

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693

ISSN Online: 2617-4707

NAAS Rating (2026): 5.29

IJABR 2026; 10(4): 711-716

www.biochemjournal.com

Received: 27-02-2026

Accepted: 30-03-2026

Salem Lallawmawmi

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Arup Kumar Samanta

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Zosangpuui

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Lalrinkima

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Banita Pator

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Pintu Saha

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Neng Thianlala

Department of Management,
Mizoram University, Tanhril,
Mizoram, India

Corresponding Author:

Salem Lallawmawmi

Department of Animal Nutrition,
College of Veterinary Sciences &
Animal Husbandry, Central
Agricultural University, Selesih,
Mizoram, India

Nanotechnology and its intervention in animal nutrition: A review

Salem Lallawmawmi, Arup Kumar Samanta, Zosangpuui, Lalrinkima, Banita Pator, Pintu Saha and Neng Thianlala

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i4j.8272>

Abstract

Nanotechnology has emerged as a transformative and innovative approach in animal nutrition, providing new strategies to enhance feed efficiency, nutrient bioavailability, and livestock productivity. Nanoparticles, particularly nano-minerals, possess unique physicochemical properties such as increased surface area, enhanced reactivity, improved solubility, and better interaction with biological systems compared to conventional feed additives. These properties facilitate improved digestion, absorption, and utilization of nutrients, thereby enhancing animal performance and reducing environmental pollution caused by nutrient excretion.

Recent advancements have demonstrated that nanotechnology can be effectively utilized in feed processing, nutrient delivery systems, disease control, and product quality improvement. However, despite its numerous advantages, concerns regarding toxicity, biosafety, and regulatory frameworks remain critical. This review provides a comprehensive discussion on the principles of nanotechnology, types and synthesis of nanoparticles, mechanisms of action, and their applications in animal nutrition, along with recent experimental findings and future prospects.

Keywords: Nanoparticles, nano-minerals, bioavailability, animal nutrition

Introduction

Nanotechnology refers to the science and engineering of materials at the nanoscale (1-100 nm), where materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts (Gelaye, 2024) ^[1]. The concept was first introduced by Richard Feynman in 1959 and later termed "nanotechnology" by Norio Taniguchi in 1974. It is an advanced and rapidly emerging field with significant potential to transform agriculture and livestock sectors worldwide (Marappan *et al.*, 2017) ^[2]. This technology focuses on reducing materials to extremely small particle sizes, often down to a few nanometers (Loghman *et al.*, 2012; Ognik *et al.*, 2016) ^[3, 4]. Various nanostructures such as nanotubes, nanofibres, nanorods, nanoparticles, and thin films have been extensively studied to understand their properties and potential applications (Pundir, 2015) ^[5]. Among these, nanoparticles are the most widely researched. Technologies including nanosensors, nanomaterials, microfluidic systems, and bioanalytical devices are being utilized to improve animal health, productivity, reproduction, as well as disease diagnosis, treatment, and prevention (Kroubi *et al.*, 2010; Tarafdar *et al.*, 2013) ^[6, 7]. With advancements in production techniques, nanotechnology is expected to bring revolutionary changes to the livestock industry (Fesseha *et al.*, 2020) ^[8].

In animal nutrition, nanotechnology is increasingly being explored as a tool to improve feed utilization, enhance growth performance, and optimize production efficiency (Hanif *et al.*, 2024) ^[9]. 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) ^[2, 5, 8]. Conventional feed additives often suffer from poor bioavailability due to low solubility, antagonistic interactions among nutrients, and inefficient absorption in the gastrointestinal tract. This results in higher supplementation levels and increased excretion of nutrients into the environment. Nanotechnology offers solutions to these challenges by reducing particle size, increasing surface area, and improving the interaction of nutrients with biological

systems. The incorporation of nanomaterials into feed or water has been shown to improve the quality of animal products and the efficiency of production systems (Hill & Li, 2007)^[10].

