based products require a case-by-case assessment and any possible changes must be presented in the product labeling. EFSA has also prioritized accurate risk and safety assessment in nanotechnology-based products, and its strictness for food consumption remains at the highest level compared to other organizations. In general, the common challenges of all organizations include the lack of long-term data on the toxicity of nanomaterials, the lack of access to a global standard for defining nanomaterials and testing methods, and the lack of transparency in product labeling for consumer awareness. Therefore, nutrition and poultry science experts in the field of specialized studies are obliged to prepare the ground for resolving the challenges and problems of this technology through efficient and applied research, and at the same time, to benefit from the benefits of this technology in a principled manner and with minimal risk [3, 5, 8].

Table 1 Benefits and disadvantages of nanotechnology in nutrition

	Benefits	Problems
1	Improvement of the bioavailability of nutrients and micronutrients in the cell	Excessive entry of nutrients and micronutrients into the cell
2	Improvement of production performance	Increase in production costs
3	Stimulation and modulation of the immune system	Increase in activity and pressure on the immune system
4	Increase in speed and effectiveness	Increase in physiological pressure and oxidative stress
5	Eliminate pathogen residues inside the cell	Excrete pathogens and unknown substances to the outside environment
6	Reduce antibiotic consumption	Increase in the consumption of synthetic supplements is unknown in terms of side effects
7	Reduce mineral antagonism	Disrupt the ionic balance of the intercellular fluid

8.1 Enzymatic nanoparticles

This class of enzyme nanoparticles are cluster-like protein structures with dimensions of 10–100 nm, which have significant stability, biocompatibility, conductivity, and sensitivity [66]. These particles can improve the performance of the enzyme-based sensor by increasing the surface area, and in fact, the potential technique of biosensor production will be created by increasing the analytical performance in terms of detection limit and current response [67, 68]. In addition, research shows that enzyme nanoparticles have high catalytic activity as well as better thermal stability [69]. For single-enzyme nanoparticles such as trypsin and chymotrypsin, this feature (increasing activity and increasing thermal stability) is considered a potential advantage [70]. Gu et al. [71] believe that enzyme nanoparticles can have the potential to increase temperature tolerance and cellulose degradation. Many enzyme additives added to animal feed products increase the possibility of the decomposition of a series of nutrients, and subsequently, the nutritional value of the feed is reduced, which can lead to digestive problems, reduce efficiency, and therefore the production of meat or eggs. Overall, research findings show that enzyme nanoparticles can be prepared through ethanol, glutaraldehyde, and cysteine/cysteamine [72]. BSA proteins are integrated and prepared in the form of nanoparticles to produce soluble proteins through emulsification in vegetable oil [73]. The method of dissolving the protein enzyme in ethanol with natural salts and then cross-linking with glutaraldehyde and high-pressure cross-linking in water–oil emulsion to produce enzyme nanoparticles was also presented in the report of Lee, et al. [74] as a valuable nano additive preparation method [13].

8.2 Green synthesis

In research, the process of producing nanoparticles from plants is referred to as "green synthesis". In general, plant extracts can contain carbohydrates, proteins, alkaloids, polyphenols, terpenoids and other bioactive compounds that are stabilized by metal ions and used in various forms with nanotechnology to synthesize these nanoparticles [75]. Review of scientific literature shows that nanotechnology for Pelargonium (*Pelargonium graveolens*) [76], Neem (*Azadirachta indica*) [77], Alfalfa (*Medicago sativa*) [1, 78], Lemongrass leaf extract (*Cymbopogon flexuosus*) [79], Camphor tree (*Cinnamomum Camphora*) [74, 80], Aloe (*Aloe vera*) [81], Okra (*Abelmoschus esculentus*) [82], Barley (*Avena sativa*) [83], Amla fruit extract (*Emblica officinalis*) [84], Concoction (*Piper nigrum*) [85] and Tamarind (*Tamarindus indica*) [86] using the green synthesis process was unprecedented and the results were very promising. In general, obtaining nano feed additives through green synthesis with nanotechnology is considered as an environmentally friendly solution for plant extracts and their combination with metal salt [87].

8.3 Zinc nanoparticles

As one of the essential mineral elements, zinc (Zn) is present in almost all the cells of the poultry body and has multiple important roles in biological activities. Research shows that this element has effective roles in strengthening growth, immune system, synthesis of nucleic acids, cell divisions, synthesis of proteins, enzyme activities, vitamin A metabolism, storage and release of insulin, energy metabolism, stabilization of macromolecules, regulation of DNA transcription, effect on gene expression, cell divisions and cofactor role [88, 89]. Zinc plays a role as a cofactor in the structure of more than 300 types of enzymes. The most well-known and important zinc-containing enzymes include carbonic anhydrase, pancreatic carboxypeptidase, lactate dehydrogenase, alkaline phosphatase, thymidine kinase, catalase, and alkaline phosphatase, respectively [90].

A review of the scientific literature shows that ZnONPs have been considered in biological research due to their good biocompatibility and acceptable chemical stability and low toxicity [91–93]. Zinc nanoparticles have been able to improve body weight, FCR, meat quality and egg quantity in many studies [88, 94]. Basically, zinc as a vital element plays a pivotal role in bone growth, as well as maintaining normal growth and healing tissue damage [95]. The feeding of additives containing zinc, which is macro and does not use nanotechnology, leads to an increase in the cost of feed production and high excretion in feces, and subsequently leads to environmental pollution and, in parallel, leads to the imbalance of other elements and vitamins decrease. In addition, the decrease in the level of zinc in the plasma can lead to the disruption of physiological processes and various liver diseases (cirrhosis and hepatitis) [93, 96]. Zinc is a component of the carbonic anhydrase enzyme, which plays a very important role in providing bicarbonate ions during the formation of the egg shell in laying hens, and any deficiency or disturbance in the absorption of this element can affect the synthesis and secretion

