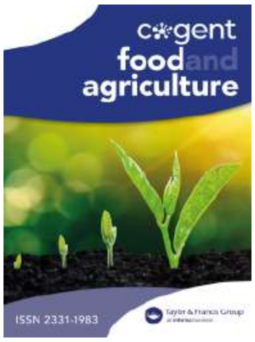

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ANIMAL HUSBANDRY & VETERINARY SCIENCE | REVIEW ARTICLE

Application of nanotechnology in animal nutrition: Bibliographic review

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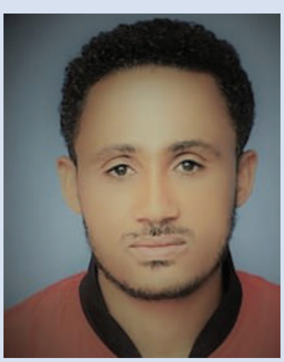
Abstract: Nanotechnology is the science and engineering that involves designing, synthesizing, characterizing, and applying materials in devices and systems for nanometer-scale matter control. This review explores the application of nanotechnology in animal nutrition. Its applications in this field encompass the administration of nutrients, probiotics, and the diagnosis and treatment of diseases through drug delivery. Nanoparticles can be classified into inorganic (*nano-minerals*), organic (*proteins, fat*, and *sugar nanomolecules*), emulsions, dispersions, and nanoclays nanopolymers. The feeding of nanoparticles has demonstrated improvements in digestive efficiency, immunity, milk, meat, and egg quality. Nano-minerals offer low dose usage and improved bioavailability, making them an effective antibiotic alternative and can also be incorporated into natural feed ingredients. Enzyme nanoparticles are protein aggregates that show their unique properties (*optical, electrical*). Nanotechnology is utilized in feed processing to deliver nutrients to target organs through methods like encapsulation, chelating, packing, and nanotubes without altering taste or color. Nanoparticles could be prepared using



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PUBLIC INTEREST STATEMENT

Nanotechnology primarily used in animal nutrition to produce nanominerals, particularly trace elements with limited bioavailability, which reduce intestinal mineral antagonism, excretion, and environmental contamination. Nanotubes are used to detect estradiol antibodies during oestrus, revolutionizing the veterinary and animal science fields by providing in-depth information about organisms' inner bodies. Nanotechnology also improved various aspects of veterinary medicine, including disease detection, treatment, vaccine development, drug administration, and addressing nutrition and reproductive issues. Moreover, nanoparticles can be integrated into smart systems, comprehending medicinal and imaging chemicals and possessing stealth properties by adjusting their size, surface properties, and composition. In general, nanotechnology has the potential to transform agriculture and livestock development through resolving animal health, production, nutrition, reproduction, and hygienic practices and making it a new avenue for the new era.

nanotools in nanotechnique such as precipitation, emulsion cross-linking, spray-drying, emulsion-droplet coalescence, etc. Nanoparticle synthesis is performed by physical (*high-energy ball milling*, *vapor deposition*), chemical methods (*forming colloids*), and biological methods. Despite nanotechnology applications having potential contributions to simplify life and enhance the animal industry in feed, health, and production, the challenges in human, animal, and environmental issues are also stated as the side effects of the technology.

Subjects: Agriculture & Environmental Sciences; Plant & Animal Ecology; Soil Sciences

Keywords: animal feed; nanotechnology; nano-mineral; enzyme nanoparticles

1. Introduction

The term "Nano" stems from the Greek word "nanos" which means "dwarf" and was originally just a prefix substituting the factor of 10^{-9} for SI units (Grunwald, 2017). Nanotechnology involves designing, synthesizing, characterizing, and applying materials for nanoscale control in devices and systems, typically ranging from 1–100 nm (Pundir, 2015). It is a remarkable and rising technology with enormous potential to transform the agriculture and livestock sectors around the world (Marappan et al., 2017). Nanotechnology was developed to reduce the particle size to a couple nanometers in size (Loghman et al., 2012; Ognik et al., 2016). Nanotubes, nanofibres, nanorods, nanoparticles, and thin films have all been studied to identify their characteristics and possible uses (Pundir, 2015). Nanoparticles are the most extensively studied among all nanomaterials. Nano sensors, nanomaterials, microfluidics, and bioanalytical devices are examples of nanotechnology devices employed to enhance animal health, production, reproduction, disease treatment, and prevention (Kroubi et al., 2010; Tarafdar et al., 2013). By improving the production methods, the application of nanotechnology will revolutionize the livestock industry (Fesseha et al., 2020).

Nanotechnology uses in animal nutrition encompass the delivery of vitamins, mineral supplements, probiotics, and drugs, disease detection and treatment (Fesseha et al., 2020). Nanotechnology is used in animal feed in the form of nanominerals, nanoenzymes, as well as additional additives (Fesseha et al., 2020; Marappan et al., 2017; Pundir, 2015). Nanoparticles enhance nutrient absorption by reducing bivalent cations' antagonistic impact, especially in tiny minerals, making them beneficial for livestock and poultry nutrition and improved feed and supplemental utilization (Marappan et al., 2017).

Despite the potential of nanotechnology to simplify life and enhance various aspects of animal industries, including feed, health, and production, the use of nanoparticles is accompanied by challenges in human, animal, and environmental concerns. Hence, this review thoroughly assesses the application of nanotechnology in the field of animal nutrition.

2. Methodology

In the course of performing a literature review, the author employed various strategies. Reputable journals from Scopus, Web of Science, and PubMed databases were utilized for the compilation of this review. Additionally, the inclusion criteria primarily focused on articles published after 2019, with the exception of relevant facts and books.

3. Nano-technology and animal nutrition

3.1. Application of nanotechnology in animal nutrition

The use of various nanoparticles in the administration of medications, nutrition, probiotics, vitamins, and additives is a prime instance of nanotechnology in the feeding of animals (Fesseha et al., 2020; Marappan et al., 2017). Nanoparticles have also been used in poultry feed to reduce the amount of harmful bacteria in the chicken microbiome, while other types of nanoparticles have been proven to increase the growth of beneficial bacteria, hence improving performance as well as growth (Mahmoud, 2012). Employing the microencapsulation enhances the solubility of fat-soluble additives in feed, improve taste, and reduces the need for fat, salt, sugar, and preservatives (Weiss et al., 2010). Nanoparticles exhibit unique transport and uptake characteristics, resulting in increased absorption efficiencies (Zha et al., 2008). Notably, nanoparticles can be ingested directly through feed and water or integrated into feed packaging (Fesseha et al., 2020). Consequently, these nanoparticles have higher bioavailability, a lower dosage rate, and more sustained interactions with other substances.

3.1.1. Nano minerals

Nano-minerals provide low-dose antibiotic alternatives, improve growth, remove residues, reduce pollutants, and produce pollution-free animal products (Hett, 2004; Schmidt, 2009). The size of mineral nanoparticles should be smaller than 100 nanometers, which lets molecules to be taken faster than bigger particle size minerals and meet mineral demands to improve the efficiency of production (King et al., 2018; Tatli Seven et al., 2018; Wen et al., 2006). Furthermore, minerals as nanoparticles minimize intestinal mineral antagonism, lessening excretion and contamination. Although numerous nanominerals find applications in animal nutrition, Table 1 presents some specific examples.

3.2. Types of nano particles

Nanoparticles are reported to be divided into inorganic, organic emulsion, dispersion, and nanoclays as illustrated on Figure 1, based on the chemical characteristics they possess (Al-Beitawi et al., 2017; Bunglavan et al., 2014). Inorganic nanoparticles, including minerals, are used in nutrition, feed, and packaging industries for various applications, including feed packaging, water purification, antimicrobial packaging, and feed storage (Al-Beitawi et al., 2017; Bunglavan et al., 2014). By encapsulating proteins, fat, and sugar, organic nanoparticles improve feed functioning while enhancing nutritional value and bioavailability. They are employed as tiny particles and liposomes within feeds, as well as biosensors, identification markers, shelf-life extenders, and antimicrobials in feed packaging techniques (Ahmadi & Rahimi, 2011). Nano-emulsions, on the contrary, can stabilize and transfer active substances by enclosing the functional feed elements in an oil/water boundary or a continuous state (Agnihotri et al., 2004).

Metals, polymers, natural chemicals, and nanostructured materials are the four areas of nanotechnology (Niemiec et al., 2021). Nanoparticles, a powder form of solid metal, can be utilized in various biotechnical applications by altering their physical characteristics through various engineering methods (Halperin, 1986). These particles have caught the curiosity of medical professionals due to their possible applications in imaging and antiseptic medications that lyse Gram-positive and Gram-negative walls of bacteria (Ramasamy et al., 2016). Certain metal nanoparticles are possibly better suited for external use to prevent buildup in the body, since a particular species might trigger detrimental dose toxicity reactions, although this is not necessarily possible (AshaRani et al., 2009; Kawata et al., 2009; Travan et al., 2009). Metal's non-biodegradability is another major barrier for these particles.

Polymeric nanoparticles are synthesized or fractured into nanoparticle-sized bits that can be grafted onto other materials, potentially increasing biocompatibility and disintegration (Travan et al., 2009). Biocompatibility is highly useful to the medical and feed sectors because it has few to no detrimental effects on patients or customers, and polymeric nanoparticles with dose toxic effects, like metal nanoparticles, would have needed to be addressed (You et al., 2007).

3.3. Nano feed additives and its application in animal nutrition

Nano-additives are reported to be found in protein micelles, capsules, and natural feed ingredients (Khalid & Arif, 2022). Nano-capsules are also mentioned to enhance the bioavailability of essential oils, flavors, antioxidants (Ozogul et al., 2022). Encapsulating nanoparticles were used to protect minerals and micronutrients from oxidation and reducing unpleasant taste (Galanakis, 2019).