2. Types of Nanoparticles

Based on their chemical properties, nanoparticles can be classified into organic nanoparticles, inorganic nanoparticles, nano-emulsions, nano-dispersions, and nano-clays. Organic nanoparticles are derived from biological molecules such as proteins, lipids, and carbohydrates. These nanoparticles can modify feed functionality while enhancing its nutritional value. They are capable of encapsulating nutrients and facilitating their transport through the gastrointestinal tract into the bloodstream; such systems are commonly referred to as nano- capsules. Due to their improved bioavailability, these delivery systems enable efficient nutrient release without altering the taste or appearance of the feed. Encapsulated nano-materials are incorporated into feeds in forms such as micelles and liposomes, and are also used in packaging systems as biosensors, identification markers, shelf-life enhancers, and antimicrobial agents. Inorganic nanoparticles consist of mineral-based components at the nanoscale and are already approved for certain applications in feed and packaging systems. Their applications in the feed and packaging industries include the use of nano-clay platelets for improved packaging properties, as well as minerals such as silicon dioxide, calcium, magnesium, and silver nanoparticles, which are utilized for water purification, antimicrobial packaging, and enhanced feed storage. Nano-emulsions, on the other hand, are designed to stabilize and deliver active compounds by encapsulating functional feed ingredients either at the oil-water interface or within a continuous phase, thereby improving their stability and bioavailability. (Marappan *et al.*, 2017)^[2]. Each type of nanoparticle has specific applications depending on its properties and intended use, making nanotechnology a versatile tool in animal nutrition.

3. Synthesis of Nanoparticles

Nanoparticles can be synthesized using top-down and bottom-up approaches. The top-down approach involves breaking down bulk materials into nanoparticles using mechanical methods such as ball milling. This method is simple but may result in uneven particle sizes. The bottom-up approach involves the assembly of nanoparticles from atoms or molecules, providing better control over size and structure.

There are three kinds of approaches for the production of nanoparticles. These methods include physical, chemical, and biological methods. Depending upon the need, the methods for synthesis of nanoparticles are selected. Every method has some advantages as well as disadvantages; the production method is selected based upon the availability of the facilities. Physical methods are suitable for small-scale production where as chemical methods are selected where the cost of production is a concern. Biological methods have different significance. (Krishnappa *et al.*, 2018; Winterer *et al.*, 2003)^[11, 12]. Chemical methods such as sol-gel and hydrothermal synthesis are widely used, while biological or green synthesis using plant extracts and microorganisms is gaining popularity due to its eco-friendly nature (Patil *et al.*, 2021)^[13]. Green synthesis is particularly important as it

reduces the use of toxic chemicals and promotes sustainable production of nanoparticles.

4. Mechanism of Action of Nanoparticles

Chen *et al.*, 2006^[14] specified the different mechanisms of action of nanoparticles as follows:

- Nanoparticles increase the surface area, allowing improved interaction with biological systems.
- They extend the duration of compounds in the gastrointestinal tract.
- They minimize the effect of intestinal clearance mechanisms.
- They can penetrate deeply into tissues through very fine capillaries.
- They are capable of passing through fenestrations in epithelial linings.
- They facilitate efficient uptake by cells.
- They ensure effective delivery of functional compounds to specific target sites, thereby enhancing bioavailability.

5. Application of Nanoparticles in Animal Nutrition

5.1 Nano-Minerals in Animal Feed

Recent studies have highlighted the significant role of nano-minerals in improving animal health, productivity, and nutrient utilization. The following summarizes key nano-minerals and their biological functions:

5.1.1. Manganese Nanoparticles

Manganese nanoparticles have been reported to enhance growth performance, antioxidant capacity, and bone development in chickens without adversely affecting feed intake, weight gain, or feed efficiency. Manganese plays a critical role in maintaining proper antioxidant and immune system functions. It also acts as a cofactor for various enzymes, including transferases, lyases, hydrolases, and oxidoreductases. Additionally, manganese is essential for mitochondrial antioxidant defense, apoptosis regulation, bone formation, and maintenance of cellular structure. (Patra and Lalhriatpuii, 2020; Palomares, 2022; Pasquini *et al.*, 2022)^[15, 16, 17].