of hormones, and eggshell weight have a negative effect [97]. In the report of Abedini, et al. [98], zinc supplementation in the form of a nano source with a concentration of 80 mg/kg ration could improve the qualitative characteristics of eggs (egg shell) compared to other forms of macro element zinc, and the reason for this is the improvement of bioavailability the provision of zinc in the nano state was attributed. These researchers concluded that nanotechnology for the production of additives containing rare mineral supplements in poultry diet can be a low-risk and successful solution to meet the needs and reduce the problems caused by deficiency. Later, Abedini, et al. [99] showed that supplementing the diet of laying hens with nano zinc oxide can improve performance, egg quality and antioxidant status, and suggested that supplementing 40 to 80 mg/kg of nano zinc oxide was recommended in the practical feeding of these birds. Javadifar, et al. [100] reported improvement of growth performance indicators, egg's shell quality, strengthening of immunity and reduction of blood lipid profile by consuming 200 mg of oxide nanoparticles. In addition, oxide nanoparticles have gained popularity as an alternative feed additive in poultry due to their effects on the metabolic activity and health status of birds, as well as antibacterial and immunostimulant effects [101, 102]. Hatab, et al. [61] using synthesized ZnONPs on chickens increased body weight, performance index and improved feed intake compared to the control group, and in the serum, cholesterol, triglycerides, and LDL and uric acid decreased, and the HDL and the liver enzymes increased. These researchers recommended supplementing with 40 or 60 mg/kg of ZnONP to improve production performance, using this form of supplement at low levels. Fawaz, et al. [103] using zinc oxide nanoparticles in laying hens improved the FCR and egg mass, and levels of 20, 40 or 60 mg/kg in the diet of laying hens were able to improve their productivity and health. Radi, et al. [104] comparing zinc oxide and zinc oxide nanoparticles in the feeding of broiler chickens, reported that at the age of 2 to 20 days, birds fed with the of zinc oxide nanoparticles with a ration dose of 90 mg/kg, had higher body weight gain compared to other experimental groups. Hussan, et al. [105] evaluated the effects of zinc supplementation in the form of nano zinc oxide on the performance of broiler chickens and concluded that supplementing diets with 2.5 ppm nano zinc oxide led to a significant increase in live weight and the FCR was improved at the age of 42 days compared to the control group. Reda, et al. [106] observed an increase in body weight and an improvement in the FCR by feeding nano zinc on Japanese quail at the intake level of 0.2 g/kg of nano zinc. In addition, the improvement of liver enzymes and the increase in the content of immunoglobulins at the levels of 0.1–0.3 g/kg of nano-zinc were quite noticeable and promising. Yusof et al. [107] showed that the nutrition of zinc oxide nanoparticles led to more retention of zinc element in the body and reduction of zinc excretion was significant. In addition, the consumption of 100 g/kg of zinc oxide nanoparticles led to a decrease in pathogens and an increase in beneficial bacteria.

In many studies, zinc nanoparticles had positive effects on performance, growth, immune modulation and strengthening the health of poultry, and at the same time, it helps to improve the feed efficiency and inhibit the growth of mycotoxic fungi and mycotoxins [13, 14].

8.4 Selenium nanoparticles

Selenium is considered a rare mineral and an essential micronutrient for poultry. This element forms part of the structure of glutathione peroxidase enzyme and can play a role in regulating energy metabolism, activating thyroid hormones and improving and modulating the immune response. Selenium acts as a pseudo-antioxidant in stress conditions and helps the body against free radicals and cell damage [108, 109]. In many reports, supplementing broiler chickens' diets with selenium has been able to be effective on production performance and health-related parameters (blood, antioxidants, gastrointestinal tract) and this effectiveness had more promising results at a young age [110, 111]. The review of scientific literature shows that the addition of selenium nanoparticles in layer feed can help improve reproduction, egg production, FCR, immune modulation, antioxidant status, egg quality and the balance of intestinal microbial flora [112].

In addition, the use of selenium in nano form is environmentally related to reducing the release of this element in the environment and reducing pollution, and subsequently maintaining public health [113]. In the conditions of various types of stress in poultry, increasing the quality and quantity of products and reducing pollution after the additive consumption of selenium in nano form can be suggested, and possibly a reassuring solution [114, 115].

Selenium is also a vital element in reproductive physiology to produce follicles and produce healthy eggs in chickens [113]. Many findings indicate that the addition of selenium nanoparticles in the nutrition of laying hens has been able to significantly increase the production and content of selenium in eggs [116]. Selim, et al. [117] showed that the consumption of 0.25 ppm of nano selenium in laying hens is associated with improved production efficiency and increased activity of glutathione peroxidase, and the produced eggs are rich in selenium, which can meet half of the needs of consumers (humans), providing this element in a day. Ismail et al. [118] improved and increased the egg production rate per day, egg weight, egg's shell quality, and albumin by supplementing the diet of turkeys with nano selenium and zinc. Zinc

oxide form (40 mg/kg) and selenium nanoparticles (0.15 mg/kg) were able to increase the nutritional value and overall digestibility and production of volatile fatty acids. In the study of Hu et al. [119] at the levels of 0.15, 0.30, 0.60, and 1.20 mg/kg, two nano selenium additives were compared with sodium selenite in feeding broilers and the results showed that in nano form the absorption of elements was done more effectively in the body and the needs of the bird were provided in a wider range, and, the growth performance improved. Ahmadi et al. [111] observed a reduction in the FCR and an increase in body weight at the levels of 0.3 and 0.4 g/kg by supplementing the diet of broiler chickens with nano selenium.

8.5 Manganese nanoparticles

Manganese (Mn), as the fifth most abundant element on the planet and one of the transition metals, was introduced as the first deficient element in poultry nutrition and its consumption was recommended as a supplement in functional diets [120]. This element plays an important role in many physiological processes as a cofactor of biological enzymes in the process of growth, metabolism of carbohydrates, fat, and blood coagulation. Manganese plays an important role in the structure of important body enzymes such as manganese superoxide dismutase, glutamine synthetase and phosphoenol pyruvate carboxykinase [120, 121]. Due to their low absorption capacity of manganese element from the intestine, chickens should meet their needs through diet [122, 123]. Then, due to the importance of this element and also its low bioavailability, the use of nano form for this element in practical poultry diets is a practical suggestion. However, to strengthen the antioxidant function and immune system, manganese is an important element that can be effective in reducing herd losses. It has been proven that this element is a cofactor of transferases, lyases, hydrolyzers and oxidoreductases and plays a central and key role for the mitochondrial antioxidant system, apoptosis, bone growth, and cell structure [13].

