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TRANSFORMING ANIMAL HUSBANDRY THROUGH NANOTECHNOLOGY IN NUTRITION, HEALTH, AND REPRODUCTION

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Nanotechnology is revolutionizing animal husbandry by offering innovative solutions that enhance nutrition, health, and reproduction in livestock. This emerging field manipulates materials at the nanoscale, enabling the development of advanced applications that address critical challenges in animal agriculture. As the industry faces increasing pressures from climate change, disease outbreaks, and the demand for sustainable practices, nanotechnology presents a pathway to improve productivity while ensuring animal welfare. The livestock production industry faces immense pressure to provide sufficient food for the rapidly growing global population. The challenges posed by advanced infections, diseases, and climate change have further intensified the demands on livestock production systems. Nanotechnology, which involves the use of particles at the nanoscale, offers promising solutions to enhance animal production, growth, health, and reproductive performance. It enables improvements in diagnostics, medicines, vaccines, therapeutics, adjuvants, animal feed, and other additives, while also supporting animal reproduction.

Enhancing Animal Nutrition

Animal feed accounts for approximately 40-50% of the operating costs in livestock production systems. The primary goal of the feed industry is to enhance the efficiency of feed and its additives. Nutritional deficiencies can lead to significant reductions in the production potential of animals, making them more susceptible to diseases. To improve both the quantity and quality of animal products such as milk, eggs, and meat, the animal feed industry should incorporate nanoparticles (NPs) with the following objectives: (a) enhancing overall feed efficiency; (b) increasing the levels and quality of animal products; (c) utilizing NPs with immune-modulating and antioxidant properties to boost animal health; (d) decreasing reliance

on antibiotics as growth promoters, which may pose risks to human health; and (e) eliminating boar taint in animal products, particularly in pork (Hill et al., 2017).

One of the most significant impacts of nanotechnology in animal husbandry is its application in nutrition. Nanotechnology enables the nanoencapsulation of feed ingredients, which protects nutrients from degradation during processing and storage. This process not only enhances the bioavailability of vitamins and minerals but also improves the overall nutritional profile of animal feed. For example, nano-ZnO has been shown to improve growth rates, immune function, and reproductive performance in livestock while reducing the prevalence of diseases such as piglet diarrhoea and mastitis in dairy cows. Moreover, nanoparticles can be used to deliver probiotics and other beneficial additives directly to target organs within the digestive system. This targeted delivery system enhances nutrient absorption and promotes a healthy gut microbiome, which is crucial for optimal growth and performance. Additionally, nanotechnology can improve the shelf life of meat, eggs, and dairy products by incorporating nanomaterials into packaging that protects against spoilage and contamination.

Furthermore, nanozinc has been linked to increased milk production and a decrease in somatic cell counts in dairy cows suffering from recessive mastitis. Liquid vitamins produced through nanotechnology can be incorporated into poultry feed. These nanoscale vitamins are designed to deliver vitamins and other nutrients directly into the bloodstream via the gastrointestinal tract, enhancing their bioavailability (Shabani et al., 2019). Nanoparticles can also reduce the need for preservatives and eliminate unpleasant feed odors that may irritate animals (Reddy et al., 2020). Additionally, they improve nutrient dispersibility and feed stability. Ingredients can be microencapsulated to protect them from light and oxidation, prevent degradation by proteases and other digestive enzymes, and maintain stability across various pH levels and temperatures. This enhanced dispersibility allows for better mixing of fat-soluble additives in the feed and extends their shelf life during storage.

Advancements in Animal Health

Healthy livestock on farms contribute to a consistent and quality food supply while reducing reliance on antibiotics and vaccines, leading to increased productivity and stable trade in animal products. Nanoparticles (NPs), which are similar in size to disease-causing viruses, present opportunities for effective diagnostic and therapeutic strategies for specific diseases. Thus, nanotechnology is a promising avenue for advancing veterinary medicine,

animal health, and drug delivery. The use of nanominerals and nanoemulsion technologies in cattle and poultry feed offers several benefits, including lower costs, reduced need for additives, and enhanced growth-promoting and immunomodulating properties. Nanominerals can inhibit harmful microorganisms in feed, regulate rumen fermentation, and address reproductive issues in cattle and sheep. Additionally, they have been employed to treat various animal diseases; for example, nanozinc oxide has been shown to boost growth rates, immunity, and reproductive performance in farm animals while decreasing diarrhea incidence in non-ruminants. Studies indicate that nanozinc can also enhance milk yield and reduce somatic cell counts in cows with recessive mastitis.

Nanotechnology also plays a pivotal role in advancing animal health through improved disease diagnosis and treatment. Nanoparticles can be engineered to deliver drugs more effectively to specific sites within an animal's body, minimizing side effects and enhancing therapeutic efficacy. For instance, targeted drug delivery systems utilizing nanoparticles can treat infections more efficiently by ensuring that higher concentrations of medication reach the affected tissues. Furthermore, nanotechnology facilitates the development of nano-vaccines that require lower doses while providing robust immune responses. These vaccines can be designed to target specific pathogens more effectively than traditional vaccines, leading to better health outcomes for livestock. The use of nanoparticles in diagnostics allows for rapid detection of diseases through biosensors that can identify pathogens with high sensitivity and specificity. This capability is crucial for early intervention and management of outbreaks in livestock populations.

