Bio Vet Innovator Magazine
Volume 2 (Issue 12) DECEMBER 2025
OPEN ACCESS POPULAR ARTICLE

Nanotechnology in Animal Nutrition: Benefits, Risks and Future Aspects

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DOI: https://doi.org/10.5281/zenodo.17951512

Received: December 01, 2025
Published: December 16, 2025
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Introduction:

Nanotechnology is an interdisciplinary nature, which deals with manipulation of matter at the atomic and molecular scales commonly on a scale of 1 to 100 nanometers. The emerging technology will transform the livestock industry by providing superior solutions to enhancing animal health, productivity and sustainability. As the world population is growing to consume more animal products, animal nutrition is now of paramount importance in order to produce at sustainable levels. Solutions to waste management, purification of water using nanomaterials. Effective use of nutrients are discussed that opens feasible ways to reduce the environmental effects of intensive farming methods. The use of nanotechnology and nanoparticles in food manufacturing, animal rearing and animal yield such as production of milk and meat is increasing rapidly. The small size of these particles enables absorption of fats, proteins and carbohydrates in the gastrointestinal tract to be enhanced leading to increased growth rate and feed:gain ratio. Of particular value are nanominerals like selenium (Se), zinc (Zn), and copper (Cu).

The supplementation of nano-Se has been reported to increase the gain in weight and Feed: gain in calf. In ruminants, nanoselenium has been reported to enhance the use of nutrients and excretion of purine derivatives in the urine, which suggests an increase in the growth of microbes in the rumen (Gelaye, 2023). Nanoparticles are used to deliver bioactive substances like vitamins, minerals and antioxidants. The nanoencapsulation methods ensure that these compounds are not destroyed during the digestive process and thus they are preserved to be active and well absorbed. This slow dosing system provides steady flow of nutrients and one does not have to take supplements frequently.

Enhancing Animal Health and Disease Resistance:

Nanoparticles are also antimicrobial and immunomodulatory which makes them a useful tool in

preventing diseases and the general well being of the animal. Silver (Ag) and copper (Cu) are examples of metallic nanoparticles that have high antibacterial and antiviral effects (Kazemi, 2025). Silver nanoparticles have been demonstrated to be useful in goat mastitis treatment because they possess a high ability to have a bactericidal effect against drug-resistant bacteria. There are also nanoparticles that have the ability to trigger the developing of immune cells like macrophages/ lymphocytes which enhances the immune response and disease resistance of the animal.

Enhance the animal products

Nanotechnology can enhance the quality of products of animal origin including milk, meat and eggs.It has been demonstrated that nano-zinc when added to dairy cows is able to decrease the number of somatic cells in the milk, a measure of health in the udder, and augment the amount of milk produced. Nanoparticles are also applicable in the production of immunosensors that detect progesterone in cow milk that helps in detecting ovulation. Nanoparticles help in increasing protein levels, enhancing fatty acid and increasing shelf life of animal products. This goes in line with the demands of the consumer to high-quality and functional foods as well (Ojebiyi *et al*., 2024).

Minimize wasting of nutrients and pollution to the environment

When using the conventional method of supplementation, a great percentage of trace minerals like copper and zinc are released into the manure, which contributes to the soil, waste, and pollution of the environment. Due to the fact that nanominerals are more bioavailable, it will be possible to use smaller amounts of them thus minimizing nutrient excretion and the environmental footprint of livestock farming. It offers new technologies like nano-encapsulation, nano-emulsions and nano-carriers to enhance the solubility, stability, and targeted delivery of essential nutrients.

Nanotechnology risks on Animal Nutrition

This is a great threat because nanoparticles have a high potential of nanotoxicity and bioaccumulation in the case of animal feeding. Their low sizes enable them to circumvent biological barriers and accumulate in vital organs that may cause oxidative stress, inflammation and dysfunction of the organs in the long term. This is not an acute exposure, a long-term exposure with a significant gap in long-term health effects. One of the biggest ethical and safety issues is that nanoparticles may be transferred to humans via the food chain whereby they are able to accumulate in tissues and products like meat, milk, and eggs. The absence of standardized procedures of detecting them hampers the monitoring of such residues. However, it raises the issue of the long-term consequences of human use, including possible toxicity, genotoxicity, and other interactions with the human microbiome about which little is known. Animal nano-particles also have the potential to be a serious environmental hazard once they are excreted, since it may potentially reach agricultural environments through dunk and wastewater. Their distinctive characteristics can lead to their unforeseen interactions, which negatively affect the positive

soil bacteria, interrupt the process of nutrient cycling and contaminate water resources that is dangerous to aquatic life. One of the biggest ethical and safety issues is that nanoparticles may be transferred to humans via the food chain whereby they are able to accumulate in tissues and products like meat, milk, and eggs. The absence of standardized procedures of detecting them hampers the monitoring of such residues. However, it raises the issue of the long-term consequences of human use, including possible toxicity, genotoxicity, and other interactions with the human microbiome about which little is known. Animal nano-particles also have the potential to be a serious environmental hazard once they are excreted, since it may potentially reach agricultural environments through dunk and wastewater. Their distinctive characteristics can lead to their unforeseen interactions, which negatively affect the positive soil bacteria, interrupt the process of nutrient cycling and contaminate water resources that is dangerous to aquatic life.