8.6 Copper nanoparticles

Copper (Cu) is important and distributed in various organs and tissues as a low-requirement and essential element for poultry, and it has many important physiological and metabolic effects. Investigations show that this element has an important and constructive role in absorbing and accepting electrons, its importance in the stages of oxidation and reduction and removal of free radicals [124]. Copper in cytochrome oxidase enzyme systems causes the reduction of O_2 to H_2O in the respiratory chain. The enzyme lysyl oxidase contains copper, which is effective in the process of connections between collagen fibers makes collagen harder and increases its elasticity. Tyrosinase enzyme also contains copper and converts tyrosine into melanin as one of the vital enzymes of the poultry body, the superoxide dismutase enzyme contains copper and plays a central role in the body's antioxidant system [114]. Research shows that copper is involved in the process of mitochondrial oxidative phosphorylation, denaturation and synthesis of neurotransmitters, detoxification of free radicals, synthesis of connective tissue, iron metabolism, and the formation of pigments in the poultry body. However, copper is considered an essential element for metabolic activities, physiological functions, immune responses, and growth of connective and nervous tissue [125].

Inorganic copper sulfate and copper oxide nanoparticles improve growth performance, immunity and reduce inflammatory responses in poultry. Copper nanoparticles present in basic diet meals reduced feed intake without affecting laying hen body weight, output, mass or egg quality. In the research of Józwick, et al. [126] using nanoparticles of copper, zinc, and manganese in feeding turkeys, they showed that copper and zinc affect the activity of aminopeptidases (alanyl, leucyl, and arginyl) in meat. For nano copper, the strongest interaction between the form and dose of mineral supplements on the activity level of aminopeptidases in the thigh muscle was observed. The highest activity for nano copper was observed in the lowest dose (2 mg/kg) and in this dose, 10% of the requirement was covered. In addition, at 20 mg/kg nano copper (100% of demand) and 10 mg/kg nano copper (50% of demand), it was able to influence the activity of all three types of aminopeptidases in muscle runners. In general, the supplementation of minerals in nanoforms in turkey diets, especially for copper and zinc at a dose of 10% of the requirement, was effective for maintaining homeostasis and modulating the activity of aminopeptidases in turkey muscles. Nguyen, et al. [127] using a premix containing copper, iron, selenium, and zinc oxide in the form of nanocrystals in the diet of broilers chickens, concluded that the consumption of this nanocrystal premix without any negative effect on the performance was able to improve the health of chickens and at the same time reduce the environmental pollution in terms of disposal of these elements. Shi MingLei, et al. [128] using copper silicate nanoparticles in the diet of broiler chickens observed an increase in *Lactobacillus* and a decrease in *E.coli* in the gut microbiota, and nitrogen metabolism was improved, and subsequently, the release of fecal ammonia with a decrease was observed. Mroczek-Sosnowska, et al. [129] were able to observe an increase in body

weight, a decrease in FCR, and an improvement in the lipid profile of the breast muscles, strengthening of leg bones and growth of blood vessels during embryogenesis, with the addition of nano copper in the diet of chickens. In ovo injection of nano copper stimulation of nuclear antigen-positive cells was observed in the long bones of broiler chickens [130]. Mroczek-Sosnowska, et al. [129] were able to observe increased growth and increased hemoglobin levels in red blood cells by intramuscular administration of copper nanoparticles in chickens. In addition, the levels of copper and protein in the blood were significantly increased.

8.7 Iron nanoparticles

The known biochemical activities of iron (Fe) elements include electron transfer in cytochromes, and iron-sulfur-containing proteins, as well as the displacement of oxygen molecules by catalase and peroxidases. In addition, the role of this element in storing and maintaining oxygen in myoglobin and hemoglobin, collagen synthesis, porphyrin metabolism, activity of granulocytes and lymphocytes, anabolism and catabolism of neurotransmitters (because iron is a cofactor of tyrosine hydroxylase and tryptophan hydroxylase enzymes) is absolutely important and vital [131]. Iron nanoparticles in poultry nutrition can have a positive effect on bird growth, improving hematology and immunity [132]. There are promising reports and results in chicken nutrition, improvement of egg quality characteristics (egg size, egg relative components, and shell strength), and chemical composition of eggs [133]. Javadifar, et al. [100] using different levels of iron nanoparticles in the diet of laying hens reported improvement of egg quality traits, blood biochemical indices, and immune response without negative effect on production performance at the level of 100 mg/kg.

8.8 Silver nanoparticles

Nutritional evaluations show that the consumption of supplements containing nano silver (Ag) in chickens can increase the level of cellular immunity [134]. Supplemental feeding of nano silver along with savory plant and thyme in feeding chickens was associated with antibacterial effects and adjustment of cecal microflora [135]. By increasing the use of nano silver with these plants, the number of lymphatic organs decreased. A review of scientific literature shows that microorganisms can lead to the growth, number, and maturation of lymphatic organs in the digestive system. While nano silver has antimicrobial properties, it can provide oxygen to beneficial microorganisms [136]. Silver elements control and inhibit bacterial respiration by forcing bacterial cells to capture ions and produce active oxygen molecules. In addition, research shows that silver nanoparticles can improve the muscle morphology of broilers toward animal health [137]. In the study of Sawosz, et al. [138], the consumption of 25 mg/kg of nano silver could increase the population of lactic acid bacteria, and the consumption of 50 mg/kg of silver nanoparticles chelated with the amino acids threonine and cysteine increased the immune capacity of the fetus and the productive chickens were effective and promising.