Table 1. List of nano-minerals used in animal nutrition

No.	List of nano-minerals and associated attributes	Ref.
1	Manganese nanoparticles enhance chicken growth performance, antioxidant status, and bone attributes without affecting feed intake, weight gain, or efficiency. Mn is described for proper antioxidant and immune system function. Mn is also reported as cofactor of transferases, lyase, hydrolysis, and oxidoreductases, essential for mitochondrial antioxidant system, apoptosis, bone development, and cell structure	Patra and Lalhriatpuii (2020) Palomares (2022) Pasquini et al. (2022).
2	Calcium and phosphorus are crucial for bone growth in animals and poultry. Nano-minerals can improve feed conversion efficiency and body weight gain by 50%, but decrease calcium and phosphorus excretion. Nano-minerals provide low-dose antibiotic possibilities, increase growth, eliminate residues, reduce pollutants, and make pollutant-free animal products. Furthermore, plant-based diets contain substantial amounts of inaccessible P phytates (60–80% of total P), which are not utilized efficiently by chickens due to the absence of phytase enzymes.	Hassan et al. (2016), Samanta et al. (2019) Selle et al. (2009) Baharuddin et al. (2009)
3	Selenium is crucial for development, fertility, immune system, hormone metabolism, cell proliferation, and antioxidant defense. Nano-Se supplementation improves pH, ammonia, fatty acid levels, fertility, sperm quality, and egg production in layer chickens. Nano-Se at 0.3 mg/g dry food was reported to have greater physiological effects in layer chicks. Similarly, purine derivative nutrition utilization and urinary excretion were dramatically enhanced by nano-Se supplementation.	Ghaffarizadeh et al. (2022) Nabi et al. (2020) Shi et al. (2011)
4	Chromium is vital for insulin sensitivity and metabolism in animals. Nanocomposite in pigs reduces glucose, cholesterol, and fatty acid content, while increasing protein and lipoprotein production. Chromium propionate improves egg production and reduces heat exhaustion in poultry. Chromium has been suggested as it promotes insulin sensitivity in cells by activating insulin receptor kinase function. Egg quality, *Cr* persistence in the body, in the eggshell, and levels in the liver has all been observed to improve as a result of Cr-picolinate nanoparticle supplementation.	Bakshi and Panigrahi (2022) Anderson (2003) Hassan et al. (2020)
5	Copper is essential for metabolic activity, physiological functions, immunological responses, connective tissue development, and nerve function. Inorganic *Cu* sulphate and *CuO* nanoparticles improve growth performance, immunity, and reduce inflammatory responses in poultry. Cu nanoparticles included in basal meals decreased intake without influencing laying hen body weight, egg output, mass, or quality. Grill chicken with *Cu* supplementation lowered growth performance but decreased excretion. Through fast absorption, toxicity, and interaction, nano-Cu improves animal production performance.	Rossi et al. (2020) Patra and Lalhriatpuii (2020)
6	Silver nanoparticles in weaned pigs reduce coliform content, pathogen concentration, bacterial counts, growth, antibacterial capability, lymphatic organ weight, newborn weight loss, and liver lesions in grilled meats. A nanosilver feed additive substantially reduces the bacterial count in the digestive tract of poultry, lowering *E. coli*, *Streptococcus*, *Salmonella*, and *mesophilic bacteria*. Nano-silver supplementation of 20, 40, and 60 ppm feeds resulted in a dose-dependent reduction in the weight of the lymphatic organs.	Fondevila et al. (2009) Bhanja and Verma, (2021) Al-Sultan et al. (2022)

(*Continued*)

No.	List of nano-minerals and associated attributes	Ref.
7	Nano-zinc supplementation enhances broiler bird immune status and bioavailability, inhibiting mycotoxic fungi growth and mycotoxins, reducing feed treatment hazards.	Hussan et al. (2022)
8	Iron is crucial for hemoglobin and oxygen transport, while Fe nanoparticles may improve chicken growth, haematology, and immunity. Research on their use is limited, but high doses can cause embryonic growth retardation and nerve damage. *Fe* nanoparticles and *Fe*-sulfate diets in quail breeders did not affect feed intake, egg mass production, quality, fertility, or chick growth.	Scott et al. (2018) Turgud and Narinç (2022)

Liposomal nano vesicles are stated to transport nutrients, enzymes, flavors, and antibacterial agents in food (Pateiro et al., 2021). Proteins and substances are also expressed to encapsulate nano-additives in micelles and oil spheres coated with bipolar molecules (Prasad et al., 2022). These are also stated to be suspended in water or encapsulated in oil, and nano-capsules contain omega-3 fish oil with unpleasant flavor (Liao et al., 2021).

Feed additives are essential raw materials in the modern feed industry, improving nutritional value, animal production efficiency, health, cost reduction, and product quality (Pandey et al., 2019).

3.4. Enzyme nanoparticles (ENPs) and its application in animal nutrition

Enzyme nanoparticles are described as clustered, protein-like structures with 10–100 nm dimensions, offering stability, biocompatibility, conductivity, and sensitivity (Xing et al., 2022). This particles have a variety of characteristics that improve enzyme-based sensor performance by enhancing the surface area (Eivazzadeh-Keihan et al., 2022). Nanoparticles are reported to cause denaturation and function loss due to protein/enzyme binding (Riley et al., 2022). To address this issue, enzyme molecules were aggregated to form nanoparticles and cross-linked within themselves in a regulated manner prior to immobilization (Liu et al., 2022). As a result, a potential technique for biosensor generation with increased analytical performance in terms of detection limit and current response has emerged (Thapa et al., 2022). Enzyme nanoparticles of horseradish peroxidase, glucose, cholesterol, and uricase were characterized for amperometric biosensor construction (Phetsang et al., 2019). Additionally, enzyme nanoparticles are reported to possess high catalytic activity and thermal stability (Khizar et al., 2022). Trypsin and chymotrypsin single enzyme nanoparticles are also stated by researchers (Hegedüs et al., 2020). Furthermore, enzyme nanoparticles are also reported to preserve activity and enhance thermal stability (Liu et al., 2022). Recent studies show that enzyme nanoparticles improve temperature tolerance and cellulose degradation (Gu et al., 2022). Animal feed enzymes break down indiscriminate components in feed products, potentially causing reduced meat or egg production, poor feed efficiency, and digestive issues (Islam et al., 2023).

3.5. Feed processing

Nanoscale particles are reported to have higher surface area, efficient nutrient absorption, and are ultrafine (Mobasser & Firoozi, 2016). Nanotechnology advances functional feed by encapsulating valuable ingredients, preventing loss during processing, and effectively delivering nutrients (Tiwari, 2022). The crucial element in the technology is the inclusion of nano capsules in the feed to deliver nutrients (Fajardo et al., 2022). The 50 nm nano-chelates are reported to efficiently deliver nutrients without affecting feed color or taste (Ahmed et al., 2023).

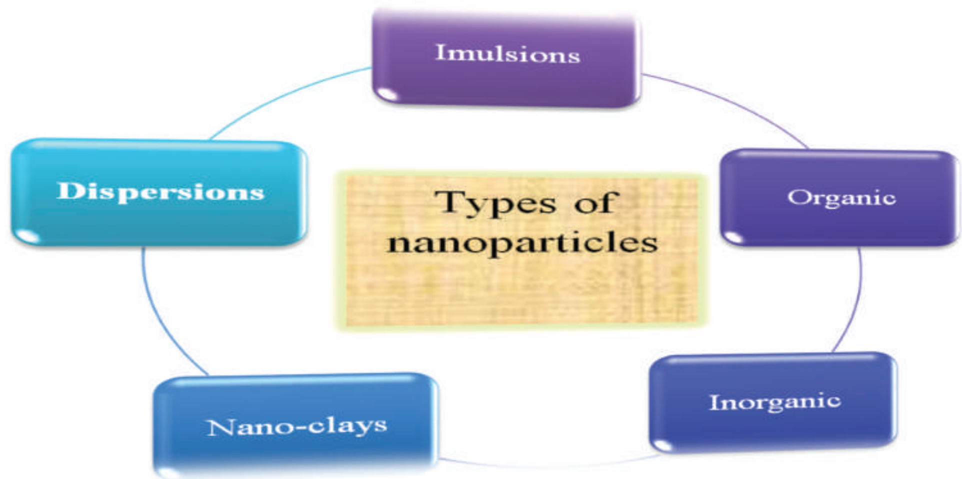

Figure 1. Summary of some types of nano particles.

3.6. Green synthesis

The process that produces nanoparticles from plants is called "green synthesis", and due to the fact that this technique uses plant extracts that contain proteins, carbohydrates, polyphenols, alkaloids, terpenoids, and other substances (Nadaf et al., 2022). Furthermore, the metal ions are stabilized by these molecules, and these plant sources, which were exploited by different researchers to synthesize these nanoparticles are as follows: Geranium (*Pelargonium graveolens*) has been used to produce green nanogold and silver particles from an array of plant resources (Khan et al., 2022), Lemongrass (*Cymbopogon flexuosus*) leaf extracts (Fiore et al., 2022), Camphor tree (*Cinnamommum camphora*) (Lee et al., 2022), neem (*Azadirachta indica*) (Reddy & Neelima, 2022), Aloe barbadensis (*Aloe vera)* (Cuvas-Limón et al., 2022), tamarind (*Tamarindus indica*) (Hasan et al., 2022), Okra (*Abelmoschus esculentus)* (Sarwar et al., 2022), and extracts of Amla fruit (*Emblica officinalis)* (Kaushik et al., 2022; Majeed et al., 2022), oat (*Avena sativa*) (Azevedo et al., 2022), alfalfa (*Medicago sativa*) (Ahmadi et al., 2022), soaked Bengal gram bean (*Cicer arietinum*) (Rizvi et al., 2022) and Concoction (*Piper nigrum)* (Bawazeer et al., 2022). Plants such as alfalfa (*Medicago sativa*) and Chinese mustard (*Brassica juncea)* were used for silver and Ag-Au-Cu alloy nanoparticle synthesis (Song et al., 2022). Lemon extract is reported to be used as a reducing agent for producing manganese acetate, and curcumin serves as a stabilizing agent (Nguyen et al., 2022).

The environmentally friendly synthesis of nanoscale metals involves obtaining a plant extract, combining it with metal salt solution, reducing metallic particles, and performing filtration (Liu et al., 2023). This technique produces various metallic nanoparticles, including green ones, used in cosmetics, pharmaceuticals, appliances, food, aquaculture research, and agricultural goods (Kumar et al., 2023).

3.7. Preparation of enzyme nanoparticles to add in the animal diet

According to reports, enzyme nanoparticles are stated to be prepared through ethanol, glutaraldehyde, and cysteine/cysteamine treatment (Javid et al., 2022). Bovine serum albumin (BSA) proteins were aggregated into nanoparticles to produce soluble proteins through emulsification in plant oil (Taha et al., 2022); desolvation in ethanol or with natural salts, then cross-linking with glutaraldehyde (Li et al., 2008); anhydrous ethanol, glutaraldehyde, and ethanolamine's simple coacervation (Shahidi & Hossain, 2022) and high pressure cross-linking in water and oil emulsion (Li et al., 2022). Nevertheless, so far, ethanol desolvation as well as concomitant glutaraldehyde cross-linking have been used to produce the enzyme nanoparticles (Fuchs et al., 2010).

