Ann. Anim. Sci., Vol. 26 (2026) 717–730 *DOI: 10.2478/aoas-2025-0081*

EMERGING APPLICATIONS OF NANOTECHNOLOGY IN LIVESTOCK: UPDATES AND PERSPECTIVES – A REVIEW

Meemansha Sharma[1♦], Yasotha Tirupathi[2], Raushan Kumar Singh[3], Ajoy Das[4], Thakur Uttam Singh[1], Ayon Tarafdar[4♦]

[1]Division of Pharmacology and Toxicology, ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh 243122, India
[2]Division of Physiology and Climatology, ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh 243122, India
[3]Krishi Vigyan Kendra, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh 250110, India
[4]Livestock Production and Management Section, ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh 243122, India
♦Corresponding author: ayontarafdar@gmail.com; ayon.tarafdar@icar.gov.in; sharmameemansha98@gmail.com

Abstract

Nanotechnology, defined by the manipulation of materials on an atomic or molecular scale, is revolutionizing diverse fields such as medicine and agriculture. In the livestock sector, nanotechnology holds immense promise for enhancing animal health, productivity, and welfare. In this review, we discuss the transformative potential of nanotechnology applications in livestock management, particularly in the areas of drug delivery, disease diagnostics, nutrition, and reproduction. Nanoscale particles enable targeted and controlled release of therapeutics, improving treatment efficacy and reducing side effects. The use of nanosensors for real-time health monitoring facilitates early disease detection and effective disease management. Furthermore, nanotechnology enhances feed efficiency by optimizing nutrient absorption and preventing spoilage through innovative nano-additives and coatings. In reproduction, nanoparticle-based techniques improve the success of artificial insemination and embryo transfer, thus supporting breeding programs. Despite these advancements, the integration of nanotechnology in livestock practices faces challenges related to safety, regulatory approval, and public perception. This review explores the types, synthesis, and characterization of various nanomaterials used in veterinary medicine, including metallic, polymeric, and lipid-based nanoparticles, as well as their applications in stem cell research and regenerative medicine. Current innovations in nanoparticle-mediated vaccine development and disease diagnosis are also explored. The future of nanotechnology in livestock management is likely to involve the development of integrated nanosystems that combine diagnostics, treatment, and monitoring, paving the way for more sustainable and effective agricultural practices. However, comprehensive research is needed to fully understand the long-term impacts of nanoparticles on animal health and the environment, ensuring their safe and responsible use.

Key words: therapeutics, vaccines, disease diagnosis, stem cells, animal science

Nanotechnology, the modification of substances on an atomic or molecular scale, holds immense potential across various fields due to its ability to create materials and devices with novel properties and functions. Nanotechnology replaces old methods and sparks fresh ideas in various fields, including medicine (Malik et al., 2023). In medicine, nanotechnology is revolutionizing diagnostics, therapy and drug transportation (Malik et al., 2023). Treatment efficacy can be increased and negative effects can be decreased by developing nanoscale particles to target particular cells. Moreover, nanodevices like quantum dots and nanosensors enhance imaging and diagnostic accuracy, enabling early disease detection and personalized treatment plans (Khazaei et al., 2023). Nanotechnology is increasingly investigated in the livestock industry, offering promising solutions for improving animal health, productivity, and welfare. Although still in its nascent stages, the integration of nanotechnology in livestock management practices is gaining attraction, driven by the demand for more efficient and sustainable agricultural practices. Nanoparticles are being developed for usage in targeted drug delivery and vaccines, ensuring precise and controlled release of therapeutics (Mitchell et al., 2021). For instance, nanoencapsulation of vaccines can protect the active ingredients from degradation, enhancing their stability and effectiveness. This approach not only improves immunization outcomes but also reduces the frequency of dosing, minimizing stress in animals. Moreover, nanosensors are being utilized for real-time monitoring of livestock health. These sensors can detect biomarkers in bodily fluids, providing early warning signs of diseases or metabolic disorders (Broza et al., 2019). Additionally, nanosensors can monitor environmental conditions such as temperature and humidity, ensuring optimal living conditions for livestock (Younis et al., 2022). Nanotechnology enhances feed efficiency and nutrition by improving nutrient absorption and preventing spoilage through nano-additives and coatings (Prasad et al., 2022). In reproduction, it boosts artificial insemination and embryo transfer success by preserving sperm and embryos, aiding breeding programs in livestock (Mukherjee et al., 2022). Despite these promising

developments, the implementation of nanotechnology in livestock also raises concerns regarding safety, regulatory frameworks, and public acceptance. To assess the long-term impacts of nanoparticles on the animal health and environment, extensive research is required. The use of nanotechnology in livestock activities is anticipated to advance and contribute to more sustainable and effective agricultural systems as research and regulatory frameworks are implemented.

Types, synthesis and characterization of nanomaterials

Nanoparticles are the amazing gift provided from nanomedicines for the diagnosis, treatment, target drug delivery, better animal reproduction, production as well as value added animal products. A wide range of nanoparticles are being employed in veterinary medicine (Table 1), including liposomes, lipid micelles, polymeric nanoparticles, metallic nanoparticles such as iron oxide, zinc oxide, silver, and gold, as well as carbon-based nanoparticles, dendrimers, quantum dots, and nanosensors (Chettupalli at al., 2024; Bai et al., 2018). For the synthesis of nanoparticles, top-down and bottom-up techniques have been used commercially (Figure 1). Bottom–up technique implies the synthesis of nanomaterial from a state of molecular or atomic species via chemical reaction that facilitates the creation of assemblies of complex structure from smaller components (Khan et al., 2022). The materials that are produced by this technique are extremely basic. Chemical vapor deposition, the sol-gel method, pyrolysis, spinning, and biological synthesis are a few methods of bottom-up technique used for the synthesis of polymeric nanoparticles (Khan et al., 2022). However, top-down technique is less commonly utilized which starts with large particles breaking down into tiny molecules. Because the synthetic nanoparticles are composed of extremely basic elements, this technique is sometimes referred to as the building up method. Ball-milling processes, thermal decomposition techniques, lithography techniques, laser ablation, and physical vapor deposition are a few methods of top-down synthesis (Khan et al., 2022). In general, the choice of method for nanoparticle preparation is dependent upon the therapeutic agent and drug delivery carrier molecules (Usman et al., 2020). The nanoparticles containing thermosensitive and less stable therapeutic substances can be prepared by cross linking, drying and reverse micellar techniques (Bashir et al., 2022). In addition, other methods of preparation include high pressure emulsification, emulsion-diffusion method and solvent displacement and precipitation (Table 2). Advanced microscopic technique can be employed to characterize the shape, surface charges and particle size of nanoparticles (Figure 2). Particle size is an important parameter for characterization of nanoparticles. In general, smaller particle size provides larger surface area for most of drug loading and its faster release (Jain and Thareja, 2019). The methods for the nanoparticle size detection are dynamic light scattering (DLS) or photon correlation spectroscopy (PCS) (Ashizawa, 2019). Surface characteristics of newly synthesized nanoparticles such as roughness, porosity and smoothness are usually studied using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) (Falsafi et al., 2020). Doppler anemometry and zetameter (based on electrophoresis principle) are utilized to calculate the zeta potential or electric charges on micro-nanoparticles (Veclin et al., 2022). The specific surface property and drug content of nanomaterials are determined by using X-ray photoelectron spectroscopy (XPS) or time-of-flight secondary ion mass spectrometry (TOF-SIMS) and high-pressure liquid chromatography (HPLC), respectively (Chaupard et al., 2021). XPS and TOF-SIMS are the methods which provide details related to molecular structure, origin of particles and chemical bonding. The drug loading efficiency (% = ratio of amount of drug to total mass of particles) and encapsulation efficiency (% = amount of drug to theoretical amount of drug in same masses) are determined after the drug contents have been analyzed through HPLC.