8.9 Chromium picolinate nanoparticles

Chromium (Cr) is an essential mineral component in poultry, which in the form of a trivalent element (CrIII) has an active role in the metabolism of proteins, lipids, and carbohydrates [14]. The primary metabolic role of chromium is to enhance insulin activity through its presence in an organometallic molecule called GTF. Chromium circulation in the blood is accompanied by plasma beta-globulin, and in physiological concentrations, it is transferred to the tissues by binding to transferring and is considered as a part of the glucose tolerance factor. Chromium protects RNA from thermal denaturation. Also, chromium accumulates in the nucleus of animal cells. Chromium increases RNA synthesis and affects gene expression. Chromium requirements in humans and animals increase during stress [139]. In the report of Sirirat, et al. [140], the use of chromium picolinate nanoparticles in laying hens could increase the quality of eggs, the accumulation of chromium, phosphorus and calcium in the liver, calcium in the eggshell, and chromium in the yolk. In addition, the use of CrPicto reduces heat stress and also improve the FCR, increases the concentration of minerals such as calcium, phosphorus, and chromium in the liver and also increases the number of lymphocytes in broiler chickens. Sahin, et al. [141] added nano chromium picolinate to the diet of laying hens and concluded that the use of this nano additive at a level of 200 µg/kg could have a positive effect on production performance and in stress conditions plasma insulin concentration increase the effects of chromium activity on the immune system as well as the relationship with the effect of chromium on blood insulin and cortisol concentrations have been investigated in many studies, and in this research, chromium probably improves the immune system function by reducing the level of cortisol and other immune mediators [13].

8.9.1 Calcium and phosphorus nanoparticles

Among the mineral elements in the poultry body, calcium is the most important and on average it makes up 50% of the weight of the body's ash. Calcium is necessary for the activity of certain enzyme systems such as nerve current transmission and muscle contractions, and it is also involved in blood coagulation in the blood plasma. In laying hens, on average, 300–400 mg of calcium is found per liter of blood plasma. This mineral element plays a role in activating lipase enzymes and fat metabolism. In addition, eggshell formation is influenced by the amount and quality of dietary calcium [12].

Phosphorus also has many roles in the body and always acts in the form of phosphate (PO_4^{-3}) in the body. The phosphate functional group is very reactive, and its compounds play a key role in metabolism (ATP, creatine phosphate, phospholipids, etc.). Phosphate as a part of hydroxyapatite also plays a key role in bone structure. In plants, about two-thirds of phosphorus is in the form of phytate phosphorus. Phytate phosphorus is chelated with several cations, usually in the form of calcium phytate, magnesium, zinc, iron, potassium, and other metals, and its availability is reduced. Poultry diets, which are based on plant food sources, always have significant amounts of unavailable phosphorus phytates (60–80% of total phosphorus), which are not effectively used due to the absence of phytase enzymes in the body of chickens [142, 143]. Therefore, the use of nano resources can be a helpful strategy in poultry nutrition to reduce the negative effects of phytate [13]. In general, the review of scientific literature shows that calcium and phosphorus in the form of nanomaterials can improve feed conversion efficiency, increase body weight, and simultaneously reduce the excretion of calcium and phosphorus to the outside environment [143]. Consuming mineral resources in nano form can increase growth, reduce pollutants, and produce healthy animal products like chickens [12, 142, 143].

Since phosphorus (P) in poultry feces causes environmental problems, Hassan, et al. [142] replaced conventional DCP with nano calcium to reduce phosphorus waste without negatively affecting the performance of broiler chickens. The NDCP was investigated on the performance of broiler chickens and the results showed that the birds fed NDCP showed an increase in weight (25%), increased feed intake (10%), and a 12% improvement in conversion rate. By consuming 0.44% of NDCP in the diet, these researchers reduced calcium and phosphorus excretion by 50% and 46%, respectively, compared to the control group.

In the report of Mohamed, et al. [144], investigating the effect of NDCP versus normal DCP, they showed that chickens improved bone parameters after feeding nano form. In addition, diets containing 25% NDCP can replace conventional dicalcium phosphate with 100%, and dicalcium phosphate with nanoparticle size is approximately 400% more effective than traditional DCP.

9 Nano biosensors

Nano biosensors are small devices that can detect and analyze biological elements at the molecular level [145]. These smart biosensor systems with nanotechnology can identify chemical pollutants and pathogens and even prevent their growth. Today, nanosensors are quite useful and effective in the field of poultry production and nutrition, agriculture, and the food industry [146]. Identification of microbiological pollutants such as bacteria, viruses, and toxins, even in small possible amounts, is performed well by nanotechnology and biosensors to take preventive measures and prevent the spread of diseases [147]. The applications of nano biosensors in the poultry industry are wide and can play a role in the future from a good perspective to help the development of this industry (Fig. 8).

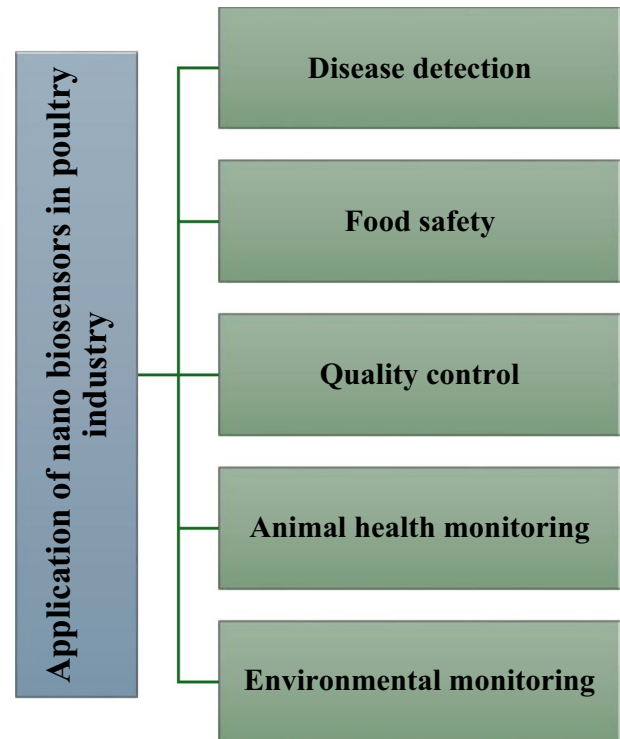
9.1 Disease detection

Research shows that pathogens or poultry diseases, such as influenza or salmonella, can be identified and diagnosed early with nano biosensors through specific biomarkers or genetic materials [148, 149].