Nanoparticles exhibit unique physical, chemical, and biological properties compared to larger particles, including material strength, solubility, conductivity, optical properties, thermal behavior, and catalytic activity (Alhashmi Alamer & Beyari, 2022; Khan & Hossain, 2022; Napagoda et al., 2022). In addition, nanoparticles have a larger surface-to-volume ratio as well as a greater number of atoms at the surface, which determine their main attributes (Haase et al., 2022; Joudeh & Linke, 2022). Nanoparticles' structures and characteristics have significantly changed due to larger surface curvatures, more catalytically active sites, and more surface flaws (Lai et al., 2022). When compared to its bulk components, the physical and chemical characteristics of nanoparticles may alter their biological consequences.

Various methods for nanoparticle synthesis, such as physical, chemical, reactive precipitation, sol-gel, microemulsion, sonochemical, and supercritical chemical processing, have been developed and extensively documented in the literature (Prakash et al., 2022).

3.8. Mode of action

These nanoparticles can carry different components in a variety of environmental settings (Brewer et al., 2022). The synthesis of nanoparticles and minerals using this approach provides two notable advantages compared to conventional chemical methods (Kumar et al., 2017). Firstly, nanosized particles play a crucial role in the targeted delivery of nanoparticles because they can more easily traverse capillary walls (Wang et al., 2022). Secondly, as biodegradable ingredients are employed in this process, there is no risk of environmental pollution or chemical accumulation (Tian et al., 2022). According to (Mahdi et al., 2022) and (Alavi et al., 2022), nanoparticles increase biological interactions, extend compound residence time, reduce intestinal clearance, penetrate tissues, cross epithelial linings, and enable efficient uptake and delivery of active compounds. Nanoparticles used for developing nanostructured materials are created from a variety of sources, including naturally occurring substances like lipid- and protein-based nanoparticles (Harish et al., 2022). Nanoparticles can encapsulate and adhere to functional groups, acting as carriers for medications and nutrients (Mushtaq et al., 2022; Zhu et al., 2022). Nature-derived nanomaterials can appear to be a safer option, but if they are not carefully developed or dispersed properly in a biological system, they could cause hazardous or immunogenic reactions (Song et al., 2022).

3.9. Effect of inclusion nanoparticles on animal feed

3.9.1. Nutrient absorption and utilization

Natural or artificial nutrient nanoparticles can help cells absorb bioactive chemicals and stabilize them (Awuchi et al., 2022). A bioactive ingredient can be added directly to feed, but doing so includes a risk of deterioration and unavailability that can be avoided by using nanotechnology (Sagar et al., 2022). Although they can more easily pass through the intestinal mucosa due to their smaller size than microparticles, nanoparticles have a higher level of bioavailability than microparticles, especially in the digestive tract (Yun et al., 2013). By encapsulating nano particles with natural nanonutrients and artificial nanoparticles like casein, it is typically possible for them to bypass the body's normal physiological pathways for nutrient transport via cell membranes and distribution in tissues (Das et al., 2023). To enable transmission from mother to child, some casein isoforms group together around calcium, protein, vitamin *D*, and other nutrients (Nadugala et al., 2022). The advantages of nanonutritional supplements may also help weaning animals and fowl grow larger. Previous studies by (Jia et al., 2018)) and (Wang et al., 2022) indicated that in mice and turkey, calcium nanoparticles produced denser bone when compared to microcalcium, respectively. By improving the bioavailability of the nutrient payload, nanoparticles designed for nutrient delivery could facilitate this supplementation and boost animal growth rates (Gopi & Balakrishnan, 2022). Due to their small particle size and large surface area in the intestinal lumen, nanoparticles often have better absorption (Kumari & Chauhan, 2022).

Nanotechnology revolutionizes animal production, breeding, disease treatment, and identity preservation, transforming medicine delivery methods and disease diagnosis (Prabha et al., 2022). Scientific research has been primarily focused on developing effective vaccines and utilizing nanoparticle technology in animal reproductive. Nanotechnology has significantly improved various aspects of veterinary medicine, including disease detection, treatment, vaccine development, drug administration, and addressing nutrition and reproductive issues (Poddar & Kishore, 2022). Ruminants can benefit from microminerals for improved digestion, metabolism, microbiota balance, and reproductive success.

3.9.2. Meat and egg quality

In addition, it has been explored whether utilizing nanoparticles could improve the quality of meat and eggs. For example (Poddar & Kishore, 2022), demonstrated that Chromium nanoparticles (200 g/kg) were fed to Finish pigs, and they were 14.06% slimmer at slaughter than the control pigs. Chitosan nanoparticles are also reported to improve pigs' skeletal muscle mass and meat quality by lowering fatty acid synthase activity (Xiong et al., 2022). The incorporation of nanomaterials to animal feed or water can improve both the final product's quality and the process of production, such as the quality of broiler meat, egg yolks, and eggshells (Dong et al., 2022). Concentration of nanoparticles makes sure that despite prolonged exposure, quality is not compromised (Mortensen et al., 2022). Consumers are likely to still favour meat and eggs made from animals fed nanoparticle supplements if they are improved or indistinguishable from the original product (Bhagat & Singh, 2022). Nevertheless, before using the nanoparticle additive in animal production, it is crucial to understand the role of the additive in a specific biological system and the byproducts from that system to make sure it is safe for consumption (Dupuis et al., 2022).

3.9.3. Milk production and quality

By developing new methods for identifying foodborne pathogens and shortening the time needed for drug withdrawal, nanotechnology can also assist and ensure that milk is of a quality that is safe for human consumption (Shenashen et al., 2022). Low levels of tilmicosin extend the half-life of the mastitis pathogen in mouse blood serum by employing hydrogenated castor oil-solid lipid nanoparticle carriers (Kareem et al., 2022). Nano-composites using *anti-S. Aureus* antibodies, gold nanoparticles, and magnetic nanoparticles can detect the presence of bacteria in milk in just forty minutes (Sung et al., 2013). These nanocomposites have an intriguing attribute in the antibody, whose selectivity and specificity may be altered to capture a range of diseases (Ozkan-Ariksoysal, 2022). Toxins in milk can be found utilizing polyclonal antibodies and gold nanoparticle immune chromatographic strips within 10 minutes (using the cancer-causing aflatoxin M_1) (Rastogi et al., 2022). While removing potentially dangerous pollutants from milk has received most of the attention, adding supplements containing nanoparticles directly to cow's milk for human consumption has generated some interest (Abdelnour et al., 2021). Comprising oyster shell nano powder in milk is reported to raise the calcium concentration from 100 to 120 mg/mL, and the level is better suited for growing youngsters and postmenopausal women (Abdelnour et al., 2021). After 16 days of storage at 4°C, adding calcium from nanopowdered oyster shell to milk did not have a negative impact on its sensory or physicochemical properties (Lee et al., 2015).

3.9.4. Immune responses of the gastrointestinal tract (GIT)

Innate defenses, acting as barriers, are present in the gut-associated lymphoid tissue (*GALT*) aggregates of the gastrointestinal tract (*GIT*) (Madakka et al., 2020). The interpretation of nano particle ingestion studies is influenced by the biological and physicochemical characteristics of the *GIT* (Mittag et al., 2022). The biological effects of a particle are influenced by factors such as size, surface area, number, aggregation/agglomeration state, charge, and surface coatings (Fubini et al., 2010). The proposal suggests a set of minimal specifications for nanomaterial characterization for toxicological investigations (Cebadero-Domínguez et al., 2022). Factors such as particle size, distribution, aggregation state, form, chemical composition, surface area, purity, and stability are some of the key considerations (Bergin & Witzmann, 2013). Absorption and biological responses are also impacted by oxidant production and rate of breakdown (Sun et al., 2022). In *vivo* experiments can introduce significant heterogeneity due to species, strains, diet, housing, dosage time, circadian rhythms, and endogenous microbiome (Lecour et al., 2022). Careful reporting of these factors can help to increase transparency and make it easier to reconcile inconsistent results between studies (Liu et al., 2022). The Metabolomics Standards Initiative and arrive guidelines aim to standardize metadata for *in vivo* experiment parameters in particle toxicity studies (Sumner et al., 2007).

The gastrointestinal system, one of the largest immunological organs in the body, typically accounts for up to 70% of an animal's immune response activity (Choct, 2009). The performance of animals is significantly influenced by a healthy gut. Thus, the performance of trace mineral dietary supplements and effective management can help achieve this goal (Sampath et al., 2023).

3.10. Side effects of nanoparticles

Nanoparticles are reported to increase bioavailability risk, inflammatory gastrointestinal diseases, altered nutrient bioavailability, and potential effects during heating or storage (Elnahal et al., 2022). Linking experimental nanoparticle toxicity to real-world human health risks is challenging due to the lack of precise environmental information (Bergin & Witzmann, 2013). It is especially challenging to extrapolate results from *in vivo* toxicity studies' higher shorter-term doses to the expected consequences of chronic, minimum dose exposures (Doe et al., 2006). According to review done by (Yip et al., 2022) consuming nanoparticles appeared to have low toxicity for *in vivo* tests. No side effects were noted for silver nanoparticles at levels lower than 125 mg/kg (Yan et al., 2022). Up to 5,000 mg/kg of TiO_2 nanoparticles were also reported to be tolerated without any negative effects (Javed et al., 2022). In vitro studies show cytotoxicity and increased membrane permeability, while *in vivo* studies show no effects except at high doses (Wang et al., 2021).

4. Challenges and limitations of nanotechnology

Nanotechnology advances disease detection, prevention, and treatment in animals, despite potential toxic side effects (Zain et al., 2022). It is possible that exposure to artificial nanoparticles will have different consequences than exposure to naturally occurring nanoparticles (Kessler, 2011). Because of their size or protective coatings, engineered nanoparticles are stated to be better to avoid the body's defenses (Liu & Huang, 2022).

Since nanoparticles are often incorporated in finished goods, they rarely come into touch with people, animals, or the environment (Hemathilake & Gunathilake, 2022). Nanotechnologies face an array of challenges, including risks to the environment from the release of nanoparticles into the environment, risks to human health and safety (for both workers and consumers), risks related to the self-replication of nanomachines and human enhancement, risks to business from the marketing of nanotechnology-enabled products, and risks related to the protection of intellectual property (Chaturvedi et al., 2022). Additional research is also required on the hazards to human health, for the animal health and the environment brought on by exposure to manmade nanoparticles (Liu et al., 2022).

5. Review gaps and future lines of work

In the coming years, nanotechnology research is poised to revolutionize the realms of animal nutrition, health, and production. With its profound influence on various aspects of human life, nanotechnology is considered an impressive tool in contemporary society. A notable area of progress in nanomedicine is the utilization of nanoparticles for the prevention, diagnosis, and treatment of complex diseases such as cancer. The field of nanotechnology in animal production is evolving and offering the potential to enhance livestock feed. Nevertheless, the substitution of antibiotics in feed will necessitate time due to the imperative processes of *in vivo* testing and adherence to regulatory requirements.