Table 1. List of different methods for preparing nanoparticles loaded with thermosensitive therapeutic agents

Method	Description	Therapeutic agents	References
1	2	3	4
1. Cross-linking techniques			
a. Physical cross linking	This method allows ionic cross-linking between nanoparticles and cross-linking agent.	Insulin, tetanus toxoid	Chen et al., 2023; Kabiri et al., 2021
b. Chemical cross-linking	Chemical cross-linking with the help of glutaraldehyde or ascorbyl palmitate and p-phthalaldehyde.	NSAIDS (non-steroidal anti-inflammatory drugs), antineoplastic, opioids, antifungal drugs	Dey et al., 2022
2. Drying methods	The process of removal of water or solvent by evaporation from liquid, solid or semisolids. The common methods of drying are spray, freeze and supercritical drying	BSA (bovine serum albumin), salmon calcitonin	Abdelkader et al., 2018

Table 1 – contd.

1	2	3	4
3. Reverse micellar method	Organic solvent mixture containing nanoparticles along with therapeutic agent has been kept overnight after adding the cross-linking agent. Further, drug loaded nanoparticles have removed by centrifugation.	Anticancer drugs	Liao et al., 2021
4. High pressure emulsification	This procedure implies high pressure emulsification of polymer solution into an aqueous solution then removal of organic solvent is done by continuous stirring or by evaporation.	Lipid soluble drugs	Mehanna and Mneimneh, 2021
5. Emulsion-diffusion method	The encapsulated polymer is mixed with water-miscible solvent such as benzyl alcohol, propylene carbonate. Further, emulsification of polymer-water saturated solvent phase is performed in aqueous solution containing stabilizer and then formation of nanoparticles has occurred according to oil : polymer ratio.	Doxorubicin, cyclosporine	Chaudhary et al., 2021; Pandey et al., 2022
6. Solvent displacement and precipitation	This method includes precipitation of preformed polymer from organic solution and diffusion of organic solvent in presence and absence of surfactant.	Poor soluble drugs	Khan et al., 2022

Table 2. Different types of nanoparticles and their therapeutic applications

Nanoparticles	Application	References
Silica based	Drug delivery, bioimaging, biosensors, delivery of vaccine against *Anaplasma marginale* in cattle	Bruckmann et al., 2022; Kumar et al., 2024
Selenium based	Enhance nutrient absorption and boost immunity in animals	Malyugina et al., 2021
Silver	As antimicrobial and anticancer agents, drug delivery, as imaging probes and as diagnostics	Harish et al., 2022
Zinc oxide	As antiviral and anticancer agents, drug delivery carriers, as a growth promotor in pigs	Krishnan et al., 2021; Baholet et al., 2022
Gold	Tumor detection, drug and vaccine delivery, photodermal and photodynamic therapy	Reddy et al., 2023; Danchuk et al., 2023
Iron oxide	Magnetic resonance imaging, cancer diagnosis and treatment	Wu et al., 2022
Polymeric NPs	Delivery of anthrax and tetanus toxoid vaccines, and used as drug carrier	Al-Nemrawi et al., 2022
Carbon and grapheme quantum dots	Bioimaging, cancer therapy, gene and drug delivery	Osorio et al., 2024
Liposomes	Cancer therapy (paclitaxel and vincristine) in dogs, *Toxoplasma gondii* vaccine in sheep, avian colibacillosis vaccine in chickens	Ahmad et al., 2021
Dendrimers	Drug delivery, therapeutics against viral and parasitic diseases and cancer	Folliero et al., 2021; Filipczak et al., 2021

Application of nanotechnology in the livestock sector

Nanotechnology in the livestock sector offers innovative solutions for improving animal health, productivity, and sustainability. It enables precision delivery of drugs and vaccines, enhances feed efficiency, and provides advanced diagnostic tools. Additionally, nanotechnology aids in detecting and controlling diseases, leading to safer and more efficient livestock management. Various applications of different nanoparticles are summarized in Table 3 and Figure 3.

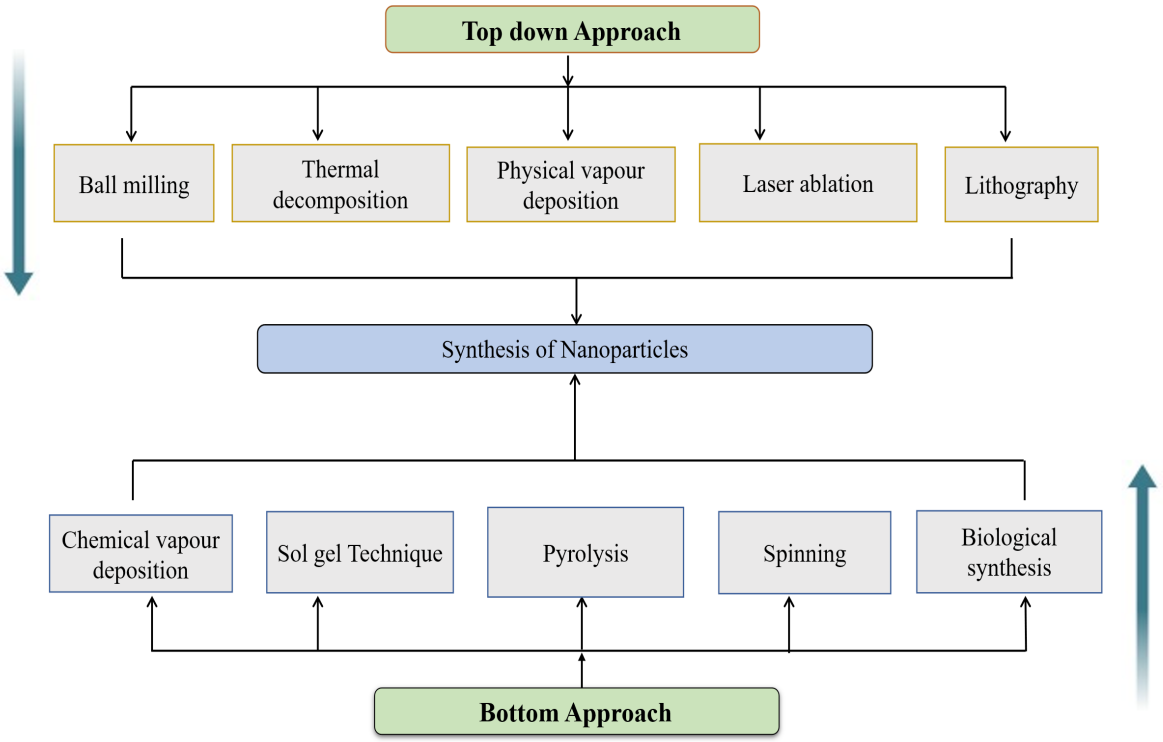


Figure 1. Techniques used in top-down and bottom-up approaches for the nanoparticle synthesis