9.2 Food safety

Nano biosensors can identify harmful pollutants such as antibiotics and heavy metals, identify the safety of poultry products, and perform quality control according to regulatory standards [146].

Fig. 8 Application and uses of nano biosensors in poultry industry



9.3 Quality control

Nano biosensors can identify different quality parameters in poultry such as freshness, spoilage, or content of poultry feed, and ultimately help ensure the quality and durability of poultry products [150]. However, smart food packaging based on biosensors and nanocomposites based on biopolymers improves the quality and safety of food and has attracted more attention in the industrial community.

The biosensor with food packaging has a range that allows monitoring of the microbial breakdown of packaged foods. The development of nanocomposites based on biopolymers (named bio nanocomposites) has made significant progress due to mechanical, thermal, optical, and antimicrobial properties [150, 151].

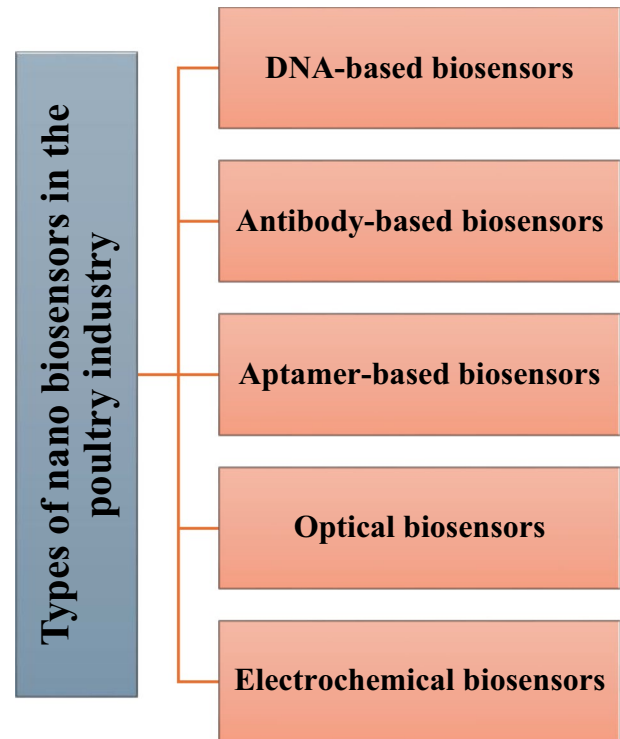
9.4 Animal health monitoring

Nano biosensors can track a series of poultry physiological parameters related to flock health, such as temperature, stress level, and heart rate, and help evaluate the health and well-being of birds [152].

9.5 Environmental monitoring

Nano biosensors have the potential to detect pollutants in poultry environments such as gases, ammonia, and suspended particles and potentially help to create optimal environmental conditions for the welfare of the flock [153].

Fig. 9 Types of nano biosensors used for the poultry industry



10 Types of biosensors in the poultry industry

The types of biosensors applied in the poultry industry are introduced in Fig. 9, each of which can be used in poultry nutrition in terms of safety and quality of feed and hygiene of edible items, as well as controlling the health of the flocks, and finally the manufactured products in terms of evaluating food safety and quality [6].

10.1 DNA-based biosensors

These biosensors can be connected to the genetic material of pathogens and identify specific DNA sequences, such as avian influenza or salmonella, helps to quickly and accurately diagnose poultry diseases [154, 155].

10.2 Antibody-based biosensors

Antibodies can be fixed on the surface of nanomaterials and can be identified and attached to specific antigens by biosensors. These antibodies against common poultry pathogens such as *E. coli* and *Campylobacter* are important for rapid diagnosis [156].

10.3 Aptamer-based biosensors

Aptamers are short and single-stranded nucleic acids that can bind to specific targets such as pathogens or toxins, and after this event, help to identify pollutants and harmful substances in poultry products [70].

10.4 Optical biosensors

This category of biosensors is used for detection methods based on light and smell and analysis of samples (pathogens or pollutants) [6].

10.5 Electrochemical biosensors

This class of biosensors can convert biochemical signals into electrical signals for analysis and provide the possibility of fast and sensitive detection of different analytes in poultry samples [157].

11 The perspective of nanotechnology in poultry nutrition

From the perspective of the future of poultry nutrition, innovative feed additives have been introduced as an effective and strategic solution for this industry, which can help improve the performance and health of the flock [3]. In the discussion of food security and sustainable development goals, the importance and value of using feed additives in animal nutrition has been mentioned to achieve two goals, including “zero hunger” (second position) and “responsible consumption and production” (twelfth position) [158].

The restriction and ban on the use of feed additives containing antibiotics in poultry feed due to the potential emergence of pathogenic microorganisms resistant to antibiotics, has pushed the trends towards the use of non-antibiotic and natural additives [159]. On the other hand, forecasts indicate a doubling of the global demand for food after 2050, and in parallel, the awareness and demand of food consumers towards quality, safety, and diverse products have increased in animal products which will increase pressures and expectations from the poultry industry in the future, and such a phenomenon is inevitable [13, 160–162].

Reducing the physical and biological availability of micronutrients has led to the growth of the phenomenon of “hidden hunger” and includes people who are overweight and obese but suffer from malnutrition and lack of micronutrients (minerals and vitamins) and such a phenomenon has doubled the efforts to solve this crisis by providing food coded programs including food additives by supporting research [163, 164]. There are novel reports on the positive effects of feed additives in human [165–167] and animals [2, 168].

Over the past two decades, research on nanotechnology applications has expanded its scope, bringing new opportunities and optimism for enhancing the quality of life. Given the potential benefits and applications of nanotechnology in agriculture and the food industry, and the growing need for global food production, nanoproducts in agricultural sectors, including the poultry industry, aim to address critical global challenges such as poverty, malnutrition, and food shortages. However, the dissemination of information about nanotechnology remains uneven, and significant limitations and concerns persist. For instance, uncertainties about the long-term environmental impacts of nanomaterials create challenges in accurately assessing the risks associated with their consumption. This highlights an urgent need for further research and effective monitoring to ensure the safe and sustainable use of these materials [3].