5.1.2. Calcium and Phosphorus Nanoparticles

Calcium and phosphorus are fundamental minerals required for proper bone development in animals and poultry. The use of nano-mineral forms has been shown to improve feed conversion efficiency and body weight gain by up to 50%, while simultaneously reducing the excretion of these minerals. Nano-minerals may also serve as potential alternatives to low-dose antibiotics by enhancing growth performance, minimizing residue accumulation, and reducing environmental pollution, thereby contributing to cleaner animal products. Furthermore, plant-based diets often contain a high proportion (60-80%) of phosphorus in the form of phytates, which are poorly utilized by poultry due to the lack of endogenous phytase enzyme. (Hassan *et al.*, 2016; Samanta *et al.*, 2019; Selle *et al.*, 2009; Baharuddin *et al.*, 2009)^[18, 19, 20, 21, 27].

5.1.3. Selenium Nanoparticles

Selenium is an essential trace element involved in growth, reproduction, immune function, hormone metabolism, cellular proliferation, and antioxidant defense mechanisms. Supplementation with nano-selenium has been shown to

improve parameters such as pH balance, ammonia levels, fatty acid composition, fertility, sperm quality, and egg production in layer chickens. A dietary inclusion level of 0.3 mg/g dry matter has demonstrated enhanced physiological responses in layer chicks. Additionally, nano-selenium has been found to significantly improve the utilization of purine derivatives and reduce urinary excretion. (Ghaffarizadeh *et al.*, 2022; Nabi *et al.*, 2020; Shi *et al.*, 2011) ^[22, 23, 24].

5.1.4. Chromium Nanoparticles

Chromium plays a vital role in regulating insulin sensitivity and metabolic processes in animals. Supplementation with chromium nanocomposites in pigs has been associated with reduced levels of glucose, cholesterol, and fatty acids, alongside increased protein synthesis and lipoprotein production. In poultry, chromium propionate has been shown to enhance egg production and alleviate heat stress. Chromium is believed to improve insulin sensitivity by activating insulin receptor kinase activity. Moreover, supplementation with chromium picolinate nanoparticles has been linked to improvements in egg quality, chromium retention in the body, eggshell quality, and liver chromium concentration. (Bakshi and Panigrahi, 2022; Anderson, 2003; Hassan *et al.*, 2020) ^[18, 25, 26, 27].

5.1.5. Copper Nanoparticles

Copper is an essential mineral required for metabolic processes, physiological functions, immune responses, connective tissue development, and proper nerve function. Both inorganic copper sulphate and copper oxide nanoparticles have been shown to enhance growth performance and immunity while reducing inflammatory responses in poultry. Inclusion of copper nanoparticles in basal diets has been reported to decrease feed intake without negatively affecting body weight, egg production, egg mass, or egg quality in laying hens. Although copper supplementation in broilers may reduce growth performance in some cases, it significantly lowers mineral excretion. Due to improved absorption, interaction, and bioavailability, nano-copper can enhance overall animal production efficiency. (Rossi *et al.*, 2020; Patra and Lalhriatpuii, 2020) ^[15, 28].

5.1.6. Silver Nanoparticles

Silver nanoparticles exhibit strong antimicrobial properties and have been widely studied in animal production. In weaned pigs, they have been shown to reduce coliform populations, pathogenic bacteria, and overall microbial load. Additionally, they improve growth performance, enhance antibacterial activity, and influence lymphoid organ development, while reducing weight loss in neonates and liver lesions. In poultry, nanosilver supplementation significantly lowers bacterial counts in the digestive tract, including pathogens such as *Escherichia coli*, *Streptococcus*, *Salmonella*, and other mesophilic bacteria. Dietary inclusion of nanosilver at levels of 20, 40, and 60 ppm has demonstrated a dose-dependent reduction in lymphoid organ weight. (Fondevila *et al.*, 2009; Bhanja and Verma, 2021; Al-Sultan *et al.*, 2022) ^[29, 30, 31].

5.2 As Feed Additives

Nano-additives are commonly present in protein micelles, nano-capsules, and natural feed components (Khalid & Arif, 2022) ^[32]. Nano-capsulation has been reported to improve

the bioavailability of compounds such as essential oils, flavors, and antioxidants (Ozogul *et al.*, 2022) ^[33]. Encapsulation techniques are also used to protect minerals and micronutrients from oxidative damage while masking undesirable tastes (Galanakis, 2019) ^[34].