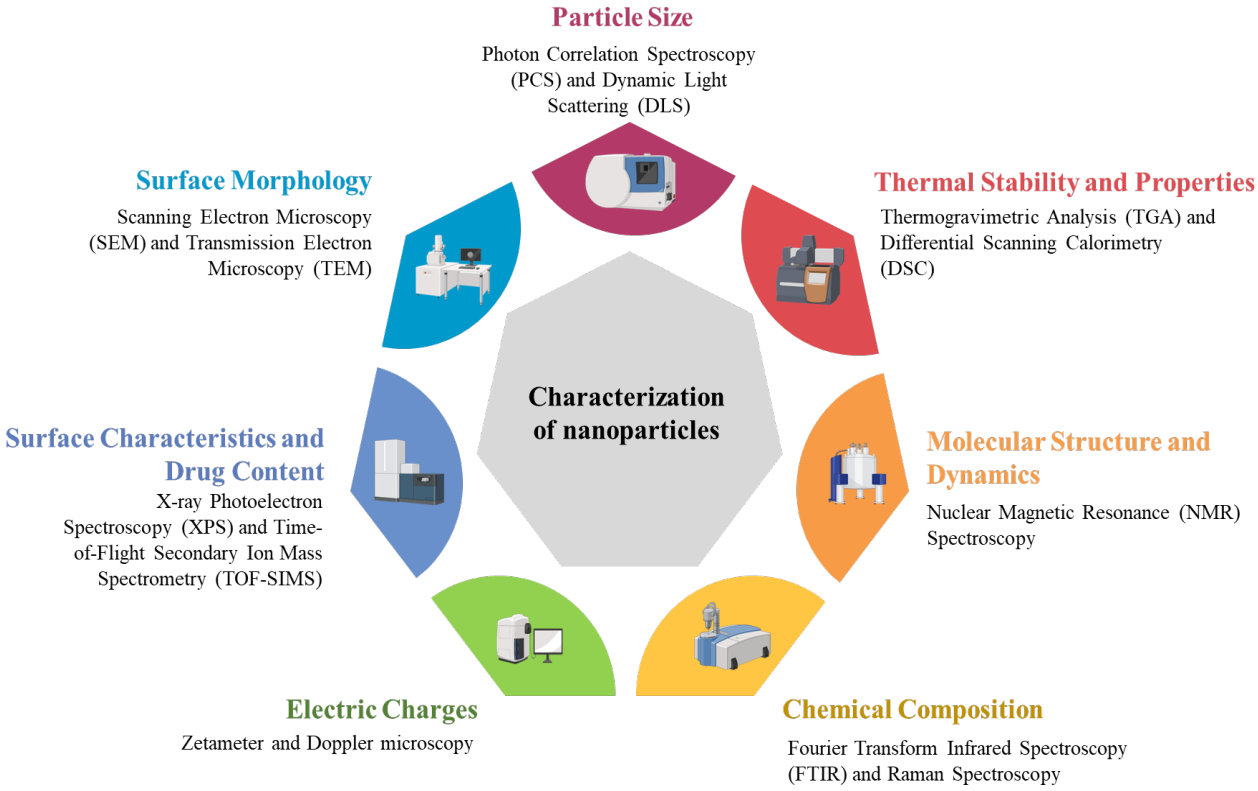


Figure 2. Methods of nanoparticle characterization

Table 3. Various therapeutic applications of nanoparticles in veterinary sector

Categories	Nanoparticles	Species of animals	Application	References
1	2	3	4	5
Drug delivery and therapeutics	Doxorubicin, paclitaxel and vincristine loaded liposomes	Canine	Canine metastatic osteosarcoma	Walewska et al., 2023; Ahmad et al., 2021
	Curcumin loaded silver nanoparticles	Bovine mastitis causing bacteria	Bovine mastitis	Vo-van et al., 2023
	Gold nanoparticles	Canine tumors	Gold NP-mediated photothermal therapy for canine osteosarcoma	Malik et al., 2023
	Polymeric chitosan nanoparticles	Chicken, cow	Colibacillosis, metritis	Carvalho et al., 2021
	Zinc oxide nanoparticles	Canine, equines and other animal species	Neoplastic diseases, mastitis and wound healing	Rahman et al., 2022
	Graphene oxide	Cow	Bovine mastitis	Neculai-valeanu et al., 2021
Vaccines	Gold nanoparticles	Poultry and bovines	Vaccines for influenza, foot-and-mouth disease and listeriosis	Ingrole et al., 2021; Teng et al., 2021; Dykman, 2020
	Silica based NPs	Cattle	Vaccine for *Anaplasma marginale* infection	Kumar et al., 2024
	Oxidized carbon NPs	Mice	Subunit vaccine for *Mycobacterium* tuberculosis	Sawutdeechaikul et al., 2019
	Polymeric NPs	Mice	Anthrax and tetanus toxoid vaccine	Al-Nemrawi et al., 2022
	Liposomes and chitosan polymer	Chicken	Influenza, Newcastle disease, and avian colibacillosis	Yang et al., 2020; Attia et al., 2021; Ahmad et al., 2021
	Dendrimers	Mice	Ebola virus, *Toxoplasma gondii* and H1N1 influenza	Kisakova et al., 2023
Disease diagnosis	Nanosensor of gold nanoparticle quantum dots	Cattle	Bovine tuberculosis, foot-and-mouth disease and bovine mastitis	Tewari et al., 2021; Rios et al., 2024
	Nucleic based nanodiagnostic	Livestock	Viral, bacterial and parasitic infection	Kumar et al., 2024
	Wearable nanosensor	Livestock	Diseases monitoring, behavior tracking, pregnancy detection and nutritional monitoring	Alipio and Villena, 2024
Nutrition	Lipid nanoparticles	Dairy cow	Enhance the rumen bypass efficiency of amino acids	Albuquerque et al., 2020
	Hydroxyapatite nanoparticles	Equine	Reduces release of urea	Reddy et al., 2020
	Selenium NPs	Ruminants	Better growth and enhance immune function	Malyugina et al., 2021
	ZnO NPs	Pig	Improve nutrients absorption as feed additives	Baholet et al., 2022
	Alginate chitosan glycerol NPs	Ruminants	Encapsulating glycerol to bypass rumen fermentation	Hashem and Ganzalez Bulnes, 2021
Reproduction	Propylene glycol	Sheep	Estrous synchronization	Santos-Jimenez et al., 2020; Saadeldin et al., 2020
	GnRH GnRH chitosan TPP Nps	Rabbit	Enhanced follicle growth and ovulation	
	SeNPs	Camel	Enhance the cryoresistance of camel epididymal spermatozoa	Shahin et al., 2020
	ZnONPs	Goat	Enhance post-thaw semen quality	Abedin et al., 2023
	Gamma-oryzanol nanoparticles	Rooster	Enhance the post-thaw quality of rooster sperm	Najafi et al., 2022
	Biochips	Ruminants	Fetus gender determination	Wang et al., 2022

Table 3 – contd.

1	2	3	4	5
Milk production	ZnNPs	Guanzhong dairy goats	Improve lactation and metabolism by modulating the rumen microbiota	Xie at al., 2024
	ZnNPs	Barbari goats	Effectively reduced somatic cell count, indicating improved udder health	Shafi et al., 2020
	ZnNPs	Baladi goats	Increase in milk yield and up-regulation of genes associated with milk production	Mansour et al., 2025
	SeNPs	Dairy goats	Increased milk yield, milk fat, and lactose content	Ying et al., 2025
	CuNPs	*In vitro* (bovine mastitis pathogens)	Biofilms from *S. aureus*, *E. coli*, others nearly fully inhibited	Lange et al., 2021
Meat production	Curcumin nanospheres	Pigs	Enhanced growth performance, improved meat quality, better intestinal health	Moniruzzaman et al., 2023
	Green zinc oxide nanoparticles	Bonsmara steers	Negative effects on growth and meat quality due to potential toxicity	Gamedze et al., 2024
	ZnO/Pectin bionanocomposite films	Poultry	Extended shelf life, reduced microbial growth	Przybyszewska et al., 2023
	Chitosan/Starch films with cellulose nanofibers and cinnamon oil	Beef	Significant microbial load reduction, improved preservation	Sreekanth et al., 2024
	Nanostructured lipid carriers with savory essential oil	Beef	Reduced microbial growth, lower pH and spoilage indicators	Ghasemi et al., 2024
	Chitosan nanoparticles	Pigs	Improved skeletal muscle mass, enhanced meat quality	Gelaye, 2024
Stem cell research	Magnetic nanoparticles	Human lung stem cells	Stem cell level and sorting	Liu et al., 2020
	Gold nanorods Quantum rods Polymeric nanoparticles Iron oxide	Human and animals	Stem cell imaging and tracking	Dong et al., 2021