In animal medicine, emerging nanomedicines offer several advantages over traditional treatments, one of which is their ability for self-regulation. For example, when gentamicin is linked to a peptide chain, it remains inactive as long as the linker is intact. Only proteases produced by *Pseudomonas aeruginosa* can degrade this linker, allowing gentamicin to be released and activated specifically in the presence of *P. aeruginosa* (Suzuki et al., 1998). In veterinary pharmaceuticals for livestock, nanomaterials can facilitate the targeted delivery of drugs to specific cells, thereby reducing the required dosage, minimizing drug residues, and shortening withdrawal times for animals raised for pasture. Nanominerals and nanoemulsion technologies provide numerous advantages in the production and use of cattle and poultry feed, including reduced costs, fewer additives, and properties that promote growth and modulate immune responses (El-Sayed and Kamel, 2020). These nanominerals can inhibit harmful pathogens in feed, regulate rumen fermentation processes, and help resolve

reproductive issues in cattle and sheep (Laurent et al., 2008). Additionally, nanominerals have been utilized in treating animal diseases; for instance, nanozinc oxide has been shown to enhance growth rates, boost immunity, and improve reproductive performance in livestock and poultry while also reducing diarrhea incidence in piglets (Hassan et al., 2021).

Innovations in Animal Reproduction

In the field of reproduction, nanotechnology offers groundbreaking advancements that enhance breeding management and reproductive success. For example, nanotubes implanted under the skin can detect hormonal changes associated with estrus through near-infrared fluorescence. This technology allows for precise timing of breeding interventions, improving conception rates and overall reproductive efficiency. Additionally, nanotechnology aids in cryopreservation techniques for gametes and embryos. By utilizing nanoparticles during freezing processes, researchers have been able to enhance the viability of stored reproductive materials, ensuring successful fertilization when used later. This innovation not only increases reproductive success rates but also contributes to genetic diversity within livestock populations.

Nanotechnology has found extensive applications in animal breeding and reproduction, including the diagnosis and treatment of reproductive issues, estrus detection, and the isolation and freezing of sperm. The use of nanodevices during calving can significantly impact maternal health and address reproductive challenges such as retained placenta, which has been implemented at various stages of production (Swain et al., 2015). For diagnosing infectious diseases of the reproductive tract and hormonal disorders, as well as detecting estrus, researchers have developed a nanosensor featuring a highly sensitive biomolecular probe at the nanoscale (Saragusty and Arav, 2011). Additionally, nanotechnology can facilitate the separation of sperm and oocytes, as well as transport nanocapsules containing bull sperm for direct artificial insemination in cows at elevated temperatures. Biochips and nanomaterials have also been employed to determine fetal gender (Joanitti and Silva, 2014). Some metal nanoparticles, such as cadmium, are toxic even at low concentrations, prompting researchers to explore the development of nanoparticles for animal sterilization contraceptives. Furthermore, nanoparticles enable the sustained release of reproductive hormones in animals, protecting certain hormones and vitamins from oxidation (e.g., vitamins and steroid hormones) or hydrolysis (e.g., gonadotropins) (Joanitti and Silva, 2014). The ultrafast freezing and rapid thawing of animal sperm can be achieved through the

microinjection of propylene glycol, a cryoprotectant containing metal nanoparticles. Nanotechnology also plays a role in the cryopreservation of sperm, oocytes, or embryos (Saragusty and Arav, 2011).

Ethical Considerations and Future Directions

While the potential benefits of nanotechnology in animal husbandry are significant, ethical considerations must be addressed. The principles of the Three Rs are Replacement, Reduction, and Refinement, should guide research involving nanotechnology to minimize pain and distress in animals. Recently introduced is a 4th R, Responsibility, which emphasizes post-experimental care and rehabilitation for animals involved in research. As research continues to explore the full potential of nanotechnology in animal agriculture, it is essential to ensure that these advancements align with ethical standards and public concerns regarding animal welfare. Transparent communication about the benefits and risks associated with nanotechnology will be crucial for gaining acceptance among consumers and stakeholders.

Conclusion and Prospect

Nanotechnology represents a transformative force in animal husbandry, enhancing nutrition, health, and reproduction while addressing critical challenges faced by the industry. By improving feed efficiency, disease management strategies, and reproductive technologies, nanotechnology holds great promise for increasing livestock productivity sustainably. Continued research and development in this field will be vital for fully realizing its potential benefits while ensuring ethical practices that prioritize animal welfare.

Nanotechnology is crucial in animal husbandry, positively influencing various aspects of farmed animals. Therefore, conducting in-depth research in this area is essential. Currently, the application of nanotechnology in pasture management is relatively basic and primarily focuses on animal feeding and production. Consequently, further exploration is needed to uncover additional roles, including nutritional control mechanisms and disease resistance effects. Looking ahead, the application of various nanomaterials and associated nano-formulations in animal husbandry is likely to expand, driven by advancements in nanotechnology within the biomedical field. These developments are expected to transform treatment methods for both humans and animals. As a multidisciplinary area, nanotechnology research encompasses biology, chemistry, engineering, medicine, and physics, necessitating

careful consideration of the characteristics of nanobiotechnology (NBI) when designing safe and effective nanoparticle-based therapeutic and diagnostic systems.

While NPs show promise in enhancing animal genetics and disease treatment, their mechanisms of action remain largely unexplored. The application of nanotechnology in animal husbandry extends beyond disease prevention and control; it also encompasses improvements in nutrition, reproduction, and overall animal welfare. This innovation offers the breeding industry enhanced management systems and breeding models. In summary, nanotechnology presents a wealth of opportunities for advancing animal medicine and health research, providing groundbreaking solutions to longstanding veterinary challenges.

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