6. Conclusions and recommendations

In conclusion, nanotechnology presents a promising avenue for enhancing the development of livestock and poultry by improving aspects such as health, feed components, additives, feed processing, food safety, and quality control, with a notable focus on mineral nanoparticles in current research. However, there is a notable gap in the exploration of other nutrients at the nanoscale level. A potential alternative to the chemical synthesis of nanoparticles is the biological method, showing promise in terms of effectiveness and biosafety to prevent harm to animals, humans, and environmental ecosystems. Nevertheless, further extensive research is imperative to fully understand and ensure the efficacy and safety of this approach.

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References

Abdelnour, S. A., Alagawany, M., Hashem, N. M., Farag, M. R., Alghamdi, E. S., Hassan, F. U., Bilal, R. M., Elnesr, S. S., Dawood, M. A., Nagadi, S. A., Elwan, H. A. M., ALmasoudi, A. G., & Attia, Y. A. (2021). Nanominerals: Fabrication methods, benefits and hazards, and their applications in ruminants with special reference to selenium and zinc nanoparticles. *Animals*, *11*(7), 1916. https://doi.org/10.3390/ani11071916

Agnihotri, S. A., Mallikarjuna, N. N., & Aminabhavi, T. M. (2004). Recent advances on chitosan-based micro-and nanoparticles in drug delivery. *Journal of Controlled Release*, *100*(1), 5–28. https://doi.org/10.1016/j.jconrel.2004.08.010

Ahmadi, F., & Rahimi, F. (2011). The effect of different levels of nano silver on performance and retention of silver in edible tissues of broilers. *World Applied Sciences Journal*, *12*, 1–4. https://www.semanticscholar.org/paper/The-effect-of-different-levels-of-Nano-Silver-on-of-Ahmadi-Rahimi/00c0b57beed4df0c7fc54aa5fa54df197ae43390

Ahmadi, A., Shahidi, S.-A., Safari, R., Motamedzadegan, A., & Ghorbani-HasanSaraei, A. (2022). Evaluation of stability and antibacterial properties of extracted chlorophyll from alfalfa (*medicago sativa* L.). *Food and Chemical Toxicology*, *163*, 112980. https://doi.org/10.1016/j.fct.2022.112980

Ahmed, J., Vasagam, K. K., & Ramalingam, K. (2023). Nanoencapsulated Aquafeeds and Current uses in Fisheries/Shrimps: A review. *Applied Biochemistry and Biotechnology*, *195*(11), 7110–7131. https://doi.org/10.1007/s12010-023-04418-9

Alavi, M., Kamarasu, P., McClements, D. J., & Moore, M. D. (2022). Metal and metal oxide-based antiviral nanoparticles: Properties, mechanisms of action, and applications. *Advances in Colloid and Interface Science*, *102726*, 102726. https://www.sciencedirect.com/science/article/abs/pii/S0001868622001282. https://doi.org/10.1016/j.cis.2022.102726

Al-Beitawi, N. A., Momani Shaker, M., El-Shuraydeh, K. N., & Bláha, J. (2017). Effect of nanoclay minerals on growth performance, internal organs and blood biochemistry of broiler chickens compared to vaccines and antibiotics. *Journal of Applied Animal Research*, *45*(1), 543–549. https://doi.org/10.1080/09712119.2016.1221827

Alhashmi Alamer, F., & Beyari, R. F. (2022). Overview of the influence of silver, gold, and titanium nanoparticles on the physical properties of PEDOT: PSS-coated cotton fabrics. *Nanomaterials*, *12*(9), 1609. https://doi.org/10.3390/nano12091609

Al-Sultan, S. I., Hereba, A. R. T., Hassanein, K. M., Abd-Allah, S. M., Mahmoud, U. T., & Abdel-Raheem, S. M. (2022). The impact of dietary inclusion of silver nanoparticles on growth performance, intestinal morphology, caecal microflora, carcass traits and blood parameters of broiler chickens. *Italian Journal of Animal Science*, *21*(1), 967–978. https://doi.org/10.1080/1828051X.2022.2083528

Anderson, R. A. (2003). Chromium and insulin resistance. *Nutrition Research Reviews*, *16*(2), 267–275. https://doi.org/10.1079/NRR200366

AshaRani, P., Low Kah Mun, G., Hande, M. P., & Valiyaveettil, S. (2009). Cytotoxicity and genotoxicity of silver nanoparticles in human cells. *Agricultural Science & Technology Nano*, *3*(2), 279–290. https://doi.org/10.1021/nn800596w

Awuchi, C. G., Morya, S., Dendegh, T. A., Okpala, C. O. R., & Korzeniowska, M. (2022). Nanoencapsulation of food bioactive constituents and its associated processes: A revisit. *Bioresource Technology Reports*, *19*, 101088. https://www.sciencedirect.com/science/article/abs/pii/S2589014X22001451. https://doi.org/10.1016/j.biteb.2022.101088

Azevedo, C. F., Nascimento, M., Carvalho, I. R., Nascimento, A. C. C., de Almeida, H. C. F., Cruz, C. D., & da Silva, J. A. G. (2022). Updated knowledge in the estimation of genetics parameters: A Bayesian approach in white oat (*Avena sativa* L.). *Euphytica*, *218*(4), 43. https://doi.org/10.1007/s10681-022-02995-0

Baharuddin, A. S., Wakisaka, M., Shirai, Y., Abd-Aziz, S., Abdul, R., & Hassan, M. (2009). Co-composting of empty fruit bunches and partially treated palm oil mill effluents in pilot scale. *International Journal of Agricultural Research*, *4*(2), 69–78. https://doi.org/10.3923/ijar.2009.69.78

Bakshi, A., & Panigrahi, A. K. (2022). Chromium contamination in soil and its bioremediation: An overview. *Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation*, 229–248. https://doi.org/10.1007/978-3-030-89984-4_15

Bawazeer, S., Khan, I., Rauf, A., Aljohani, A. S., Alhumaydhi, F. A., Khalil, A. A., Qureshi, M. N., Ahmad, L., & Khan, S. A. (2022). Black pepper (*Piper* *nigrum*) fruit-based gold nanoparticles (BP-AuNPs): Synthesis, characterization, biological activities, and catalytic applications–A green approach. *Green Processing and Synthesis*, *11*(1), 11–28. https://doi.org/10.1515/gps-2022-0002

Bergin, I. L., & Witzmann, F. A. (2013). Nanoparticle toxicity by the gastrointestinal route: Evidence and knowledge gaps. *International Journal of Biomedical Nanoscience and Nanotechnology*, *3*(1/2), 163–210. https://doi.org/10.1504/IJBNN.2013.054515

Bhagat, S., & Singh, S. (2022). Nanominerals in nutrition: Recent developments, present burning issues and future perspectives. *Food Research International*, *160*, 111703. https://doi.org/10.1016/j.foodres.2022.111703

Bhanja, S., & Verma, S. (2021). Prospects of nano minerals in poultry nutrition. *Indian Journal of Poultry Science*, *56*(1), 1–8. https://doi.org/10.5958/0974-8180.2021.00006.4

Brewer, A., Dror, I., & Berkowitz, B. (2022). Electronic waste as a source of rare earth element pollution: Leaching, transport in porous media, and the effects of nanoparticles. *Chemosphere*, *287*, 132217. https://doi.org/10.1016/j.chemosphere.2021.132217

Bunglavan, S. J., Garg, A., Dass, R., & Shrivastava, S. (2014). Use of nanoparticles as feed additives to improve digestion and absorption in livestock. *Livestock Research International*, *2*(3), 36–47. https://d1wqtxts1xzle7.cloudfront.net/82068395/5-lriArticle_1-libre.pdf?1647111564=&response-content-disposition=inline%3B+filename%3DUse_of_nanoparticles_as_feed_additives_t.pdf&Expires=1702366214&Signature=AJ-ixko7-2RRDI5IopYvo~R5lc9xGhdJVrFCKaZCNDE1C1YriptIjfF07aISIDBd0TachoTw8F3LZ8ckiZVobT9zT-N–NpN~3PXqB6Z0Z83UkmAOglJMtOElTQndydpqtMdPpl4ipudzGnAfG2g6fs8CFXgfslcJAsP08V8tebDyUTR19BuHeSCh6LTPxtU9Z2CuvMitUOGVQphznfortuGnVL1InEnnAd6vqg9JMewGktB~joUsT1wbbdE2vBecKv8b0iHP15SA1bff5X3f-9oelujbUSi5fql13ZhYCOALJ0CH77yu8QMkt~rLAEA-i0vMmEdKirn-0kouobWKQ__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Cebadero-Domínguez, Ó., Jos, A., Cameán, A. M., & Cătunescu, G. M. (2022). Hazard characterization of graphene nanomaterials in the frame of their food risk assessment: A review. *Food & Chemical Toxicology*, *164*, 113014. https://www.sciencedirect.com/science/article/pii/S0278691522002125. https://doi.org/10.1016/j.fct.2022.113014

Chaturvedi, R., Sharma, A., Sharma, K., & Saraswat, M. (2022). Nanotech Science as well as its multifunctional implementations. *Recent Trends in Industrial and Production Engineering: Select Proceedings of ICCEMME*, *2021*, 217–228. https://link.springer.com/chapter/10.1007/978-981-16-3330-0_18

Choct, M. (2009). Managing gut health through nutrition. *British Poultry Science*, *50*(1), 9–15. https://doi.org/10.1080/00071660802538632

Cuvas-Limón, R. B., Ferreira-Santos, P., Cruz, M., Teixeira, J. A., Belmares, R., & Nobre, C. (2022). Novel bio-functional aloe vera beverages fermented by probiotic enterococcus faecium and lactobacillus lactis. *Molecules*, *27*(8), 2473. https://doi.org/10.3390/molecules27082473

Das, A., Adhikari, S., Deka, D., Baildya, N., Sahare, P., Banerjee, A., Paul, S., Bisgin, A., & Pathak, S. (2023). An updated review on the role of nanoformulated phytochemicals in colorectal cancer. *Medicina*, *59*(4), 685. https://doi.org/10.3390/medicina59040685

Doe, J. E., Boobis, A. R., Blacker, A., Dellarco, V., Doerrer, N. G., Franklin, C., Goodman, J. I., Kronenberg, J. M., Lewis, R., McConnell, E. E., Mercier, T., Moretto, A., Nolan, C., Padilla, S., Phang, W., Solecki, R., Tilbury, L., van Ravenzwaay, B., & Wolf, D. C. (2006). A tiered approach to systemic toxicity testing for agricultural chemical safety assessment. *Critical Reviews in Toxicology*, *36*(1), 37–68. https://doi.org/10.1080/10408440500534370