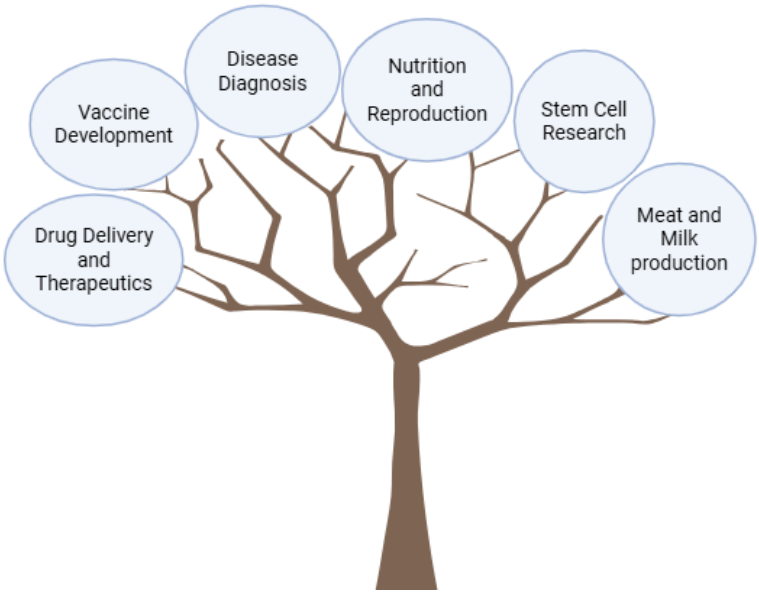


Figure 3. Diverse applications of nanotechnology in the veterinary sector

Drug delivery and therapeutics

Numerous nanocarriers are being utilized for the supply of medicines towards the target site in the body system. Effective concentration at desired site and extended period of retention in bloodstream serves the main purpose of targeted drug delivery of nanoparticles to achieve good efficacy of drugs. Additionally, these nanocarriers have the ability to deliver different water-soluble medications into the brain since they can pass through impermeable barriers like the blood-brain barrier (Zorkina et al., 2020). Moreover, animal antibiotic usage can be decreased and drug residues in animal tissues can be decreased by using nanoparticles for targeted drug delivery (Hanafy, 2018). Drugs used for tumors have been delivered through lipid-based nanomaterials for their efficient delivery towards the target sites (Walewska et al., 2023). Previous research has shown the applicability of various nanoparticles (Nps) like Ag-Nps employed for giving rabies vaccine in dogs (Hassan et al., 2020) and carbon nanoparticles applied in cancer treatment (Zhao et al., 2019). Animal diseases of many kinds are being treated with micronanoparticle-based medicines. Among these nanomaterials, silica based nanoparticles have been easily conjugated with other medicinal compounds and employed as an effective target drug carrier in diseased animals (Hassan et al., 2020). Metallic nanoparticles are frequently utilized in animal medicine, especially against a variety of pathogenic organisms, arthropods, and malignant disorders. Many literatures report that silver nanoparticles exhibit strong bactericidal action against resistant bacterial strains. The antibacterial activity of silver nanoparticles (AgNPs) against *S. aureus* and *P. aeruginosa* proved to be effective in curing mastitis in goats (Yuan et al., 2017). Green AgNPs and their eco-friendly phyto-preparation with neem, 2, 3-dehydrosalanol and quercetin were found effective against arthropods of livestock (Avinash et al., 2017). These green silver nanoparticles were also used in cancerous diseases because they produce selective toxic effects on cancer cells but exhibit less toxic effects on normal cells (Avinash et al., 2017). Frequently occurring neoplastic conditions in animals such as venereal tumor, blood cancer and equine sarcoid could be effectively treated with the ZnO Nps (Rahman et al., 2022; Hozyen et al., 2019). Apart from neoplastic conditions, the other application of ZnO Nps is in subclinical mastitis where they can reduce somatic cell count and enhance milk production in cattle (Rahman et al., 2022; Hozyen et al., 2019). Similarly, a radioactive gold nanoparticle with gum arabic was found effective against prostate cancer in canines (Ambrosio et al., 2022). Iron oxide and platinum containing nanoparticles have shown therapeutic effects in cancerous diseases and also delivered conjugated medicines to the target cancer cells (Hernández et al., 2023). Natural and synthetic polymeric nanoparticles like PEG (polyethylene glycol), PLGA (poly lactic-co-glycolic acid), and PLA (poly lactic acid) are being used in veterinary medicine for their biological properties that include enhanced perfusion, long retaining effects, low toxicity and high solubility in biological fluids (Carvalho et al., 2021). These nanoparticles of polymeric material are applied for many animal diseases caused by different bacteria, viruses and protozoa (Carvalho et al., 2021). Nanoparticles of carbon composite are utilized for a variety of applications including diagnostic and therapeutic in veterinary science. Graphene based single walled nano tubes used as antiviral drug carrier and graphine oxide nanoparticles are found effective against mastitis in cow (Neculai-Valeanu et al., 2021). Liposomes are lipid vesicles with particle size ranging from 50 to 700 nm, and have potential to be used as diagnostic agent in MRI and drug delivery carrier especially in treatment of malignancy (Shivanna et al., 2019). Nanoparticle based nanosensors have been applied for diagnosis of animal diseases in livestock such as anthrax, avian influenza, foot-and-mouth disease, mastitis and bovine tuberculosis (Rios et al., 2024).

Vaccine development

In order to prevent and treat a variety of infectious diseases in cattle, vaccination is a crucial strategy. Nanoparticle based vaccines may increase vaccine efficacy, immune response and make it easier for the vaccine to reach the intended site of action (Pati et al., 2018). Nanocarriers protect the active substances or antigens from destruction and help in their delivery, processing and release (Pati et al., 2018). Generally, nanoparticles have enhanced synthesis of genes involved in defense mechanism and inflammation and are thereby able to induce immune responses in the body (Liu et al., 2022). Among metallic nanoparticles, gold nanoparticle encapsulated antigen of bacteria and virus have been applied to induce immune responses against infectious diseases like influenza (Ingrole et al., 2021), foot-and-mouth disease (Teng et al., 2021), listeriosis (Dykman, 2020). Kumar et al. (2024) demonstrated the application of novel silica-based nanoparticle vaccine against *Anaplasma marginale,* which has been responsible for major threat to cattle industry. Recently, oxidized carbon nanoparticles were applied to deliver recombinant *Mycobacterium tuberculosis* protein effectively and produced robust T-cell responses in mice (Sawutdeechaikul et al., 2019). Natural polymers such as chitosan nanoparticles have been extensively used for vaccine antigen and delivery of drugs because of its lesser toxic load and good adhesive property (Li et al., 2017). Studies show that polymeric nanoparticles such as PLGA (poly lactic-co-glycolic acid) and PLA-PEG (polylactic acid–polyethylene glycol) had been utilized for the delivery of anthrax and tetanus toxoid vaccine antigen, respectively (Al-Nemrawi et al., 2022)). Furthermore, chickens are getting vaccinated against influenza and Newcastle disease via nasal sprays using liposomes and other polymers based on chitosan (Yang et al., 2020; Attia et al., 2021). Some researchers have explored the application of dendrimers such as polypropylene imine (PPI) and polyamido amine (PAMAM) in the transportation of different antigenic molecules. Kisakova et al. (2023) re-

ported that multiple antigens containing dendrimer can generate strong immune response against Ebola virus, *Toxoplasma gondii*, and H1N1 influenza. Biocompatible hollow polymeric and chaperna-based nanoparticles have been utilized for excellent delivery of Middle East respiratory syndrome coronavirus (MERS-CoV) subunit vaccine and its recombinant vaccine, respectively (Lin et al., 2019; Kim et al., 2018). However, gold nanoparticles containing S protein have failed to induce protective antibodies against severe acute respiratory syndrome corona virus (SARS-CoV) infection (Sekimukai et al., 2020).