Liposomal nano-vesicles play an important role in delivering nutrients, enzymes, flavors, and antimicrobial agents within food systems (Pateiro *et al.*, 2021) ^[35]. Additionally, proteins and other biomolecules can encapsulate nano-additives within micelles and oil droplets that are stabilized by amphiphilic (bipolar) molecules (Prasad *et al.*, 2022) ^[36]. These nano-additives may either remain dispersed in aqueous systems or be enclosed within lipid-based structures. For instance, nano-capsules are often used to carry omega-3 fish oil, helping to reduce its unpleasant odor and taste (Liao *et al.*, 2021). Feed additives constitute essential raw materials in the modern feed industry by improving nutritional value, animal production efficiency, health, cost reduction, and product quality (Pandey *et al.*, 2019) ^[37, 38].

5.3 Feed Processing

Nanoscale particles are characterized by their ultrafine size, increased surface area, and enhanced capacity for nutrient absorption (Mobasser & Firoozi, 2016) ^[39]. Advances in nanotechnology have contributed to the development of functional feeds by enabling the encapsulation of valuable ingredients, thereby preventing nutrient losses during processing and ensuring efficient delivery within the animal system (Tiwari, 2022) ^[40]. A key aspect of this technology is the incorporation of nano-capsules into feed formulations, which facilitate targeted and controlled nutrient delivery (Fajardo *et al.*, 2022) ^[41]. In particular, nano-chelates of approximately 50 nm in size have been reported to effectively deliver nutrients without altering the sensory properties of feed, such as color and taste (Ahmed *et al.*, 2023) ^[42].

6. Impact of inclusion of nanoparticles on animal feed.

6.1 Improve Nutrient absorption, Nutrient utilization and Growth performance

Nanoparticles play a pivotal role in enhancing nutrient absorption by mitigating the adverse effects of bivalent cations, particularly in the case of trace minerals. This advantage is especially evident in livestock and poultry, where nanoparticles improve nutritional efficiency and optimize the utilization of feed and dietary supplements (Marappan *et al.*, 2017) ^[2]. For instance, studies have demonstrated that nano-sized zinc oxide (ZnO) promotes growth performance and improves feed efficiency in both piglets (Li *et al.*, 2018) and poultry (Mishra *et al.*, 2014; Lina *et al.*, 2009). Similarly, Shi *et al.* (2011) ^[24, 44, 45] observed that selenium supplementation not only improved growth performance but also enhanced selenium bioavailability in the blood and various tissues of growing male goats.

6.2 Enhance meat and egg quality

The potential of nanoparticles to enhance the quality of meat and eggs has been extensively investigated. For instance, Poddar & Kishore (2022) ^[46] reported that supplementation of chromium nanoparticles (200 g/kg) in finishing pigs resulted in animals that were 14.06% leaner at slaughter compared to control groups. Similarly, Xiong *et al.* (2022)

[47] demonstrated that chitosan nanoparticles improved skeletal muscle mass and meat quality in pigs by reducing fatty acid synthase activity. Moreover, the incorporation of nanomaterials into animal feed or drinking water has been shown to enhance both product quality and production efficiency, including improvements in broiler meat, egg yolk characteristics, and eggshell quality (Dong *et al.*, 2022) [48]. Appropriate nanoparticle concentrations are critical, as they help maintain product quality even under prolonged exposure (Mortensen *et al.*, 2022) [49]. From a consumer perspective, acceptance of meat and eggs derived from animals supplemented with nanoparticles remains favorable, particularly when product quality is improved or remains comparable to conventional products (Bhagat & Singh, 2022) [50]. However, prior to the application of nanoparticle-based additives in animal production systems, it is essential to thoroughly evaluate their biological interactions and potential byproducts to ensure safety for consumption (Dupuis *et al.*, 2022) [51].