Dong, Y., Zhang, K., Han, M., Miao, Z., Liu, C., & Li, J. (2022). Low level of dietary organic trace minerals improved egg quality and modulated the status of eggshell gland and intestinal microflora of laying hens during the late production stage. *Frontiers in Veterinary Science*, *9*, 920418. https://doi.org/10.3389/fvets.2022.920418

Dupuis, V., Cerbu, C., Witkowski, L., Potarniche, A.-V., Timar, M. C., Żychska, M., & Sabliov, C. M. (2022). Nanodelivery of essential oils as efficient tools against antimicrobial resistance: A review of the type and physical-chemical properties of the delivery systems and applications. *Drug Delivery*, *29*(1), 1007–1024. https://doi.org/10.1080/10717544.2022.2056663

Eivazzadeh-Keihan, R., Noruzi, E. B., Chidar, E., Jafari, M., Davoodi, F., Kashtiaray, A., Gorab, M. G., Hashemi, S. M., Javanshir, S., & Cohan, R. A. (2022). Applications of carbon-based conductive nanomaterials in biosensors. *Chemical Engineering Journal*, *442*, 136183. https://doi.org/10.1016/j.cej.2022.136183

Elnahal, A. S., El-Saadony, M. T., Saad, A. M., Desoky, E.-S. M., El-Tahan, A. M., Rady, M. M., AbuQamar, S. F., & El-Tarabily, K. A. (2022). The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review. *European Journal of Plant Pathology*, *162*(4), 759–792. https://doi.org/10.1007/s10658-021-02393-7

Fajardo, C., Martinez-Rodriguez, G., Blasco, J., Mancera, J. M., Thomas, B., & De Donato, M. (2022). Nanotechnology in aquaculture: Applications, perspectives and regulatory challenges. *Aquaculture and Fisheries*, *7*(2), 185–200. https://doi.org/10.1016/j.aaf.2021.12.006

Fesseha, H., Degu, T., & Getachew, Y. (2020). Nanotechnology and its application in animal production: A review. *Veterinary Medicine – Open Journal*, *5*(2), 43–50. https://doi.org/10.17140/VMOJ-5-148

Fiore, V., Badagliacco, D., Sanfilippo, C., Pirrone, R., Siengchin, S., Rangappa, S. M., & Botta, L. (2022). Lemongrass plant as potential sources of reinforcement for biocomposites: A preliminary experimental comparison between leaf and culm fibers. *Journal of Polymers and the Environment*, *30*(11), 4726–4737. https://doi.org/10.1007/s10924-022-02545-8

Fondevila, M., Herrer, R., Casallas, M., Abecia, L., & Ducha, J. (2009). Silver nanoparticles as a potential antimicrobial additive for weaned pigs. *Animal Feed Science and Technology*, *150*(3–4), 259–269. https://doi.org/10.1016/j.anifeedsci.2008.09.003

Fubini, B., Ghiazza, M., & Fenoglio, I. (2010). Physico-chemical features of engineered nanoparticles relevant to their toxicity. *Nanotoxicology*, *4*(4), 347–363. https://doi.org/10.3109/17435390.2010.509519

Fuchs, S., Kutscher, M., Hertel, T., Winter, G., Pietzsch, M., & Coester, C. (2010). Transglutaminase: new insights into gelatin nanoparticle cross-linking. *Journal of Microencapsulation*, *27*(8), 747–754. https://doi.org/10.3109/02652048.2010.518773

Galanakis, C. M. (2019). *Trends in non-alcoholic beverages academic press*. Book, 2020. https://www.sciencedir ect.com/book/9780128169384/trends-in-non-alcoholic-beverages#book-info

Ghaffarizadeh, A., Sotoudeh, E., Mozanzadeh, M. T., Sanati, A. M., & Ghasemi, A. (2022). Supplementing dietary selenium nano-particles increased growth, antioxidant capacity and immune-related genes transcription in Pacific whiteleg shrimp (*Penaeus vannamei*) juveniles. *Aquaculture Reports*, *25*, 101215. https://doi.org/10.1016/j.aqrep.2022.101215

Gopi, S., & Balakrishnan, P. (2022). *Handbook of Nutraceuticals and natural*. Products Wiley Online Library.

Grunwald, P. (2017). *Biocatalysis and nanotechnology CRC press*. ISBN: 978-1-119-74683-6. https://www.wiley.com/en-us/Handbook+of+Nutraceuticals+and+Natural+Products%2C+2+Volume+Set-p-9781119746836.

Gu, Y., Yuan, L., Li, M., Wang, X., Rao, D., Bai, X., Shi, K., Xu, H., Hou, S., & Yao, H. (2022). Co-immobilized bienzyme of horseradish peroxidase and glucose oxidase on dopamine-modified cellulose–chitosan composite beads as a high-efficiency biocatalyst for degradation of acridine. *RSC Advances*, *12*(35), 23006–23016. https://doi.org/10.1039/D2RA04091C

Haase, F. T., Bergmann, A., Jones, T. E., Timoshenko, J., Herzog, A., Jeon, H. S., Rettenmaier, C., & Cuenya, B. R. (2022). Size effects and active state formation of cobalt oxide nanoparticles during the oxygen evolution reaction. *Nature Energy*, *7*(8), 765–773. https://doi.org/10.1038/s41560-022-01083-w

Halperin, F. W. (1986). Quantum size effects in metal particles. *Reviews of Modern Physics*, *58*(3), 533. https://doi.org/10.1103/RevModPhys.58.533

Harish, V., Tewari, D., Gaur, M., Yadav, A. B., Swaroop, S., Bechelany, M., & Barhoum, A. (2022). Review on nanoparticles and nanostructured materials: Bioimaging, biosensing, drug delivery, tissue engineering, antimicrobial, and agro-food applications. *Nanomaterials*, *12*(3), 457. https://doi.org/10.3390/nano12030457

Hasan, M. N., Chand, N., Naz, S., Khan, R. U., Ayaşan, T., Laudadio, V., & Tufarelli, V. (2022). Mitigating heat stress in broilers by dietary dried tamarind (Tamarindus indica L.) pulp: Effect on growth and blood traits, oxidative status and immune response. *Livestock Science*, *264*, 105075. https://doi.org/10.1016/j.livsci.2022.105075

Hassan, M., Ding, W., Shi, Z., & Zhao, S. (2016). Methane enhancement through co-digestion of chicken manure and thermo-oxidative cleaved wheat straw with waste activated sludge: AC/N optimization case. *Bioresource Technology*, *211*, 534–541. https://doi.org/10.1016/j.biortech.2016.03.148

Hassan, S., Hassan, F.-U., & Rehman, M. S.-U. (2020). Nano-particles of trace minerals in poultry nutrition: Potential applications and future prospects. *Biological Trace Element Research*, *195*(2), 591–612. https://doi.org/10.1007/s12011-019-01862-9

Hegedüs, I., Vitai, M., Jakab, M., & Nagy, E. (2020). Study of prepared α-chymotrypsin as enzyme nanoparticles and of biocatalytic membrane reactor. *Catalysts*, *10*(12), 1454. https://doi.org/10.3390/catal10121454

Hemathilake, D., & Gunathilake, D. (2022). *Agricultural productivity and food supply to meet increased demands, future foods*. Elsevier.

Hett, A. (2004). Nanotechnology: Small matter, many unknowns. Swiss re, https://www.nanowerk.com/nanotechnology/reports/reportpdf/report93.pdf.

Hussan, F., Krishna, D., Preetam, V. C., Reddy, P., & Gurram, S. (2022). Dietary supplementation of nano zinc oxide on performance, carcass, serum and meat quality parameters of commercial broilers. *Biological Trace Element Research*, *200*(1), 348–353. https://doi.org/10.1007/s12011-021-02635-z

Islam, M. R., Martinez-Soto, C. E., Lin, J. T., Khursigara, C. M., Barbut, S., & Anany, H. (2023). A systematic review from basics to omics on bacteriophage applications in poultry production and processing. *Critical Reviews in Food Science and Nutrition*, *63*(18), 3097–3129. https://doi.org/10.1080/10408398.2021.1984200

Javed, R., Ain, N. U., Gul, A., Arslan Ahmad, M., Guo, W., Ao, Q., & Tian, S. (2022). Diverse biotechnological applications of multifunctional titanium dioxide nanoparticles: An up-to-date review. *IET Nanobiotechnology*, *16*(5), 171–189. https://doi.org/10.1049/nbt2.12085

Javid, A., Amiri, H., Kafrani, A. T., & Rismani-Yazdi, H. (2022). Post-hydrolysis of cellulose oligomers by cellulase immobilized on chitosan-grafted magnetic nanoparticles: A key stage of butanol production from waste textile. *International Journal of Biological Macromolecules*, *207*, 324–332. https://doi.org/10.1016/j.ijbiomac.2022.03.013

Jia, J., Ahmed, I., Liu, L., Liu, Y., Xu, Z., Duan, X., Li, Q., Dou, T., Gu, D., Rong, H., Wang, K., Li, Z., Talpur, M. Z., Huang, Y., Wang, S., Yan, S., Tong, H., Zhao, S. … Su, Z. (2018). Selection for growth rate and body size have altered the expression profiles of somatotropic axis genes in chickens. *PLoS One*, *13*(4), e0195378. https://doi.org/10.1371/journal.pone.0195378

Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *Journal of Nanobiotechnology*, *20*(1), 262. https://doi.org/10.1186/s12951-022-01477-8

Kareem, E. H., Dawood, T. N., & Al-Samarai, F. R. (2022). Application of nanoparticle in the Veterinary medicine. *Magna Scientia Advanced Research and Reviews*, *4*(1), 027–038. https://doi.org/10.30574/msarr.2022.4.1.0082

Kaushik, J., Yadav, M., Sharma, N., Jindal, D. K., Joshi, K., Dahiya, M., & Deep, A. (2022). Phytochemical analysis and in vitro evidence of antimalarial, antibacterial, antifungal, antioxidant and anti-inflammatory activities of ethanol extract of Emblica officinalis fruit. *Anti-Infective Agents*, *20*(4), 70–79. https://doi.org/10.2174/2211352520666220318091023

Kawata, K., Osawa, M., & Okabe, S. (2009). In vitro toxicity of silver nanoparticles at noncytotoxic doses to HepG2 human hepatoma cells. *Environmental Science & Technology*, *43*(15), 6046–6051. https://doi.org/10.1021/es900754q

Kessler, R. (2011). *Engineered nanoparticles in consumer products: Understanding a new ingredient*. National Institute of Environmental Health Sciences. https://doi.org/10.1289/ehp.119-a120

Khalid, M. Y., & Arif, Z. U. (2022). Novel biopolymer-based sustainable composites for food packaging applications: A narrative review. *Food Packaging and Shelf Life*, *33*, 100892. https://doi.org/10.1016/j.fpsl.2022.100892

Khan, S., & Hossain, M. K. (2022). *Classification and properties of nanoparticles, nanoparticle-based polymer composites*. Elsevier.