The use of both synthetic and natural additives in poultry nutrition is on the rise, supported by extensive practical studies and a wide variety of options that have demonstrated positive effects in research and industry. However, it is noted that high excretion rates may impact production efficiency and increase costs. [159]. For example, L-carnitine, whose role in improving the health status of poultry has been confirmed in terms of blood fat profile, but in research, the bioavailability of L-carnitine has been reported to be less than 20% [18, 160]. Therefore, by taking advantage of new knowledge in biotechnology, the use of such additives with nanotechnology should be able to help solve the animal feed crisis without any negative impact on food security and consumer health [93]. In the field of feed additives, the use of biotechnological approaches to meet the nutritional needs of consumers using nanotechnology is considered one of the strategic solutions in the future perspective of poultry nutrition (Fig. 10) [14, 169, 170].

In general, bioavailability may play a key role in the bio efficacy of bioactive compounds, which can reflect the relationship between food and health and is also considered as a key indicator for qualitative and quantitative assessment of the risks of a substance to the environment and host health [171, 172]. Essentially, a chemical element is more readily available for absorption when it exists as a free ionic species or is readily converted to it, and this ability can affect a wide

Fig. 10 The general introduction of feed additives that can have better bioavailability with nanotechnology

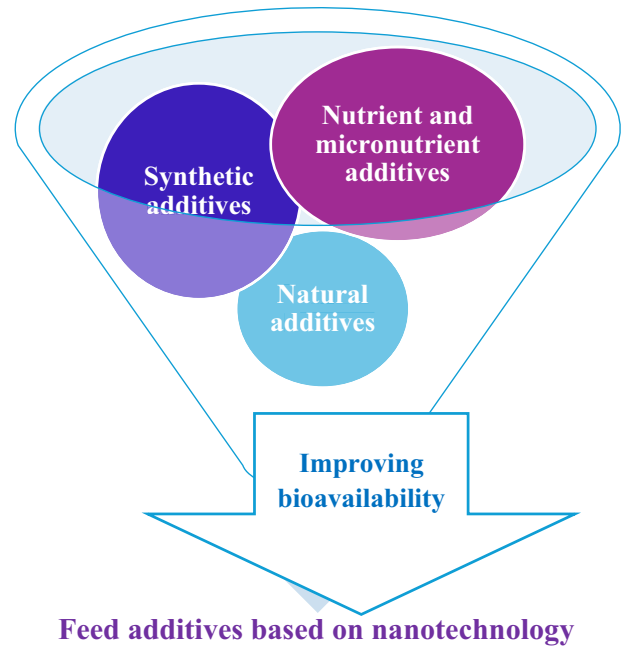


Fig. 11 Schematic representation of the importance of monitoring the improvement of bioavailability of food and pharmaceutical ingredients

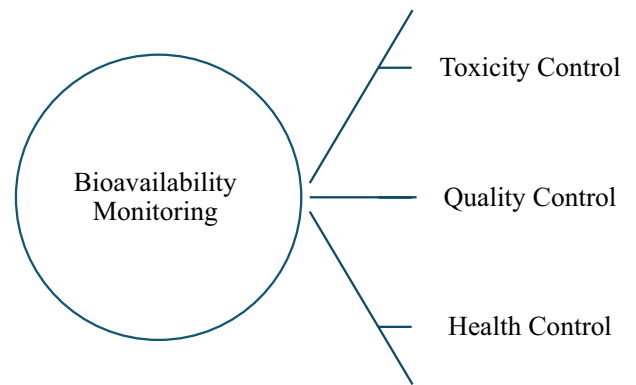
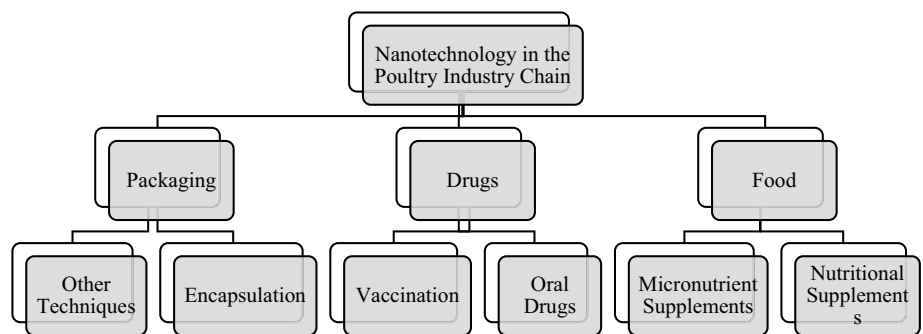


Fig. 12 The role of nanotechnology in the poultry industry



range of ecological receptors, including bacteria, fungi, algae, terrestrial invertebrates, vertebrates, and humans, in terms of assessing the environmental risk profile [172].

However, with the help of nanotechnology, functional foods can be developed as products that go beyond their primary nutritional value. This category of food has additional benefits in the prevention and management of diseases for the consumer by facilitating Access to bioactive compounds, and in other words, the ancient proverb of Hippocrates, who said “let food be the medicine” is realized [173]. Nanotechnology-assisted bioavailability enhancement is a way to deliver important nutritional compounds to biological systems in food applications that can improve consumer health.

Determining the standard dosage of active ingredients to enhance host health and avoid toxicity risks in supplements or drugs based on nanomaterials may have different effects on the body, therefore, regulatory oversight and scientific control should always be a priority (Fig. 11) [171].

Therefore, the use of nanotechnology-based feed additives can have a promising and valuable position in the future perspective of poultry nutrition and this technology, and it is suggested that applied research in this field continue with greater strength and intensity in the future and that support for the development of this sector be increased. If we want to present a schematic framework of the role of nanotechnology in the poultry industry chain, as shown in Fig. 12, the three axes of food, medicine and their packaging can be the goal of nanotechnology practitioners for bread products in the poultry industry.

Enriching the diet simultaneously with improving the availability of micronutrients and active compounds with the help of this technology is such that these food groups can enter the systemic circulation more easily and quickly and subsequently show better performance in organs and tissues.

To provide a consolidated overview of current findings, Table 2 presents nanoparticles in poultry nutrition and compares their reported effects on bioavailability, immune modulation, and zootechnical performance such as feed conversion ratio (FCR) and body weight gain (BWG). This synthesis aims to support clearer evaluation of the current evidence and guide future application and research efforts.