Future of Nanotechnology in Animal Nutrition

The field of nanoparticles which can deliver nutrition precisely is a highly promising direction. The application of nanoparticles to provide precision in nutrient supply is one of such critical fields of research. Nanoparticles have been cited as an area of the most promising research due to the ability to deliver nutrients to specific areas. Traditional feed additives are often low in bioavailability because they are broken down in the gut. Their surface-to-volume ratio is high and, therefore, Nanoparticles can pick up and preserve fragile nutrients including vitamins, minerals, and essential fatty acids. This protection assures that nutrients get their desired destination to the intestine where they will be better absorbed. As an illustration, interactions of other feed components can be inhibited by nano-encapsulated zinc or iron which does not hinder absorption (Yang *et al*., 2025). Decreasing the quantity to be ingested in the diet and reducing excretion in the environment. Future studies will be focused on development of smart nanoparticles that can undergo release under certain environmental conditions, e.g. pH variations or enzymatic action in different portions of the digestive system. The targeted release will optimize nutrient use leading to enhanced growth rates and feed:gain ratio (Hanif *et al*., 2024).

Nanocarriers of antimicrobials and probiotics are particularly significant in the face of increasing interest in antibiotic resistance in livestock production. Nanoparticles have the ability to target the antimicrobial agent to the location of infection in the gut, which decreases the amount of dosage needed, and affects resistance formation. In the same way, the probiotic nanocarriers can shield the useful bacteria in the highly acidic stomach environment, which will determine that more live microorganisms arrive at the intestine. This enhances the microbiome of the gut, which is required in nutrient absorption and resistance to diseases. Future studies will be on the application of natural, biodegradable nanoparticles. In order to make these applications safe and sustainable, it is recommended to use materials derived out of polysaccharides. These carriers can help to improve gut health and limit the use of conventional antibiotics. Helps to make the animal agriculture system more sustainable and humane (Bhagat and

Sharma, 2022). Despite the promise of nanotechnology in animal nutrition, its wide adoption will require a major effort to overcome the serious ethical and regulatory dilemmas. One of the main issues is that it is necessary to conduct the research on the long-term effects of the consumption of nanoparticles on the health of animals and humans. In particular, their capacity to conglomerate in the food chain. Consequently, regulatory authorities need to set and implement strict regulations regarding the use and labeling of the nano-enabled feed products. The biodegradability and safety of such materials should also be considered in the future research since other than the technical side, one has to pay attention to the awareness and acceptance of the people, and therefore the open communication of the benefits and safety measures is necessary. Research on this issue ought to therefore extend past technological breakthroughs and incorporate the development of resilient risk assessment systems and holistic codes of ethics.Such a wholesome solution will see to it that the potential benefits of nanotechnology are indeed realized in ways that are responsible and do not put the livelihoods of the animals and the general population at risk. Nanobiosensors, and these are insertable either into feed or water, are able to identify biomarkers of disease, stress, or nutritional deficiencies. As an illustration, a nanobiosensor may be developed to measure particular toxins or pathogens or even alterations in the metabolic levels of an animal in the gut. This technology may be used to provide an early warning system to the veterinarians and farmers. Encouraging early interventions and avoiding the spread of diseases. These sensors would also be able to be used to monitor the efficacy of new feed formulations by tracking the way in which specific nutrients are used. This information-driven model allows designing highly individualized and responsive feeding systems that are no longer based on the classical model of animal nutrition of one size fits all.

Conclusion

Nanotechnology can fundamentally change animal nutrition to offer solutions to old problems of feed efficiency, health and sustainability. The fact that nanoparticles have been shown to enhance the absorption of nutrients, targeted therapeutics and have high potential to serve as effective antimicrobials indicates that animal agriculture will be more efficient and productive in the future. Nevertheless, the way forward is not that easy. The dangers of nanotoxicity, bioaccumulation into food chain, and environmental pollution, along with an insufficient regulatory framework require a responsible and careful stance that the scientific community can take a step forward towards a new age of animal nutrition not only technologically proficient, but also ethical.

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