6.3 Improve Milk Production and Quality

Rajendran (2013) [52] observed that supplementing with nano ZnO led to increased milk production. Nanotechnology also holds significant potential for improving the safety and nutritional quality of milk intended for human consumption. For example, Sung *et al.*, (2013) [53] developed a nanocomposite system comprising anti-Staphylococcus aureus antibodies, gold nanoparticles, and magnetic nanoparticles, enabling a rapid colorimetric assay capable of detecting *S. aureus* in milk within 40 minutes. Furthermore, Lee *et al.* (2015) [54] reported that the incorporation of nano-powdered oyster shells into milk significantly increased its calcium content from 100 to 120 mg/ml.

6.4 Improve the immune responses

Studies conducted by Sahoo *et al.* (2014a; 2014b) [55] found that adding nano zinc to the diet of broiler birds at a concentration of 0.06 ppm considerably enhanced the immune response compared to the conventional dosage of 15 ppm, whether it was organic or inorganic. Furthermore, Saki and Salary (2014) [56] revealed that chicks hatched from eggs treated with nano-silver exhibited significantly stronger humoral immunity in their laying hens.

6.5 Effect on Rumen

Supplementation of nano-selenium in the diet of sheep has shown to modify the pattern of fermentation in the rumen, by increasing the production of propionate, which in turn reduce the acetate: propionate ratio (Shi *et al.*, 2011). In a study by El-Nile *et al.* (2023) [24, 57], natural zeolite in nano form, was introduced as a feed additive, which ultimately resulted in improved rumen fermentation pattern, blood metabolites, milk production and feed intake in dairy goats. The findings showed a boost in milk production and short-chain fatty acids. Additionally, incorporating nano selenium into the basic diet has been observed to improve rumen fermentation and feed efficiency, likely by promoting the activity of rumen microbes, digestive microorganisms, or enzymes (Shi *et al.*, 2011) [24].

7. Toxicity and Safety Concerns

Despite its advantages, nanotechnology raises concerns regarding toxicity and safety. Nanoparticles can generate reactive oxygen species, leading to oxidative stress and

cellular damage. They may also trigger inflammatory responses and affect cellular functions. Prolonged exposure may result in genetic damage and mutations (Egbuna *et al.*, 2021) [58]. Therefore, it is essential to conduct thorough risk assessments and establish safe dosage levels before widespread application.

8. Challenges and Future Prospects

The application of nanotechnology in animal nutrition faces challenges such as lack of standardization, limited regulatory frameworks, and insufficient long-term safety data. Due to their unique characteristics, nanomaterials may cause unforeseen environmental and health risks. It's crucial to establish appropriate dosage limits to prevent the dangers of over-supplementation. Issues concerning safety thresholds and toxicity are significant barriers to the commercial use of nanoparticles (Radha *et al.*, 2014) [59]. The elevated cost of nano-feed additives also present a challenge that cannot be overlooked (Dumlu, 2024). Future research should focus on developing safe and cost-effective nano-feed additives, establishing regulatory guidelines, and exploring new applications in livestock production. With proper regulation and research, nanotechnology has the potential to revolutionize animal nutrition and contribute to sustainable livestock production systems.

10. Conclusion

Nanotechnology represents a revolutionary approach in animal nutrition, offering innovative solutions to improve feed efficiency, nutrient utilization, and animal health. Its applications, including nano-minerals, nano additives and nano-encapsulation have demonstrated significant benefits in livestock production. However, challenges related to safety, cost, and regulation must be addressed to ensure sustainable adoption. With continued research and technological advancements, nanotechnology is expected to play a vital role in the future of animal nutrition.

References

1. Gelaye Y. Application of nanotechnology in animal nutrition: bibliographic review. *Cogent Food Agric.* 2024;10(1):2290308. DOI:10.1080/23311932.2023.2290308.
2. Marappan G, Beulah P, Kumar RD, Muthuvel S, Govindasamy P. Role of nanoparticles in animal and poultry nutrition: modes of action and applications in formulating feed additives and food processing. *Int J Pharmacol.* 2017;13(7):724-731. DOI:10.3923/ijp.2017.724.731.
3. Loghman A, Iraj SH, Naghi DA, Pejman M. Histopathologic and apoptotic effect of nanosilver in liver of broiler chickens. *Afr J Biotechnol.* 2012;11(22):6207-11. DOI:10.5897/AJB11.1768.
4. Ognik K, Stępniewska A, Cholewińska E, Kozłowski K. The effect of administration of copper nanoparticles to chickens in drinking water on intestinal absorption of iron, zinc and calcium. *Poult Sci.* 2016;95(9):2045-2051. DOI:10.3382/ps/pew200.
5. Pundir C. Enzyme nanoparticles: preparation, characterisation, properties and applications. Amsterdam: Elsevier; 2015.
6. Kroubi M, Daulouede S, Karembe H, Jallouli Y, Howsam M, Mossalayi D, *et al.* Development of