Khan, F., Shariq, M., Asif, M., Siddiqui, M. A., Malan, P., & Ahmad, F. (2022). Green nanotechnology: Plant-mediated nanoparticle synthesis and application. *Nanomaterials*, *12*(4), 673. https://doi.org/10.3390/nano12040673

Khizar, S., Elaissari, A., Al-Dossary, A. A., Zine, N., Jaffrezic-Renault, N., & Errachid, A. (2022). Advancement in nanoparticle-based biosensors for point-of-care in vitro diagnostics. *Current Topics in Medicinal Chemistry*, *22*(10), 807–833. https://doi.org/10.2174/1568026622666220401160121

King, T., Osmond McLeod, M. J., & Duffy, L. L. (2018). Nanotechnology in the food sector and potential applications for the poultry industry. *Trends in Food Science & Technology*, *72*, 62–73. https://doi.org/10.1016/j.tifs.2017.11.015

Kroubi, M., Daulouede, S., Karembe, H., Jallouli, Y., Howsam, M., Mossalayi, D., Vincendeau, P., & Betbeder, D. (2010). Development of a nanoparticulate formulation of diminazene to treat African trypanosomiasis. *Nanotechnology*, *21*(50), 505102. https://doi.org/10.1088/0957-4484/21/50/505102

Kumari, A., & Chauhan, A. K. (2022). Iron nanoparticles as a promising compound for food fortification in iron deficiency anemia: A review. *Journal of Food Science and Technology*, *59*(9), 3319–3335. https://doi.org/10.1007/s13197-021-05184-4

Kumar, A., Shah, S. R., Jayeoye, T. J., Kumar, A., Parihar, A., Prajapati, B., Singh, S., & Kapoor, D. U. (2023). Biogenic metallic nanoparticles: Biomedical, analytical, food preservation, and applications in other consumable products. *Frontiers in Nanotechnology*, *5*, 1175149. https://doi.org/10.3389/fnano.2023.1175149

Kumar, P., Singh, P., Kumar, D., Prakash, V., Hussain, M., & Das, A. (2017). A novel application of micro-EDM process for the generation of nickel nanoparticles with different shapes. *Materials and Manufacturing Processes*, *32*(5), 564–572. https://doi.org/10.1080/10426914.2016.1244832

Lai, W., Ma, Z., Zhang, J., Yuan, Y., Qiao, Y., & Huang, H. (2022). Dynamic evolution of active sites in electrocatalytic CO2 reduction reaction: Fundamental understanding and recent progress. *Advanced Functional Materials*, *32*(16), 2111193. https://doi.org/10.1002/adfm.202111193

Lecour, S., Du Pré, B. C., Bøtker, H. E., Brundel, B. J., Daiber, A., Davidson, S. M., Ferdinandy, P., Girao, H., Gollmann-Tepeköylü, C., Gyöngyösi, M., Hausenloy, D. J., Madonna, R., Marber, M., Perrino, C., Pesce, M., Schulz, R., Sluijter, J. P. G., Steffens, S. ... Young, M. E. (2022). Circadian rhythms in ischaemic heart disease: Key aspects for preclinical and translational research: Position paper of the ESC working group on cellular biology of the heart. *Cardiovascular Research*, *118*(12), 2566–2581. https://doi.org/10.1093/cvr/cvab293

Lee, Y., Ahn, S., Chang, Y., & Kwak, H. (2015). Physicochemical and sensory properties of milk supplemented with dispersible nanopowdered oyster shell during storage. *Journal of Dairy Science*, *98*(9), 5841–5849. https://doi.org/10.3168/jds.2014-9105

Lee, S.-H., Kim, D.-S., Park, S.-H., & Park, H. (2022). Phytochemistry and applications of Cinnamomum camphora essential oils. *Molecules*, *27*(9), 2695. https://doi.org/10.3390/molecules27092695

Liao, W., Badri, W., Dumas, E., Ghnimi, S., Elaissari, A., Saurel, R., & Gharsallaoui, A. (2021). Nanoencapsulation of essential oils as natural food antimicrobial agents: An overview. *Applied Sciences*, *11*(13), 5778. https://doi.org/10.3390/app11135778

Li, J., Fu, J., Ma, Y., He, Y., Fu, R., Qayum, A., Jiang, Z., & Wang, L. (2022). Low temperature extrusion promotes transglutaminase cross-linking of whey protein isolate and enhances its emulsifying properties and water holding capacity. *Food Hydrocolloids*, *125*, 107410. https://doi.org/10.1016/j.foodhyd.2021.107410

Li, F.-Q., Su, H., Wang, J., Liu, J.-Y., Zhu, Q.-G., Fei, Y.-B., Pan, Y.-H., & Hu, J.-H. (2008). Preparation and characterization of sodium ferulate entrapped bovine serum albumin nanoparticles for liver targeting. *International Journal of Pharmaceutics*, *349*(1–2), 274–282. https://doi.org/10.1016/j.ijpharm.2007.08.001

Liu, A. A., Henin, S., Abbaspoor, S., Bragin, A., Buffalo, E. A., Farrell, J. S., Foster, D. J., Frank, L. M., Gedankien, T., Gotman, J., Guidera, J. A., Hoffman, K. L., Jacobs, J., Kahana, M. J., Li, L., Liao, Z., Lin, J. J., Losonczy, A. & Zugaro, M. (2022). A consensus statement on detection of hippocampal sharp wave ripples and differentiation from other fast oscillations. *Nature Communications*, *13*(1), 6000. https://doi.org/10.1038/s41467-022-33536-x

Liu, W., & Huang, Y. (2022). Cell membrane-engineered nanoparticles for cancer therapy. *Journal of Materials Chemistry B*, *10*(37), 7161–7172. https://doi.org/10.1039/D2TB00709F

Liu, X., Hu, Y., Wei, B., Liu, F., Xu, H., Liu, C., Li, Y., & Liang, H. (2022). Immobilized glucosyltransferase and sucrose synthase on Fe3O4@ uio-66 in cascade catalysis for the one-pot conversion of rebaudioside D from rebaudioside a. *Process Biochemistry*, *118*, 323–334. https://doi.org/10.1016/j.procbio.2022.05.004

Liu, L., Li, Y., AL-Huqail, A. A., Ali, E., Alkhalifah, T., Alturise, F., & Ali, H. E. (2023). Green synthesis of Fe3O4 nanoparticles using Alliaceae waste (*allium sativum*) for a sustainable landscape enhancement using support vector regression. *Chemosphere*, *334*, 138638. https://doi.org/10.1016/j.chemosphere.2023.138638

Liu, F., Wei, B., Cheng, L., Zhao, Y., Liu, X., Yuan, Q., & Liang, H. (2022). Co-immobilizing two glycosidases based on cross-Linked enzyme aggregates to enhance enzymatic properties for achieving high titer icaritin biosynthesis. *Journal of Agricultural and Food Chemistry*, *70*(37), 11631–11642. https://doi.org/10.1021/acs.jafc.2c04253

Liu, W., Worms, I. A., Jakšić, Ž., & Slaveykova, V. I. (2022). Aquatic organisms modulate the bioreactivity of engineered nanoparticles: Focus on biomolecular corona. *Frontiers in Toxicology*, *4*, 933186. https://doi.org/10.3389/ftox.2022.933186

Loghman, A., Iraj, S. H., Naghi, D. A., & Pejman, M. (2012). Histopathologic and apoptotic effect of nanosilver in liver of broiler chickens. *African Journal of Biotechnology*, *11*(22), 6207–6211. https://doi.org/10.5897/AJB11.1768

Madakka, M., Rajesh, N., & Rajeswari, J. (2020). Immunocomposition of gastrointestinal tract of gut. *Immunotherapy for Gastrointestinal Malignancies*, 17–39. https://link.springer.com/chapter/10.1007/978-981-15-6487-1_2

Mahdi, M. A., Yousefi, S. R., Jasim, L. S., & Salavati-Niasari, M. (2022). Green synthesis of DyBa2Fe3O7. 988/DyFeO3 nanocomposites using almond extract with dual eco-friendly applications: Photocatalytic and antibacterial activities. *International Journal of Hydrogen Energy*, *47*(31), 14319–14330. https://doi.org/10.1016/j.ijhydene.2022.02.175

Mahmoud, U. T. (2012). Silver nanoparticles in poultry production. *Journal of Advanced Veterinary Research*, *2*(4), 303–306. https://advetresearch.com/index.php/AVR/article/view/202

Majeed, M., Mundkur, L., Paulose, S., & Nagabhushanam, K. (2022). Novel emblica officinalis extract containing β-glucogallin vs. metformin: A randomized, open-label, comparative efficacy study in newly diagnosed type 2 diabetes mellitus patients with dyslipidemia. *Food & Function*, *13*(18), 9523–9531. https://doi.org/10.1039/D2FO01862D

Marappan, G., Beulah, P., Kumar, R. D., Muthuvel, S., & Govindasamy, P. (2017). Role of nanoparticles in animal and poultry nutrition: Modes of action and applications in formulating feed additives and food processing. *International Journal of Pharmacology*, *13*(7), 724–731. https://doi.org/10.3923/ijp.2017.724.731

Mittag, A., Singer, A., Hoera, C., Westermann, M., Kämpfe, A., & Glei, M. (2022). Impact of in vitro digested zinc oxide nanoparticles on intestinal model systems. *Particle and Fibre Toxicology*, *19*(1), 1–15. https://doi.org/10.1186/s12989-022-00479-6

Mobasser, S., & Firoozi, A. A. (2016). Review of nanotechnology applications in science and engineering. *Journal of Civil Engineering Urban*, *6*, 84–93. https://www.researchgate.net/profile/Shariat-Mobasser/publication/318752748_Review_of_Nanotechnology_Applications_in_Science_and_Engineering/links/597b4b6a4585151e35c0c379/Review-of-Nanotechnology-Applications-in-Science-and-Engineering.pdf