Since many biological components and compounds have little stability in the digestive tract of humans and animals and are affected by digestive fluid, acidity, flora and digestive enzymes, using colloidal drug delivery systems of nanomaterials can help improve the effectiveness of the compounds as expected. As shown in Fig. 11, when using this class of nano compounds, toxicity, quality, and health controls should be carried out [171].

11.1 Potential risks and challenges of using nanoparticles in poultry industry and nutrition

In general, when using nanotechnology in poultry nutrition, giving priority to the welfare and safety of the birds and finally the health of the consumers is necessary and inevitable [13]. Despite the application and potential of this technology, there are still unknown risks due to the creation of unique properties in the nano state. However, nanoparticles cannot be evaluated based on the regulations of new chemicals because the nature and behavior of matter in the nano state can undergo many changes. On the other hand, safety recommendations and nanotechnology methods are not yet sufficient, and, in parallel, many safety assessments in industrial studies are confidential [11].

Every emerging technology will face different perspectives and limitations, and the negative effects of nanoparticles accumulating in the environment, which may lead to environmental toxicity, cannot be ignored [3]. As mentioned, nanotechnology is considered a very promising science with great potential and wide applications in various fields to help human and poultry health [174]. This technology, by controlling the molecular scale of materials, makes them perform differently compared to bulk materials. Important and promising aspects as well as strategic goals of nanotechnology in the poultry industry, in addition to improving bioavailability, reducing the release of materials into the environment, and providing an environmentally friendly approach in the future perspective are considered [174].

Dumlu [13] believes that most of the products produced in this technology with humans, animals or the environment do not interact well. However, there have always been concerns such as the undesirable accumulation of nanomaterials in tissues and potentially unknown environmental effects in nanomaterials, which require extensive and efficient research and detailed tests [175].

Compounds such as gold, silver, zinc oxide, titanium dioxide, silicon dioxide and copper oxide have potentially toxic properties if consumed in excess, and if these sources are used in the form of nanoparticles, there are concerns. It can be aggravated [14]. For example, the use of silver nanoparticles in high doses will lead to serious damage to DNA, disruption in mitochondria, cell death, apoptosis and strengthening the toxic and cytotoxic effects of free radicals. The use of gold nanoparticles in high doses can lead to destruction of the actin cytoskeleton, depolarization of the mitochondrial membrane, and apoptosis. Taking a high dose of titanium dioxide nanoparticles will lead to inflammation, bleeding, oxidative stress, lipid peroxidation, and a decrease in antioxidant capacity. There are numerous reports of negative and adverse effects after consuming high doses of some substances in nano form.

On the other hand, the size of nanoparticles also plays a role in determining their toxicity. In general, smaller diameter nanoparticles are likely to be more dangerous to body cells than larger diameter nanoparticles because smaller particles are more likely to reach intracellular sites such as mitochondria and nucleus [176]. Another concern and danger of using nanomaterials is their potential to mix with other compounds. Of course, the biggest concern is the excessive

Table 2 Comparative summary of different nanoparticles used in poultry nutrition, their impacts, and key references

Nanoparticle	Impact on Bioavailability	Immunomodulatory Effects	Zootechnical Outcomes	Reference	Reference number
Zinc Oxide (ZnONP)	Enhanced zinc absorption and retention	Boosted mucosal and systemic immunity	Improved FCR and BWG; enhanced egg quality	Fawaz et al., (2019); Yusof et al., (2023)	[103, 107]
Selenium NP	Improved selenium uptake and deposition	Stimulated immune enzymes and antibody production	Increased egg production and BW; reduced FCR	Ahmadi et al., (2020); Selim et al., 2015	[111, 117]
Copper NP	Improved absorption and enzymatic support	Increased phagocytic activity and immune profile	Increased BW and protein deposition; improved aminopeptidase activity	Jóźwik et al., (2018); Nguyen et al., (2015)	[126, 127]
Iron NP	Better iron uptake and blood profile	Enhanced hematology and immune markers	Improved egg quality and immune response	Javadifar et al., (2020)	[100]
Chromium Picolinate NP	Efficient low-dose delivery of chromium	Reduced stress-induced immune suppression	Stress mitigation and improved performance	Selim et al., (2015)	[117]
Silver NP	Improved gut delivery and cellular uptake	Enhanced cellular immunity and gut health	Increased lactic acid bacteria and lymphoid organs	Sawosz et al., (2012); Ahmed et al., (2023)	[135, 138]

accumulation of nanoparticles in cellular organs such as the spleen, liver, kidneys, and respiratory system, with the possibility of damaging or causing toxic effects [177, 178].

Despite the available reports on the dangers of nanoparticles, it is recommended that scientific research be followed more carefully, and subsequently, strict regulations and more ethical considerations be provided to ensure the safety and effectiveness of nanotechnology in the nutrition and poultry industry [14]. However, knowing the advantages and disadvantages as well as the risks of using nanotechnology and nanoparticles in various forms in the industry and poultry nutrition is an inevitable necessity so that better solutions can be provided to solve concerns and challenges in the future [179].

The aspects and challenges that this technology poses for researchers include functional expectations, emerging concerns, access to updated information, and research to understand the complex interactions of nanomaterials in nature and living organisms. Adopting preventive management measures and following guidelines to help control potential health risks are essential for the use of nanotechnology in sustainable agriculture [179].

From a perspective, toxicological research should help to define and understand the potential hazards of nanomaterials and the exposure levels and life cycle of nano active products, and to investigate the physicochemical properties affecting toxicity and possible interactions with co-formulations, risk management strategies, and safety policies, as well as to build a consensus on responsible regulatory approaches to nanotechnology in agriculture and the poultry industry [179].

The use of emerging nanotechnology in agriculture and other sectors of the global economy has raised concerns about potential consequences for human health and the environment. Concerns include exposure to residues of nanomaterials in the environment, bioaccumulation in the host, and short- and long-term adverse effects in the environment and the food chain [179].