Disease diagnosis

Nanotechnology offers innovative solutions for disease detection in livestock, significantly enhancing the capacity to monitor and manage animal health. The integration of nano-technique in disease diagnosis is driven by its potential to provide rapid, accurate, and cost-effective diagnostic tools, leading to early disease detection, improved animal welfare, and reduced economic losses (Thwala et al., 2023). One of the key uses is the fabrication of nanosensors, which can detect disease biomarkers in biological samples such as blood, urine, saliva, or breath (Noah and Ndangili, 2022). These sensors, often made from gold nanoparticles or quantum dots, are more specific and sensitive, capable of identifying minute concentrations of biomarkers that indicate diseases like bovine tuberculosis, foot-and-mouth disease, and mastitis in cattle (Tewari et al., 2021). Lab-on-a-chip devices, another nanotechnology innovation, integrate multiple laboratory functions on a single chip, allowing for complex diagnostic tests at the point of care (Manessis et al., 2022). In just a few minutes, these devices may provide thorough health assessments by detecting disease biomarkers using microfluidics and nanomaterials (Manessis et al., 2022). Additionally, nucleic acid-based nanodiagnostics, involving nanoparticles to detect specific DNA or RNA sequences, increase the accuracy and speed of traditional PCR assays, enabling rapid diagnosis of viral, bacterial, or parasitic infections (Kumar et al., 2024). Wearable nanosensors further contribute by continuously monitoring physiological parameters and detecting signs of illness in real-time, allowing for prompt intervention and reducing the spread of contagious diseases within herds (Alipio and Villena, 2023). These advancements collectively promise to transform livestock disease management, making it more efficient, proactive, and sustainable.

Nutrition and reproduction

Utilizing nanoparticles in veterinary sector has shown to have significant promise for enhancing animal nutrition and reproductive health. Vital components like vitamins and minerals are better delivered, absorbed, stabilized, and bioavailable when they are encapsulated by nanoparticles (Arshad et al., 2021). As a case study, it is currently demonstrated that selenium encapsulated in nanoparticles increases absorption in animals, leading to better growth rates and immunological function (Malyugina et al., 2021). Furthermore, nanoparticles enhance feed efficiency by producing more potent feed additives. Nano-sized zinc oxide in pig diet reduces intestinal infections, improves nutrient absorption, and helps in efficient feed utilization that may lead to better growth and promote overall health (Baholet et al., 2022). Moreover, nanotechnology also makes it possible for nutrients to be released under controlled conditions inside the digestive system, assuring a steady supply of vital nutrients that promote greater growth and protect feed expenses (Iqbal et al., 2022).

Researchers are employing nanoparticles to deliver drugs or reproductive hormones straight to the uterus or ovaries in an effort to increase the effectiveness of treatments in the domain of animal reproduction (Saadeldin et al., 2020). In order to induce ovulation in cattle, for instance, gonadotropin delivery methods based on nanoparticles have been investigated. Nano-delivery of reproductive hormones enhances pharmacokinetics and pharmacodynamics, especially for short-lived hormones like GnRH. Biodegradable nanoparticles offer controlled release, improved mucosal absorption, and alternative administration routes. This approach reduces hormone dosage, enhances animal welfare, and minimizes exposure risks for workers in livestock management. A CIDR-based protocol using propylene glycol-diluted GnRH successfully synchronized estrus in sheep (Santos-Jimenez et al., 2020). Additionally, preliminary findings indicate that GnRH-chitosan-TPP nanoparticles enhance follicular growth and ovulation in rabbits, demonstrating their potential as a viable eCG substitute (Saadeldin et al., 2020). Additionally, sperm cells are shielded from oxidative stress by nanotechnology, increasing their viability during storage and raising the success rates of breeding programs, which improves the preservation of semen utilized in artificial insemination (Saadeldin et al., 2020). Now, cryopreservation of sperm, oocytes, or embryos can be accomplished via nanotechnology (Remião et al., 2018). Selenium nanoparticles (SeNPs) and zinc oxide nanoparticles (ZnONPs) have been shown to enhance the cryoresistance of camel epididymal spermatozoa, improving their viability post-thaw (Shahin et al., 2020). Similarly, gamma-oryzanol nanoparticles have been reported to enhance the post-thaw quality of rooster sperm, contributing to better fertility outcomes (Najafi et al., 2022). In goats, ZnO nanoparticles have demonstrated the potential to improve semen quality after freezing and thawing, ensuring higher sperm motility and integrity (Abedin et al., 2023). These findings highlight the promising role of nanotechnology in preserving sperm quality across different livestock species. The gender of the fetus has also been determined using biochips and nanoparticles (Wang et al., 2022). The productivity, well-being, and reproductive efficiency of animals are all being improved by numerous applications of nanotechnology, and this is creating opportunities for more innovative and fruitful approaches to veterinary research.

Stem cell therapy

Stem cells are parent cells to all tissue types of the body and possess the distinct characteristics of self-renewal and differentiation into any type of cell in the body (Siddharth, 2022). The embryonic, adult, and induced pluripotent stem cells are different types based on their developmental potential. The embryonic and induced pluripotent cells can differentiate into any type of cell in the body, whereas the adult stem cell differentiates only into specific cell lineages similar to its origin. Stem cells such as iPSCs (induced pluripotent stem cells) were generated and mesenchymal stem cells (MSCs) were isolated from livestock and pet animals (Weeratunga et al., 2023; Prządka et al., 2021). Nanotechnology and stem cell research are promising research areas, but the application of nanotechnology in livestock stem cell research is an emerging field. Nanotechnology can enhance stem cell applications in cell sorting, imaging, tracking, retention, delivery, directed differentiation and regeneration therapies. Most of the research work on cell imaging, cell sorting, tracking and retention has been carried out in human stem cells. Magnetic nanoparticle (MNP) conjugates were used to label and sort the stem cells by using the magnetic force (Liu et al., 2020). Several reports suggested the higher efficiency of magnetic nanoparticles in isolation and enrichment of stem cells (Semeano et al., 2022; Kuru et al., 2024). The current most widely used methods for tracking injected stem cells include magnetic resonance imaging (MRI) (Klontzas et al., 2021), quantum dots (QDs) (Ma et al., 2023) and gold nanorods (Sun et al., 2019). Quantum dots are known as nanoscale semiconductor crystals, which emit light of various colors based on the size, upon exposure to UV light. CdSe/ZnS quantum dots-labeled MSCs demonstrated success in reducing glucose content in the type-1 diabetic rat model. After 8 weeks of treatment, the fluorescent imaging suggested a significant accumulation of labeled cells in the rat pancreas compared to the control group (Liu et al., 2015). The role of MSC and macrophages in vascular regeneration was demonstrated using golden nanorods. Photoacoustic imaging for cell tracking and the detection of infiltrating macrophages in the wound area was demonstrated by Ricles et al. (2014) with the use of dual golden nanorods. The higher efficiency of nanoparticles in improving the number and retention of transplanted cells at the site of repair has been proven in many disease models including liver (Wang et al., 2016), heart (Wang and Bai, 2023), vascular system (Wang and Bai, 2023) and brain (Shen et al., 2016). Human neuroprogenitor cells (hNPCs) labeled with ultrasmall superparamagnetic iron oxide (USPIO) nanoparticle Molday ION Rhodamine B (MIRB™), enhanced the cell retention at the cortical site of the brain in traumatic brain injury model in rats (Shen et al., 2016). Stem cells are highly responsive to the biochemical and biophysical cues received from their environment. Stem cells grown on nano-scaffold coupled with growth factors can improve the outcome of regeneration therapies with the achievement of directed differentiation. In response to nano-topography, stem cells establish integrin-mediated focal adhesions, which initiate the events of mechanical transduction and ultimately lead to changes in gene and protein levels and the differentiation status of the cells (Lee et al., 2017). Nano-fiber, nano-tube and micro/nano vesicles have been successfully utilized to direct stem cell differentiation. The collagen-nanoparticle composite fiber induced the tenogenic differentiation of adipose-derived stem cells by topographical cues received from the collagen fibril and the controlled release of PDGFs (platelet-derived growth factor) (Cheng et al., 2014). Thin film scaffolds made of carbon nanotubes (CNT), chitosan and poly-Ɛ-caprolactone were used to culture canine BMSCs (bone-marrow derived MSCs) and they showed the similar rate of proliferation as that of the standard method (Das et al., 2017 a). Canine BMSCs cultured over hydroxyl functionalized multiwalled CNT showed reduced proliferation and enhanced osteogenic and chondrogenic differentiation, whereas neuronal differentiation was supported by single walled CNT (Das et al., 2017 b; Madhusoodan et al., 2019). Nerve growth factor encapsulated chitosan nanoparticles transdifferentiated canine MSCs into nerve cells (Mili et al., 2018). In canine iPSC culture, functionalized CNTs were used as a feeder layer and found suitable for supporting cardiac and neuronal differentiation (Natarajan et al., 2021; Mondal et al., 2022). Rabbit BMSC-laden nanocomposite scaffolds also showed enhanced bone regeneration in rabbit critical size segmental bone defect model (Kalaiselvan et al., 2024). These research findings indicate the significant potential of nanomaterials in directing stem cell fate and tremendous possibilities of applications in regenerative medicine.