Mortensen, N. P., Pathmasiri, W., Snyder, R. W., Caffaro, M. M., Watson, S. L., Patel, P. R., Beeravalli, L., Prattipati, S., Aravamudhan, S., & Sumner, S. J. (2022). Oral administration of *TiO2* nanoparticles during early life impacts cardiac and neurobehavioral performance and metabolite profile in an age- and sex-related manner. *Particle and Fibre Toxicology*, *19*(1), 1–18. https://doi.org/10.1186/s12989-021-00444-9

Mushtaq, F., Raza, Z. A., Batool, S. R., Zahid, M., Onder, O. C., Rafique, A., & Nazeer, M. A. (2022). Preparation, properties, and applications of gelatin-based hydrogels (GHs) in the environmental, technological, and biomedical sectors. *International Journal of Biological Macromolecules*, *218*, 601–633. https://doi.org/10.1016/j.ijbiomac.2022.07.168

Nabi, F., Arain, M., Hassan, F., Umar, M., Rajput, N., Alagawany, M., Syed, S., Soomro, J., Somroo, F., & Liu, J. (2020). Nutraceutical role of selenium nanoparticles in poultry nutrition: a review. *World's Poultry Science Journal*, *76*, 459–471. https://doi.org/10.1080/00439339.2020.1789535

Nadaf, S. J., Jadhav, N. R., Naikwadi, H. S., Savekar, P. L., Sapkal, I. D., Kambli, M. M., & Desai, I. A. (2022). Green synthesis of gold and silver nanoparticles: Updates on research, patents, and future prospects. *OpenNano*, *8*, 100076. https://www.sciencedirect.com/science/article/pii/S235295202200038X. https://doi.org/10.1016/j.onano.2022.100076

Nadugala, B. H., Pagel, C. N., Raynes, J. K., Ranadheera, C., & Logan, A. (2022). The effect of casein genetic variants, glycosylation and phosphorylation on bovine milk protein structure, technological properties, nutrition and product manufacture. *International Dairy Journal*, *133*, 105440. https://doi.org/10.1016/j.idairyj.2022.105440

Napagoda, M., Jayathunga, D., & Witharana, S. (2022). *Introduction to nanotechnology, nanotechnology in modern medicine*. Springer.

Nguyen, N. T. T., Nguyen, L. M., Nguyen, T. T. T., Liew, R. K., Nguyen, D. T. C., & Van Tran, T. (2022). Recent advances on botanical biosynthesis of nanoparticles for catalytic, water treatment and agricultural applications: A review. *Science of the Total Environment*, *827*, 154160. https://www.sciencedirect.com/science/article/abs/pii/S0048969722012529. https://doi.org/10.1016/j.scitotenv.2022.154160

Niemiec, T., Łozicki, A., Pietrasik, R., Pawęta, S., Rygało-Galewska, A., Matusiewicz, M., & Zglińska, K. (2021). Impact of ag nanoparticles (*AgNPs*) and multimicrobial preparation (EM) on the carcass, mineral, and fatty acid composition of Cornu aspersum aspersum snails. *Animals*, *11*(7), 1926. https://doi.org/10.3390/ani11071926

Ognik, K., Stępniowska, A., Cholewińska, E., & Kozłowski, K. (2016). The effect of administration of copper nanoparticles to chickens in drinking water on estimated intestinal absorption of iron, zinc, and calcium. *Poultry Science*, *95*(9), 2045–2051. https://doi.org/10.3382/ps/pew200

Ozkan-Ariksoysal, D. (2022). Current perspectives in graphene oxide-based electrochemical biosensors for cancer diagnostics. *Biosensors*, *12*(8), 607. https://doi.org/10.3390/bios12080607

Ozogul, Y., Karsli, G. T., Durmuş, M., Yazgan, H., Oztop, H. M., McClements, D. J., & Ozogul, F. (2022). Recent developments in industrial applications of nanoemulsions. *Advances in Colloid and Interface Science*, *304*, 102685. https://www.sciencedirect.com/science/article/abs/pii/S0001868622000872. https://doi.org/10.1016/j.cis.2022.102685

Palomares, R. A. (2022). Trace minerals supplementation with Great Impact on Beef Cattle immunity and health. *Animals*, *12*(20), 2839. https://doi.org/10.3390/ani12202839

Pandey, A. K., Kumar, P., & Saxena, M. (2019). Feed additives in animal health. *Nutraceuticals in Veterinary Medicine*, 345–362. https://link.springer.com/chapter/10.1007/978-3-030-04624-8_23

Pasquini, M., Grosjean, N., Hixson, K. K., Nicora, C. D., Yee, E. F., Lipton, M., Blaby, I. K., Haley, J. D., & Blaby-Haas, C. E. (2022). Zng1 is a GTP-dependent zinc transferase needed for activation of methionine aminopeptidase. *Cell Reports*, *39*(7), 110834. https://doi.org/10.1016/j.celrep.2022.110834

Pateiro, M., Gómez, B., Munekata, P. E., Barba, F. J., Putnik, P., Kovačević, D. B., & Lorenzo, J. M. (2021). Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality and the appearance of the final food products. *Molecules*, *26*(6), 1547. https://doi.org/10.3390/molecules26061547

Patra, A., & Lalhriatpuii, M. (2020). Progress and prospect of essential mineral nanoparticles in poultry nutrition and feeding—A review. *Biological Trace Element Research*, *197*(1), 233–253. https://doi.org/10.1007/s12011-019-01959-1

Phetsang, S., Jakmunee, J., Mungkornasawakul, P., Laocharoensuk, R., & Ounnunkad, K. (2019). Sensitive amperometric biosensors for detection of glucose and cholesterol using a platinum/reduced graphene oxide/poly (*3-aminobenzoic acid*) film-modified screen-printed carbon electrode. *Bioelectrochemistry*, *127*, 125–135. https://doi.org/10.1016/j.bioelechem.2019.01.008

Poddar, K., & Kishore, A. V. (2022). *Nanotechnology in animal production, emerging issues in climate smart livestock production*. Elsevier.

Prabha, A. S., Thangakani, J. A., Devi, N. R., Dorothy, R., Nguyen, T. A., Kumaran, S. S., & Rajendran, S. (2022). *Nanotechnology and sustainable agriculture*. Nanosensors for Smart Agriculture, Elsevier.

Prakash, M., Kavitha, H. P., Abinaya, S., Vennila, J. P., & Lohita, D. (2022). Green synthesis of bismuth based nanoparticles and its applications-A review. *Sustainable Chemistry and Pharmacy*, *25*, 100547. https://doi.org/10.1016/j.scp.2021.100547

Prasad, R. D., Sahoo, A., Shrivastav, O. P., Charmode, N., Kamat, R., Kajave, N., Chauhan, J., Banga, S., Tamboli, U., & MS, P. (2022). A review on aspects of nanotechnology in food science and animal nutrition. *ES Food & Agroforestry*, *8*, 12–46.

Pundir, C. (2015). *Enzyme nanoparticles Preparation, characterisation, properties and applications, micro-nano technologies series, Elsevier*. Book. https://www.sciencedirect.com/book/9780323389136/enzyme-nanoparticles

Ramasamy, M., Kim, S., Lee, S. S., & Yi, D. K. (2016). Recyclable photo-thermal nano-aggregates of magnetic nanoparticle conjugated gold nanorods for effective pathogenic bacteria lysis. *Journal of Nanoscience and Nanotechnology*, *16*(1), 555–561. https://doi.org/10.1166/jnn.2016.10603

Rastogi, S., Kumari, V., Sharma, V., & Ahmad, F. (2022). Gold nanoparticle-based sensors in food safety applications. *Food Analytical Methods*, 1–17. https://link.springer.com/article/10.1007/s12161-021-02131-z

Reddy, I., & Neelima, P. (2022). Neem (*Azadirachta indica*): A review on medicinal Kalpavriksha. *International Journal of Economic Plants*, *9*(1), 59–63. https://doi.org/10.23910/2/2021.0437d

Riley, M. B., Strandquist, E., Weitzel, C. S., & Driskell, J. D. (2022). Structure and activity of native and thiolated α-chymotrypsin adsorbed onto gold nanoparticles. *Colloids and Surfaces B: Biointerfaces*, *220*, 112867. https://doi.org/10.1016/j.colsurfb.2022.112867

Rizvi, N. B., Aleem, S., Khan, M. R., Ashraf, S., & Busquets, R. (2022). Quantitative estimation of protein in sprouts of Vigna radiate (*mung Beans*), lens culinaris (*Lentils*), and Cicer arietinum (*Chickpeas*) by Kjeldahl and Lowry methods. *Molecules*, *27*(3), 814. https://doi.org/10.3390/molecules27030814

Rossi, B., Toschi, A., Piva, A., & Grilli, E. (2020). Single components of botanicals and nature-identical compounds as a non-antibiotic strategy to ameliorate health status and improve performance in poultry and pigs. *Nutrition Research Reviews*, *33*(2), 218–234. https://doi.org/10.1017/S0954422420000013

Sagar, N. A., Kumar, N., Choudhary, R., Bajpai, V. K., Cao, H., Shukla, S., & Pareek, S. (2022). Prospecting the role of nanotechnology in extending the shelf-life of fresh produce and in developing advanced packaging. *Food Packaging and Shelf Life*, *34*, 100955. https://doi.org/10.1016/j.fpsl.2022.100955

Samanta, G., Mishra, S., Behura, N., Sahoo, G., Behera, K., Swain, R., Sethy, K., Biswal, S., & Sahoo, N. (2019). Studies on utilization of calcium phosphate nano particles as source of phosphorus in broilers. *Animal Nutrition and Feed Technology*, *19*(1), 77–88. https://doi.org/10.5958/0974-181X.2019.00008.8

Sampath, V., Sureshkumar, S., Seok, W. J., & Kim, I. H. (2023). Role and functions of micro and macro-minerals in swine nutrition: A short review. *Journal of Animal Science and Technology*, *65*(3), 479. https://doi.org/10.5187/jast.2023.e9

Sarwar, S., Akram, N. A., Saleem, M. H., Zafar, S., Alghanem, S. M., Abualreesh, M. H., Alatawi, A., Ali, S., & Sarker, U. (2022). Spatial variations in the biochemical potential of okra [*abelmoschus esculentus* L.(*Moench*)] leaf and fruit under field conditions. *PLoS One*, *17*(2), e0259520. https://doi.org/10.1371/journal.pone.0259520

Schmidt, C. W. (2009). Nanotechnology-related environment, health, and safety research: Examining the national strategy. *National Institute of Environmental Health Sciences*, *117*(4), A158–A161. https://doi.org/10.1289/ehp.117-a158