- nanoparticulate diminazene formulation. *Nanotechnology*. 2010;21(50):505102. DOI:10.1088/0957-4484/21/50/505102.
7. Tarafdar J, Sharma S, Raliya R. Nanotechnology: interdisciplinary science of applications. *Afr J Biotechnol*. 2013;12(3):219-226. DOI:10.5897/AJB12.2481.
 8. Fesseha H, Degu T, Getachew Y. Nanotechnology and its application in animal production: a review. *Vet Med Open J*. 2020;5(2):43-50. DOI:10.17140/VMOJ-5-148.
 9. Hanif M, Shujaat NUS, Khan K, Haq IU, Rafiq M, Sattar M, *et al*. Enhancing livestock health with nanoparticles as feed additives. In: Abbas RZ, Akhtar T, Asrar R, Khan AMA, Saeed Z, editors. *Complementary and alternative medicine: feed additives*. Faisalabad: Unique Scientific Publishers; 2024. p. 65-74. DOI:10.47278/book.CAM/2024.089.
 10. Hill EK, Li J. Current and future prospects for nanotechnology in animal production. *J Anim Sci Biotechnol*. 2017;8:26. DOI:10.1186/s40104-017-0157-5.
 11. Krishnappa K, Pandiyan J, Paramanandham J, Elumalai K. Antibacterial and mosquitocidal potentials of selected Indian medicinal plants extracts and synthesized silver nanoparticles. *Int J Zool Stud*. 2018;3:15-15.
 12. Winterer M, Hahn H. Nanoceramics by chemical vapour synthesis. *Z Metallkd*. 2003;94:1084-1090.
 13. Patil N, Bhaskar R, Vyavhare V, Dhadge R, Khaire V, Patil Y. Overview on methods of synthesis of nanoparticles. *Int J Curr Pharm Res*. 2021;13(2):11-16. DOI:10.22159/ijcpr.2021v13i2.41556.
 14. Chen H, Weiss J, Shahidi F. Nanotechnology in nutraceuticals and functional foods. *Food Technol*. 2006;60(3):30-36.
 15. Patra A, Lalhriatpuii M. Progress and prospect of essential mineral nanoparticles in poultry nutrition and feeding: a review. *Biol Trace Elem Res*. 2020;197(1):233-253. DOI:10.1007/s12011-019-01959-1.
 16. Palomares RA. Trace mineral supplementation in beef cattle. *Animals*. 2022;12(20):2839. DOI:10.3390/ani12202839.
 17. Pasquini M, Grosjean N, Hixson KK, Nicora CD, Yee EF, Lipton M, *et al*. Zng1 zinc transferase activation. *Cell Rep*. 2022;39(7):110834. DOI:10.1016/j.celrep.2022.110834.
 18. Hassan M, Ding W, Shi Z, Zhao S. Methane enhancement through co-digestion of chicken manure and wheat straw. *Bioresour Technol*. 2016;211:534-554. DOI:10.1016/j.biortech.2016.03.148.
 19. Samanta G, Mishra S, Behura N, Sahoo G, Behera K, Swain R, *et al*. Utilization of calcium phosphate nanoparticles in broilers. *Anim Nutr Feed Technol*. 2019;19(1):77-88. DOI:10.5958/0974-181X.2019.00008.8.
 20. Selle PH, Cowieson AJ, Ravindran V. Consequences of calcium interactions with phytate and phytase. *Livest Sci*. 2009;124(1-3):126-141. DOI:10.1016/j.livsci.2009.01.006.
 21. Baharuddin AS, Wakisaka M, Shirai Y, Abd-Aziz S, Abdul R, Hassan M. Co-composting of empty fruit bunches. *Int J Agric Res*. 2009;4(2):69-78. DOI:10.3923/ijar.2009.69.78.