Milk production

Nanotechnology has emerged as a promising tool to enhance milk production and quality in livestock. Recent studies have explored the effects of various nanoparticles, particularly zinc oxide (ZnO) and selenium (Se) nanoparticles, on lactation performance, nutrient utilization, and udder health. Zinc is an essential trace element involved in numerous physiological functions. Traditional zinc supplements often suffer from low bioavailability, leading to inefficiencies and environmental concerns. Recent studies have demonstrated that zinc oxide nanoparticles (ZnONPs) can overcome these limitations. A study by Xie at al. (2024) investigated the effects of dietary ZnONPs on dairy goats. The supplementation with ZnONPs at 30 mg/kg dry matter in Guanzhong dairy goats led to increased milk yield and fat content. The treatment also positively influenced rumen microbiota, enhancing the abundance of beneficial bacteria like *Prevotella*, which are associated with improved nutrient absorption and energy metabolism. Dietary inclusion of nano zinc at 10 and 20 ppm did not significantly alter milk composition but effectively reduced somatic cell count, indicating improved udder health in Barbari

goats (Shafi et al., 2020). Supplementation with ZnONPs at 15 mg/day led to a significant increase in milk yield and upregulation of genes associated with milk production, such as POU1F1, IGF-1, PPARγ, CSN2, and FASN in Baladi goats (Mansour et al., 2025). Selenium plays a crucial role in antioxidant defense and immune function. Under heat stress conditions, dairy animals often experience oxidative stress, leading to decreased milk production. A recent study explored the impact of selenium nanoparticles (SeNPs) supplementation in dairy goats subjected to heat stress. The findings revealed that SeNPs significantly increased milk yield, milk fat, and lactose content. This enhancement was attributed to the modulation of rumen microbiota, notably increasing beneficial bacteria like *Prevotella* and *Ruminococcus*, which improved fiber degradation and energy metabolism. Additionally, SeNPs enhanced antioxidant capacity by upregulating glutathione metabolism, thereby mitigating oxidative stress associated with heat stress (Ying et al., 2025). Copper is vital for various enzymatic processes and immune function. Traditional copper supplements can interact with dietary antagonists, reducing their efficacy. A study evaluated the use of copper oxide nanoparticles (CuONPs) coated with lysine in dairy cows. The results indicated that CuONPs maintained adequate copper status in cows, even in the presence of antagonists like sulfur and molybdenum. This suggests that CuONPs can serve as a more effective copper source, potentially supporting better health and productivity in dairy animals (Williams et al., 2024). Mastitis, particularly in its subclinical form, can significantly lower milk yield; therefore, its prevention is crucial for maintaining or even improving milk production. Lange et al. (2021) found that 200 ppm CuNPs significantly reduce biofilms of major mastitis pathogens. Nanoparticles, including CuNPs, generate reactive oxygen species (ROS), disrupt bacterial membranes, and impair biofilm structures. Kalinska et al. (2019) confirmed CuNPs can reduce pathogen viability with low mammary-cell toxicity. Reducing mastitis incidence and severity theoretically supports higher milk yield, improved quality, and reduced somatic cell count (SCC).

Meat production

Incorporating nanoparticles into animal feed has shown promise in improving nutrient absorption, growth performance, and meat quality. For instance, nanoemulsions containing omega-3 fatty acids have been found to increase the content of beneficial fatty acids in poultry meat and eggs, enhancing their nutritional value (Almeida et al., 2024). The overuse of antibiotics in livestock has led to increased antimicrobial resistance. Recent research suggests that carbon and polymer-based nanoparticles can serve as effective substitutes for antibiotics, reducing the prevalence of resistant pathogens and promoting healthier meat production. Advancements in nanotechnology have also facilitated the development of cultured meat. Nanomaterials are utilized in scaffolding techniques to support cell growth and tissue formation, aiming to replicate the texture and flavor of conventional meat. This approach addresses ethical concerns and environmental impacts associated with traditional meat production (Ebenebe et al., 2024). Dietary inclusion of curcumin nanospheres in pigs led to improved growth metrics, meat quality, and gut health without adverse effects (Moniruzzaman et al., 2023). Supplementation of chitosan nanoparticles in pigs resulted in increased skeletal muscle mass and better meat quality by modulating fatty acid synthesis (Gelaye, 2024). Contrary to this, green zinc oxide nanoparticles in steers negatively impacted growth and meat quality, possibly due to toxicity from phytochemicals used in their synthesis (Gamedze et al., 2024). ZnO/pectin bionanocomposite films effectively reduced microbial growth, extending shelf life in poultry meat (Przybyszewska et al., 2023). Chitosan/starch films with cellulose nanofibers and cinnamon oil were used for raw beef packaging and these films significantly decreased microbial load, enhancing preservation (Sreekanth et al., 2024). Nanostructured lipid carriers with savory essential oil coatings on beef showed reduced microbial counts and spoilage indicators, improving meat stability (Ghasemi et al., 2024).

Conclusion

Nanotechnology has the potential to revolutionize livestock management by offering unprecedented advancements in disease prevention, diagnostics, nutrition, and reproduction. This technique can help improve animal health, lessen the need for antibiotics, and increase overall production by facilitating accurate drug administration, nanoencapsulation of bioactive substances, and real-time disease monitoring. Additionally, nanoscale innovations in feed supplements, nutrient absorption, and reproductive success are set to optimize livestock efficiency and welfare. Beyond these applications, nanotechnology is also revolutionizing meat and milk production by enhancing product quality, safety, and shelf-life. In order to ensure safer and longer-lasting dairy and meat products, nano-based packaging and preservation procedures minimize microbial contamination and spoiling. Moreover, real-time pathogen and contaminant detection via nanosensors enhances food safety and consumer confidence. In stem cell research and regenerative veterinary medicine, nanotechnology plays a critical role in tissue engineering and targeted cell therapy. By promoting stem cell differentiation, proliferation, and targeted delivery, nanostructured scaffolds and nanoparticles provide new therapeutic options for musculoskeletal injuries, reproductive issues, and organ regeneration in animals. However, the widespread adoption of nanotechnology in livestock management must address critical challenges, including safety concerns, regulatory frameworks, and public acceptance. In order to maximize advantages while reducing potential hazards, it will be essential to ensure the appropriate use of nanomaterials by means of thorough research and open communication. Nanotech-

nology has the potential to completely transform livestock management with further development and regulatory control, resulting in better-quality products, healthier animals, and a more sustainable agricultural future.