Scott, A., Vadalasetty, K., Łukasiewicz, M., Jaworski, S., Wierzbicki, M., Chwalibog, A., & Sawosz, E. (2018, February). Effect of different levels of copper nanoparticles and copper sulphate on performance, metabolism and blood biochemical profiles in broiler chicken. *Journal of Animal Physiology and Animal Nutrition*, *102*(1), e364–e373. https://doi.org/10.1111/jpn.12754

Selle, P. H., Cowieson, A. J., & Ravindran, V. (2009). Consequences of calcium interactions with phytate and phytase for poultry and pigs. *Livestock Science*, *124*(1–3), 126–141. https://doi.org/10.1016/j.livsci.2009.01.006

Shahidi, F., & Hossain, A. (2022). Preservation of aquatic food using edible films and coatings containing essential oils: A review. *Critical Reviews in Food Science and Nutrition*, *62*(1), 66–105. https://doi.org/10.1080/10408398.2020.1812048

Shenashen, M. A., Emran, M. Y., El Sabagh, A., Selim, M. M., Elmarakbi, A., & El-Safty, S. A. (2022). Progress in sensory devices of pesticides, pathogens, coronavirus, and chemical additives and hazards in food assessment: Food safety concerns. *Progress in Materials Science*, *124*, 100866. https://doi.org/10.1016/j.pmatsci.2021.100866

Shi, L., Xun, W., Yue, W., Zhang, C., Ren, Y., Liu, Q., Wang, Q., & Shi, L. (2011). Effect of elemental nano-selenium on feed digestibility, rumen fermentation, and purine derivatives in sheep. *Animal Feed Science and Technology*, *163*(2–4), 136–142. https://doi.org/10.1016/j.anifeedsci.2010.10.016

Song, M., Cui, M., Fang, Z., & Liu, K. (2022). Advanced research on extracellular vesicles based oral drug delivery systems. *Journal of Controlled Release*, *351*, 560–572. https://doi.org/10.1016/j.jconrel.2022.09.043

Song, X., Fang, C., Yuan, Z.-Q., Li, F.-M., Sardans, J., & Penuelas, J. (2022). Long-term alfalfa (*Medicago sativa* L.) establishment could alleviate phosphorus limitation induced by nitrogen deposition in the carbonate soil. *Journal of Environmental Management*, *324*, 116346. https://doi.org/10.1016/j.jenvman.2022.116346

Sumner, L. W., Amberg, A., Barrett, D., Beale, M. H., Beger, R., Daykin, C. A., Fan, T. W.-M., Fiehn, O., Goodacre, R., Griffin, J. L., Hankemeier, T., Hardy, N., Harnly, J., Higashi, R., Kopka, J., Lane, A. N., Lindon, J. C., Marriott, P. & Thaden, J. J. (2007). Proposed minimum reporting standards for chemical analysis: Chemical analysis working group (*CAWG*) metabolomics standards initiative (*MSI*). *Metabolomics*, *3*(3), 211–221. https://doi.org/10.1007/s11306-007-0082-2

Sung, Y. J., Suk, H.-J., Sung, H. Y., Li, T., Poo, H., & Kim, M.-G. (2013). Novel antibody/gold nanoparticle/magnetic nanoparticle nanocomposites for immunomagnetic separation and rapid colorimetric detection of Staphylococcus aureus in milk. *Biosensors and Bioelectronics*, *43*, 432–439. https://doi.org/10.1016/j.bios.2012.12.052

Sun, Y., Kinsela, A. S., Cen, X., Sun, S., Collins, R. N., Cliff, D. I., Wu, Y., & Waite, T. D. (2022). Impact of reactive iron in coal mine dust on oxidant generation and epithelial lung cell viability. *Science of the Total Environment*, *810*, 152277. https://doi.org/10.1016/j.scitotenv.2021.152277

Taha, A., Casanova, F., Šimonis, P., Jonikaitė-Švėgždienė, J., Jurkūnas, M., Gomaa, M. A., & Stirkė, A. (2022). Pulsed electric field-assisted glycation of bovine serum albumin/starch conjugates improved their emulsifying properties. *Innovative Food Science & Emerging Technologies*, *82*, 103190. https://doi.org/10.1016/j.ifset.2022.103190

Tarafdar, J., Sharma, S., & Raliya, R. (2013). Nanotechnology: Interdisciplinary science of applications. *African Journal of Biotechnology*, *12*(3), 219–226. https://doi.org/10.5897/AJB12.2481

Tatli Seven, P., Seven, I., Gul Baykalir, B., Iflazoglu Mutlu, S., & Salem, A. Z. (2018). Nanotechnology and nano-propolis in animal production and health: An overview. *Italian Journal of Animal Science*, *17*(4), 921–930. https://doi.org/10.1080/1828051X.2018.1448726

Thapa, K., Liu, W., & Wang, R. (2022). Nucleic acid-based electrochemical biosensor: Recent advances in probe immobilization and signal amplification strategies. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, *14*(1), e1765. https://doi.org/10.1002/wnan.1765

Tian, L., van Putten, R. J., & Gruter, G. J. M. (2022). Plastic pollution. The role of (bio) degradable plastics and other solutions. *Biodegradable Polymers in the Circular Plastics Economy*, 59–81. https://doi.org/10.1002/9783527827589.ch3

Tiwari, P. (2022). *Nanotechnologies and sustainable Agriculture for food and nutraceutical production: An update, plant and nanoparticles*. Springer.

Travan, A., Pelillo, C., Donati, I., Marsich, E., Benincasa, M., Scarpa, T., Semeraro, S., Turco, G., Gennaro, R., & Paoletti, S. (2009). Non-cytotoxic silver nanoparticle-polysaccharide nanocomposites with antimicrobial activity. *Biomacromolecules*, *10*(6), 1429–1435. https://doi.org/10.1021/bm900039x

Turgud, F. K., & Narinç, D. (2022). Influences of dietary supplementation with Maca (*Lepidium meyenii*) on performance, parameters of growth curve and carcass characteristics in Japanese quail. *Animals*, *12*(3), 318. https://doi.org/10.3390/ani12030318

Wang, L., Mello, D. F., Zucker, R. M., Rivera, N. A., Rogers, N. M., Geitner, N. K., Boyes, W. K., Wiesner, M. R., Hsu-Kim, H., & Meyer, J. N. (2021). Lack of detectable direct effects of silver and silver nanoparticles on mitochondria in mouse hepatocytes. *Environmental Science & Technology*, *55*(16), 11166–11175. https://doi.org/10.1021/acs.est.1c02295

Wang, B., Wang, H., Li, Y., & Song, L. (2022). Lipid metabolism within the bone micro-environment is closely associated with bone metabolism in physiological and pathophysiological stages. *Lipids in Health and Disease*, *21*(1), 1–14. https://doi.org/10.1186/s12944-021-01615-5

Wang, M., Zhao, J., Jiang, H., & Wang, X. (2022). Tumor-targeted nano-delivery system of therapeutic RNA. *Materials Horizons*, *9*(4), 1111–1140. https://doi.org/10.1039/D1MH01969D

Weiss, J., Gibis, M., Schuh, V., & Salminen, H. (2010). Advances in ingredient and processing systems for meat and meat products. *Meat Science*, *86*(1), 196–213. https://doi.org/10.1016/j.meatsci.2010.05.008

Wen, H.-W., DeCory, T. R., Borejsza-Wysocki, W., & Durst, R. A. (2006). Investigation of NeutrAvidin-tagged liposomal nanovesicles as universal detection reagents for bioanalytical assays. *Talanta*, *68*(4), 1264–1272. https://doi.org/10.1016/j.talanta.2005.07.032

Xing, Y., Dorey, A., Jayasinghe, L., & Howorka, S. (2022). Highly shape-and size-tunable membrane nanopores made with DNA. *Nature Nanotechnology*, *17*(7), 708–713. https://doi.org/10.1038/s41565-022-01116-1

Xiong, R.-G., Zhou, D.-D., Wu, S.-X., Huang, S.-Y., Saimaiti, A., Yang, Z.-J., Shang, A., Zhao, C.-N., Gan, R.-Y., & Li, H.-B. (2022). Health benefits and side effects of short-chain fatty acids. *Foods*, *11*(18), 2863. https://doi.org/10.3390/foods11182863

Yan, X., Pan, Z., Chen, S., Shi, N., Bai, T., Dong, L., Zhou, D., White, J. C., & Zhao, L. (2022). Rice exposure to silver nanoparticles in a life cycle study: Effect of dose responses on grain metabolomic profile, yield, and soil bacteria. *Environmental Science: Nano*, *9*(6), 2195–2206. https://doi.org/10.1039/D2EN00211F

Yip, Y. J., Lee, S. S. C., Neo, M. L., Teo, S. L.-M., & Valiyaveettil, S. (2022). A comparative investigation of toxicity of three polymer nanoparticles on acorn barnacle (*amphibalanus amphitrite*). *Science of the Total Environment*, *806*, 150965. https://doi.org/10.1016/j.scitotenv.2021.150965

You, C.-C., Miranda, O. R., Gider, B., Ghosh, P. S., Kim, I.-B., Erdogan, B., Krovi, S. A., Bunz, U. H., & Rotello, V. M. (2007). Detection and identification of proteins using nanoparticle–fluorescent polymer 'chemical nose'-sensors. *Nature Nanotechnology*, *2*(5), 318–323. https://doi.org/10.1038/nnano.2007.99

Yun, Y., Cho, Y. W., & Park, K. (2013). Nanoparticles for oral delivery: Targeted nanoparticles with peptidic ligands for oral protein delivery. *Advanced Drug Delivery Reviews*, *65*(6), 822–832. https://doi.org/10.1016/j.addr.2012.10.007

Zain, M., Yasmeen, H., Yadav, S. S., Amir, S., Bilal, M., Shahid, A., & Khurshid, M. (2022). *Applications of nanotechnology in biological systems and medicine, nanotechnology for hematology, blood transfusion, and artificial blood*. Elsevier.

Zha, L. Y., Xu, Z. R., Wang, M. Q., & Gu, L. Y. (2008). Chromium nanoparticle exhibits higher absorption efficiency than chromium picolinate and chromium chloride in Caco-2 cell monolayers. *Journal of Animal Physiology and Animal Nutrition*, *92*(2), 131–140. https://doi.org/10.1111/j.1439-0396.2007.00718.x

Zhu, J., Zhang, Z., Wang, R., Zhong, K., Zhang, K., Zhang, N., Liu, W., Feng, F., & Qu, W. (2022). Review of natural phytochemical-based self-assembled nanostructures for applications in medicine. *Acs Applied Nano Materials*, *5*(3), 3146–3169. https://doi.org/10.1021/acsanm.2c00056