 22. Ghaffarizadeh A, Sotoudeh E, Mozanzadeh MT, Sanati AM, Ghasemi A. Selenium nanoparticles in shrimp. *Aquac Rep*. 2022;25:101215. DOI:10.1016/j.aqrep.2022.101215.
 23. Nabi F, Arain M, Hassan F, Umar M, Rajput N, Alagawany M, *et al*. Selenium nanoparticles in poultry. *Worlds Poult Sci J*. 2020;76:459-471. DOI:10.1080/00439339.2020.1789535.
 24. Shi L, Yue W, Zhang C, Ren Y, Liu Q, Wang Q, *et al*. Nano-selenium in sheep. *Anim Feed Sci Technol*. 2011;163:136-142.
 25. Bakshi A, Panigrahi AK. Chromium contamination and bioremediation. In: *Advances in bioremediation*. Cham: Springer; 2022. p. 229-248. DOI:10.1007/978-3-030-89984-4_15.
 26. Anderson RA. Chromium and insulin resistance. *Nutr Res Rev*. 2003;16(2):267-275. DOI:10.1079/NRR200366.
 27. Hassan S, Hassan FU, Rehman MSU. Nano-particles of trace minerals in poultry nutrition. *Biol Trace Elem Res*. 2020;195(2):591-612. DOI:10.1007/s12011-019-01862-9.
 28. Rossi B, Toschi A, Piva A, Grilli E. Botanicals as non-antibiotic strategy. *Nutr Res Rev*. 2020;33(2):218-234. DOI:10.1017/S0954422420000013.
 29. Fondevila M, Herrero R, Casallas M, Abecia L, Duchá J. Silver nanoparticles in pigs. *Anim Feed Sci Technol*. 2009;150(3-4):259-269. DOI:10.1016/j.anifeedsci.2008.09.003.
 30. Bhanja S, Verma S. Prospects of nano minerals in poultry nutrition. *Indian J Poult Sci*. 2021;56(1):1-8. DOI:10.5958/0974-8180.2021.00006.4.
 31. Al-Sultan SI, Hereba ART, Hassanein KM, Abd-Allah SM, Mahmoud UT, Abdel-Raheem SM. Impact of dietary silver nanoparticles on growth performance and health of broiler chickens. *Ital J Anim Sci*. 2022;21(1):967-978. DOI:10.1080/1828051X.2022.2083528.
 32. Khalid MY, Arif ZU. Novel biopolymer-based sustainable composites for food packaging applications: a review. *Food Packag Shelf Life*. 2022;33:100892. DOI:10.1016/j.fpsl.2022.100892.
 33. Ozogul Y, Karsli GT, Durmuş M, Yazgan H, Oztop MH, McClements DJ, *et al*. Industrial applications of nanoemulsions. *Adv Colloid Interface Sci*. 2022;304:102685. DOI:10.1016/j.cis.2022.102685.
 34. Galanakis CM. *Trends in non-alcoholic beverages*. Amsterdam: Academic Press; 2020.
 35. Pateiro M, Gómez B, Munekata PE, Barba FJ, Putnik P, Kovačević DB, *et al*. Nanoencapsulation of bioactive compounds. *Molecules*. 2021;26(6):1547. DOI:10.3390/molecules26061547.
 36. Prasad RD, Sahoo A, Shrivastav OP, Charmode N, Kamat R, Kajave N, *et al*. Nanotechnology in food science and animal nutrition. *ES Food Agrofor*. 2022;8:12-46.
 37. Liao W, Badri W, Dumas E, Ghnimi S, Elaissari A, Saurel R, *et al*. Nanoencapsulation of essential oils. *Appl Sci*. 2021;11(13):5778. DOI:10.3390/app11135778.
 38. Pandey AK, Kumar P, Saxena M. Feed additives in animal health. In: *Nutraceuticals in Veterinary Medicine*. Cham: Springer; 2019. p. 345-362.