Future perspective

As nanotechnology continues to advance, its role in livestock management is expected to expand, driving innovation in disease management, nutrition, reproduction, and overall productivity in livestock. Future advancements will probably concentrate on precision livestock farming, where real-time surveillance of environmental variables, disease biomarkers, and animal health is made possible by nanosensors and intelligent monitoring systems. These advancements will help in early disease detection, reducing the need for antibiotics and improving livestock welfare through timely interventions. The future of nanomaterials will improve food safety, quality, and sustainability in the production of meat and milk. Cutting-edge nano-packaging technologies with oxygen-scavenging and antibacterial qualities will minimize food waste by extending shelf life and lowering spoilage. Furthermore, the incorporation of nanoscale food safety sensors in retail and processing settings would enable immediate contamination detection, guaranteeing both consumer safety and legal compliance. Additionally, feed additives made using nanotechnology will improve nutrient absorption and bioavailability, which will boost growth rates and reproductive efficiency. New nano-based supplements will optimize feed utilization while minimizing environmental waste by being customized for species-specific metabolic needs. Nanotechnology is revolutionizing stem cell research and regenerative veterinary medicine by developing biocompatible nanoscaffolds for organ and tissue regeneration, offering new treatments for musculoskeletal injuries and reproductive health disorders. Despite these promising advancements, the widespread adoption of nanotechnology in livestock management will require significant efforts to address biosafety, regulatory frameworks, and ethical considerations. Future research must focus on assessing the long-term effects of nanomaterials on animal health, food safety, and environmental sustainability. Nanotechnology is expected to become a key component in contemporary livestock management as a result of continuous technological advancement. Its integration with regenerative medicines, nutrition, disease management, and food safety will make agriculture more robust, sustainable, and efficient, ultimately ensuring food production for coming generations.

Conflict of interest

The authors declare that they have no conflict of interest.

References

Abdelkader H., Hussain S.A., Abdullah N., Kmaruddin S. (2018). Review on micro-encapsulation with chitosan for pharmaceuticals applications. MOJ Curr. Res. Rev., 1: 77–84.

Abedin S.N., Baruah A., Baruah K.K., Kadirvel G., Katiyar R., Khargharia G., Bora A., Dutta D.J., Sinha S., Tamuly S., Phookan A., Deori S. (2023). In vitro and in vivo studies on the efficacy of zinc-oxide and selenium nanoparticle in cryopreserved goat (*Capra hircus*) spermatozoa. Biol. Trace Elem. Res., 201: 4726–4745.

Ahmad S.U., Li B., Sun J., Arbab S., Dong Z., Cheng F., Zhou X., Mahfuz S., Zhang J. (2021). Recent advances in microencapsulation of drugs for veterinary applications. J. Vet. Pharmacol. Ther., 44: 298–312.

Albuquerque J., Casal S., Páscoa R.N.M.J., Van Dorpe I., Fonseca A.J.M., Cabrita A.R.J., Neves A.R., Reis S. (2020). Applying nanotechnology to increase the rumen protection of amino acids in dairy cows. Sci. Rep., 10: 6830.

Alipio M., Villena M.L. (2023). Intelligent wearable devices and biosensors for monitoring cattle health conditions: A review and classification. Smart Health, 27: 100369.

Almeida C.F., Faria M., Carvalho J., Pinho E. (2024). Contribution of nanotechnology to greater efficiency in animal nutrition and production. J. Anim. Physiol. Anim. Nutr., 108: 1430–1452.

Al-Nemrawi N.K., Darweesh R.S., Al-Shriem L.A., Al-Qawasmi F.S., Emran S.O., Khafajah A.S., Abu-Dalo M.A. (2022). Polymeric nanoparticles for inhaled vaccines. Polymers, 14: 4450.

Ambrosio N., Voci S., Gagliardi A., Palma E., Fresta M., Cosco D. (2022). Application of biocompatible drug delivery nanosystems for the treatment of naturally occurring cancer in dogs. J. Funct. Biomater., 13: 116.

Arshad R., Gulshad L., Haq I.U., Farooq M.A., Al-Farga A., Siddique R., Manzoor M.F., Karrar E. (2021). Nanotechnology: A novel tool to enhance the bioavailability of micronutrients. Food Sci. Nutr., 9: 3354–3361.

Ashizawa K. (2019). Nanosize particle analysis by dynamic light scattering (DLS). Yakugaku Zasshi, 139: 237.

Attia M.A., Essa E.A., Elebyary T.T., Faheem A.M., Elkordy A.A. (2021). Brief on recent application of liposomal vaccines for lower respiratory tract viral infections: from influenza to COVID-19 vaccines. Pharmaceuticals, 14: 1173.

Avinash B., Venu R., Prasad T.N., Alpha Raj M., Srinivasa Rao K., Srilatha C. (2017). Synthesis and characterisation of neem leaf extract, 2,3-dehydrosalanol and quercetin dihydrate mediated silver nanoparticles for therapeutic applications. IET Nanobiotechnol., 11: 383–389.

Baholet D., Skalickova S., Batik A., Malyugina S., Skladanka J., Horky P. (2022). Importance of zinc nanoparticles for the intestinal microbiome of weaned piglets. Front. Vet. Sci., 9: 852085.

Bai D.P., Lin X.Y., Huang Y.F., Zhang X.F. (2018). Theranostics aspects of various nanoparticles in veterinary medicine. Int. J. Mol. Sci., 19: 3299.

Bashir S.M., Ahmed Rather G., Patrício A., Haq Z., Sheikh A.A., Shah M.Z.U.H., Singh H., Khan A.A., Imtiyaz S., Ahmad S.B., Nabi S., Rakhshan R., Hassan S., Fonte P. (2022). Chitosan nanoparticles: a versatile platform for biomedical applications. Materials, 15: 6521.

Broza Y.Y., Zhou X., Yuan M., Qu D., Zheng Y., Vishinkin R., Khatib M., Wu W., Haick H. (2019). Disease detection with molecular biomarkers: from chemistry of body fluids to nature-inspired chemical sensors. Chem. Rev., 119: 11761–11817.

Bruckmann F.D.S., Nunes F.B., Salles T.D.R., Franco C., Cadoná F.C., Bohn Rhoden C.R. (2022). Biological applications of silica-based nanoparticles. Magnetochemistry, 8: 131.

Carvalho S.G., Silvestre A.L.P., Martins Dos Santos A., Fonseca-Santos B., Rodrigues W.D., Palmira Daflon Gremião M., Chorilli M., Villanova J.C.O. (2021). Polymeric-based drug delivery systems for veterinary use: state of the art. Int. J. Pharm., 604: 120756.

Chaudhary S.A., Patel D.M., Patel J.K., Patel D.H. (2021). Solvent emulsification evaporation and solvent emulsification diffusion techniques for nanoparticles. In: Emerging Technologies for Nanoparticle Manufacturing. Springer, pp. 287–300.

Chaupard M., de Frutos M., Gref R. (2021). Deciphering the structure and chemical composition of drug nanocarriers: from bulk approaches to individual nanoparticle characterization. Part. Part. Syst. Char., 38: 2100022.

Chen S., Miao Q., Liu Y., Xiao Q., Lin Y., Yang Y., Guo F. (2023).