Therefore, a conceptual approach to create a balanced situation between the advantages and disadvantages of nanoproducts to solve environmental challenges by managing environmental, health, and safety risks throughout the life cycle of the use of nanomaterials in the future life of humans is important. Because this technology has been practically entered into the human life cycle for about two decades, and understanding its long-term effects is still considered a potential challenge.

Due to some unknown properties of nanomaterials in several studies, this category of materials is referred to as xenobiotics. Evaluating the toxicological characteristics of such xenobiotics and ultimately adopting adequate preventive and protective measures to reduce the harmful effects of nanomaterials and the initial biological changes caused by it may be important to understand the relationship between nanomaterial properties and toxicity, and to support this process, risk assessment, monitoring and safety should be considered sufficient and necessary [179].

Modeling toxicological research with the aim of obtaining information on unknown or hazardous behaviors, dose–response relationships, and environmental fate of xenobiotics in the field of nanotechnology is considered a practical solution and will lead to the establishment of an ethical and responsible regulatory consensus on nanomaterials for the confident use of this technology for the future of modern agriculture and the poultry industry [179]. The collection of biological monitoring information is considered an integral tool for the assessment and risk management process in nanotechnology.

A review of the scientific literature shows that sustainable agriculture can use methods that minimize human and environmental harms through early preventive measures to produce nanomaterials and nano-enabled products [179]. It has been shown that established principles of green chemistry can be followed for the design and production of nanomaterials as an innovative approach, avoiding dependence on processes that lead to environmental pollutants and health risks. Therefore, focusing on green nanotechnology on the life cycle can better prepare users to minimize new risks through unintended consequences of nanotechnology [179]. It is hypothesized that the development of *in vitro* and *in vivo* models to screen the impact of property changes on the biological activity of nanomaterials, as well as dose–response relationships and consideration of other aspects such as pH of nanomaterial suspensions and oxidation as potentially modifiable factors in nanomaterial production, will enable the prediction of nanomaterial interactions in different biological environments. In addition, the use of high-throughput screening and assessment techniques to more quickly identify the risks of nanomaterials and investigate the mechanisms of toxicity is effective and helps to develop predictive models for the design of safer products and greener nanotechnology [179]. In general, for nanoparticles, unexpected toxicological effects should always be considered by risk assessors [180]. To this end, for good governance and regulatory framework for nanomaterials, issues such as establishing a definition based on risk assessment and facilitating regulatory and research discussions and exchange of study results, developing analytical and diagnostic tools, estimating toxicity values, evaluating and investigating dose–response relationships, and evaluating standard dose criteria to

facilitate scientific interpretation should be considered [180]. In addition, the frequent use of laboratory approaches for more accurate and realistic risk assessment and the use of various techniques in research are important requirements in assessing the safety of this technology in order to provide the necessary conditions for decision-makers and legislators based on the knowledge and findings collected [180].

Studies and evaluations related to nanotechnology are considered an attractive and valuable research option for researchers because the potential of this technology in solving many human problems and crises in the future is impressive and promising. However, mankind will widely introduce this technology in his life, and the poultry industry is no exception. Currently, the formulation of poultry diets is based on the minimum cost, if nutrients, micronutrients, and bioactive compounds are used in the form of nano technology, the possibility of increasing feed costs will be predicted, and this cost increase will be for the pioneers, and experts of poultry industry are not acceptable. Therefore, efforts should be made to eliminate potential disadvantages, concerns, and challenges in addition to finding the qualitative and quantitative benefits of nanotechnology in the poultry industry. This technology should create conditions that make economic and profitable aspects acceptable and rational for investors, and the poultry industry is no exception to this rule. At the dawn of the nanotechnology revolution in poultry nutrition, whatever step is taken, it is necessary to examine the critical views realistically and with a moderate and rational approach and in accordance with standards compatible with the environment and compliance with ethical issues and welfare, to move this technology forward and successfully in the direction of serving and helping mankind for the future [13, 14].

11.2 Monitoring and concerns legislation for the use of nanotechnology and products

According to reviews, nanotechnology has posed many obstacles, including environmental risks from the release of nanoparticles into the environment, concerns about the health and safety of workers and consumers and their impact on human development, commercial challenges in commercializing nanotechnology-based products, and concerns about the protection of intellectual property rights such as nanomaterials, which have created restrictions on the use of nanomaterials in animal nutrition, and comprehensive and ongoing research is needed to fully understand the long-term implications and potential risks of using nanotechnology-based additives in animal feed [177].

There is currently agreement that in many countries, adequate monitoring of the safety of nanoparticles is still insufficient, and existing legislation is inadequate to assess the risks arising from the use of these materials in food applications because their toxicity risks are largely unknown due to their unique properties. On the other hand, nanoparticles are not assessed as new chemicals under many regulations, and many safety assessments in specialized and industrial studies are confidential, and in fact, there are no consistent international regulations on nanotechnology or nanoproducts [15]. It should be noted that considerations about the ethical implications of nanotechnology in agriculture are involved in the discussion and regulation of ethical and animal welfare guidelines. In order to promote and expand the use of nano-food additives, continued investment in research and development, technological innovation, education and awareness, and sustainable practices should be on the agenda, in collaboration with regulatory agencies, and participatory regulatory actions by industry stakeholders and scientific experts [177–179].

12 Conclusion and future perspective

Nanotechnology is emerging as a powerful tool in precision, sustainable, and modern agriculture. It holds significant potential to become an economic driver in addressing current agricultural and environmental challenges, particularly those related to productivity, sustainability, and food safety.

In the poultry industry, nanotechnology offers promising opportunities—especially in nutrition—to improve feed conversion ratios, enhance health markers, reduce disease incidence, and increase productivity. Other notable applications include improving nutrient bioavailability, modulating immune function and gut microbiota, reducing environmental pollutants, and ultimately boosting poultry product yields for economic gain.

Despite its potential, key challenges remain. These include understanding the behavior of nanoparticles in poultry systems, determining optimal dosing strategies, and evaluating potential toxicity and physiological stress, which are critical to poultry welfare and health.

Addressing these challenges requires targeted, interdisciplinary research. By developing a deeper mechanistic understanding and implementing robust safety evaluations, the poultry sector can responsibly harness nanotechnology's benefits, contributing to sustainable production systems and supporting global food security.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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