39. Mobasser S, Firoozi AA. Nanotechnology applications in science and engineering. *J Civ Eng Urban*. 2016;6:84-93.
40. Tiwari P. Nanotechnologies and sustainable agriculture. Cham: Springer; 2022.
41. Fajardo C, Martinez-Rodriguez G, Blasco J, Mancera JM, Thomas B, De Donato M. Nanotechnology in aquaculture: applications and challenges. *Aquac Fish*. 2022;7(2):185-200. DOI:10.1016/j.aaf.2021.12.006.
42. Ahmed J, Vasagam KK, Ramalingam K. Nanoencapsulated aquafeeds in fisheries. *Appl Biochem Biotechnol*. 2023;195(11):7110-31. DOI:10.1007/s12010-023-04418-9.
43. Li JL, Zhang L, Yang ZY. Selenium sources and poultry performance. *Biol Trace Elem Res*. 2018;181(2):340-346.
44. Mishra A, Swain RK, Mishra SK, Panda N, Sethy K. Nano zinc supplementation in layer chicks. *Indian J Anim Nutr*. 2014;31(4):384-388.
45. Lina T, Jianyang J, Fenghua Z, Huiying R, Wenli L. Effect of nano-zinc oxide in broilers. *Chin Agric Sci Bull*. 2009;2:003.
46. Poddar K, Kishore AV. Nanotechnology in animal production. In: *Climate smart livestock production*. Amsterdam: Elsevier; 2022.
47. Xiong RG, Zhou DD, Wu SX, Huang SY, Saimaiti A, Yang ZJ, *et al*. Short-chain fatty acids: health effects. *Foods*. 2022;11(18):2863. DOI:10.3390/foods11182863.
48. Dong Y, Zhang K, Han M, Miao Z, Liu C, Li J. Organic trace minerals in laying hens. *Front Vet Sci*. 2022;9:920418. DOI:10.3389/fvets.2022.920418.
49. Mortensen NP, Pathmasiri W, Snyder RW, Caffaro MM, Watson SL, Patel PR, *et al*. TiO₂ nanoparticles and health effects. *Part Fibre Toxicol*. 2022;19(1):1-18. DOI:10.1186/s12989-021-00444-9.
50. Bhagat S, Singh S. Nanominerals in nutrition. *Food Res Int*. 2022;160:111703. DOI:10.1016/j.foodres.2022.111703.
51. Dupuis V, Cerbu C, Witkowski L, Potarniche AV, Timar MC, Żychska M, *et al*. Nanodelivery of essential oils. *Drug Deliv*. 2022;29(1):1007-24. DOI:10.1080/10717544.2022.2056663.
52. Rajendran D, Kumar G, Ramakrishnan S, Shibi TK. Zinc oxide supplementation in dairy cows. *Res J Biotechnol*. 2013;8(5):11-17.
53. Sung YJ, Suk HJ, Sung HY, Li T, Poo H, Kim MG. Gold nanoparticle detection of *Staphylococcus aureus*. *Biosens Bioelectron*. 2013;43:432-439. DOI:10.1016/j.bios.2012.12.052.
54. Lee YK, Ahn SI, Chang YH, Kwak HS. Nanopowdered oyster shell in milk. *J Dairy Sci*. 2015;98:5841-5849.
55. Sahoo A, Swain RK, Mishra SK. Nano zinc in broilers. *Int J Adv Res*. 2014;2(11):828-837.
56. Saki A, Salary J. In ovo injection of silver nanoparticles. *Anim Sci J*. 2014;101:70-78.
57. El-Nile AE, Elazab MA, Soltan YA, Elkomy AE, ElZaiat HM, Sallam SMA, *et al*. Nano zeolite in dairy goats. *Anim Feed Sci Technol*. 2023;295:115522.
58. Egbuna C, Parmar VK, Jeevanandam J, *et al*. Toxicity of nanoparticles in biomedical applications. *J Toxicol*. 2021;2021:9954443. DOI:10.1155/2021/9954443.
59. Radha K, Thomas A, Sathian CT. Nanotechnology in dairy industry. *Indian J Dairy Sci*. 2014;67(5):367-374.