Construction and functional evaluation of oral long-acting insulin hydrogel microparticles based on physical and chemical double crosslinking. Int. J. Biol. Macromol., 253: 126915.
Cheng X., Tsao C., Sylvia V.L., Cornet D., Nicolella D.P., Bredbenner T.L., Christy R.J. (2014). Platelet-derived growth-factor-releasing aligned collagen-nanoparticle fibers promote the proliferation and tenogenic differentiation of adipose-derived stem cells. Acta Biomater., 10: 1360–1369.
Chettupalli A.K., Srivani A., Sarvani P., Unnisa A. (2024). Nanoparticles and their prospective solicitations in veterinary medicine. In: Sustainable Agriculture Reviews: Animal Biotechnology for Livestock Production 4. Springer, pp. 229–262.
Danchuk O., Levchenko A., da Silva Mesquita R., Danchuk V., Cengiz S., Cengiz M., Grafov A. (2023). Meeting contemporary challenges: development of nanomaterials for veterinary medicine. Pharmaceutics, 15: 2326.
Das K., Mili B., Madhusoodan A.P., Saxena A.C., Kumar A., Singh P., Verma M.R., Sarkar M., Bag S. (2017 a). Proliferation of canine bone marrow derived mesenchymal stem cells on different nanomaterial based thin film scaffolds. Tissue Cell, 49: 270–274.
Das K., Madhusoodan A.P., Mili B., Kumar A., Saxena A.C., Kumar K., Sarkar M., Singh P., Srivastava S., Bag S. (2017 b). Functionalized carbon nanotubes as suitable scaffold materials for proliferation and differentiation of canine mesenchymal stem cells. Int. J. Nanomed., 12: 3235–3252.
Dey S., Majumdar S., Hasnain M.S., Nayak A.K. (2022). Cross-linking of chitosan in drug delivery. In: Chitosan in Drug Delivery. Academic Press, pp. 277–299.
Dong Y., Wu X., Chen X., Zhou P., Xu F., Liang W. (2021). Nanotechnology shaping stem cell therapy: recent advances, application, challenges, and future outlook. Biomed. Pharmacother., 137: 111236.
Dykman L.A. (2020). Gold nanoparticles for preparation of antibodies and vaccines against infectious diseases. Expert Rev. Vaccines, 19: 465–477.
Ebenebe C.I., Iheukwumere E.I., Ezenyilimba B.N., Oyisi M., Ekugba C.U., Nwankwo C.A., Ikeogu C.F. (2024). Nanotechnology in livestock production: a review. e-Proc. Fac. Agric. Int. Conf., pp. 262–266.
Falsafi S.R., Rostamabadi H., Assadpour E., Jafari S.M. (2020). Morphology and microstructural analysis of bioactive-loaded micro/nanocarriers via microscopy techniques; CLSM/SEM/TEM/AFM. Adv. Colloid Interface Sci., 280: 102166.
Filipczak N., Yalamarty S.S.K., Li X., Parveen F., Torchilin V. (2021). Developments in treatment methodologies using dendrimers for infectious diseases. Molecules, 26: 3304.
Folliero V., Zannella C., Chianese A., Stelitano D., Ambrosino A., De Filippis A., Galdiero M., Franci G., Galdiero M. (2021). Application of dendrimers for treating parasitic diseases. Pharmaceutics, 13: 343.
Gamedze N.P., Mthiyane D.M.N., Kgaswane K.S., Mavengahama S., Onwudiwe D.C. (2024). Growth, physiological responses, and meat quality of feedlot-finished Bonsmara steers offered unprocessed *Mucuna pruriens utilis* seed meal with or without conventional and green zinc oxide nanoparticles. Trop. Anim. Health Prod., 56: 1–13.
Gelaye Y. (2024). Application of nanotechnology in animal nutrition: bibliographic review. Cogent Food Agric., 10: 2290308.
Ghasemi M.A.G., Hamishehkar H., Javadi A., Homayouni-Rad A., Jafarizadeh-Malmiri H. (2024). Natural-based edible nanocomposite coating for beef meat packaging. Food Chem., 435: 137582.
Hanafy M.H. (2018). Myconanotechnology in veterinary sector: status quo and future perspectives. Int. J. Vet. Sci. Med., 6: 270–273.
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: 457.
Hashem N.M., Gonzalez-Bulnes A. (2021). Nanotechnology and reproductive management of farm animals: challenges and advances. Animals, 11: 1932.
Hassan A.A., Mansour M.K., El Hamaky A.M., El Ahl R.M.S., Oraby N.H. (2020). Nanomaterials and nanocomposite applications in veterinary medicine. In: Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems. Elsevier, pp. 583–638.
Hernández Á.P., Iglesias-Anciones L., Vaquero-González J.J., Piñol R., Criado J.J., Rodriguez E., Juanes-Velasco P., García-Vaquero M.L., Arias-Hidalgo C., Orfao A., Millán Á. (2023). Enhancement of tumor cell immunogenicity and antitumor properties derived from platinum-conjugated iron nanoparticles. Cancers, 15: 3204.
Hozyen H.F., Ibrahim E.S., Khairy E.A., El-Dek S.I. (2019). Enhanced antibacterial activity of capped zinc oxide nanoparticles: a step towards the control of clinical bovine mastitis. Vet. World, 12: 1225.
Ingrole R.S.J., Tao W., Joshi G., Gill H.S. (2021). M2e conjugated gold nanoparticle influenza vaccine displays thermal stability at elevated temperatures and confers protection to ferrets. Vaccine, 39: 4800–4809.
Iqbal M., Niazi M.B.K., Jahan Z., Ahmad T., Hussain Z., Sher F. (2022). Fabrication and characterization of carbon-based nanocomposite membranes for packaging application. Polym. Bull., 79: 5019–5040.
Jain A.K., Thareja S. (2019). In vitro and in vivo characterization of pharmaceutical nanocarriers used for drug delivery. Artif. Cells Nanomed. Biotechnol., 47: 524–539.
Kabiri M., Bolourian H., Dehghan S., Tafaghodi M. (2021). The dry powder formulation of mixed cross-linked dextran microspheres and tetanus toxoid-loaded trimethyl chitosan nanospheres as a potent adjuvant for nasal delivery system. Iran. J. Basic Med. Sci., 24: 116–122.
Kalaiselvan E., Maiti S.K., Shivaramu S., Banu S.A., Sharun K., Mohan D., Palakkara S., Bag S., Sahoo M., Ramalingam S., Hescheler J. (2024). Bone marrow-derived mesenchymal stem cell-laden nanocomposite scaffolds enhance bone regeneration in rabbit critical-size segmental bone defect model. J. Funct. Biomater., 15: 66.
Kalinska A., Jaworski S., Wierzbicki M., Gołębiewski M. (2019). Silver and copper nanoparticles – an alternative in future mastitis treatment and prevention? Int. J. Mol. Sci., 20: 1672.
Khan K.U., Minhas M.U., Badshah S.F., Suhail M., Ahmad A., Ijaz S. (2022). Overview of nanoparticulate strategies for solubility enhancement of poorly soluble drugs. Life Sci., 291: 120301.
Khazaei M., Hosseini M.S., Haghighi A.M., Misaghi M. (2023). Nanosensors and their applications in early diagnosis of cancer. Sens. Bio-Sens. Res., 39: 100569.
Kim Y.S., Son A., Kim J., Kwon S.B., Kim M.H., Kim P., Yu J.E. (2018). Chaperna-mediated assembly of ferritin-based Middle East respiratory syndrome-coronavirus nanoparticles. Front. Immunol., 9: 1093.
Kisakova L.A., Apartsin E.K., Nizolenko L.F., Karpenko L.I. (2023). Dendrimer-mediated delivery of DNA and RNA vaccines. Pharmaceutics, 15: 1106.
Klontzas M.E., Kakkos G.A., Papadakis G.Z., Marias K., Karantanas A.H. (2021). Advanced clinical imaging for the evaluation of stem cell-based therapies. Expert Opin. Biol. Ther., 21: 1253–1264.
Krishnan S., Thirunavukarasu A., Jha N.K., Gahtori R., Roy A.S., Dholpuria S., Kesari K.K., Singh S.K., Dua K., Gupta P.K. (2021). Nanotechnology-based therapeutic formulations in the battle against animal coronaviruses: an update. J. Nanopart. Res., 23: 1–16.
Kumar R., Chowdhury A., Mamatha D., Rose M.K., Ghosh M. (2024). Nanotechnology in protozoan livestock disease diagnosis. In: Nanotechnology Theranostics in Livestock Diseases and Management. Springer, pp. 177–194.
Kuru C.İ., Ulucan-Karnak F., Dayıoğlu B., Şahinler M., Şendemir A., Akgöl S. (2024). Affinity-based magnetic nanoparticle development for cancer stem cell isolation. Polymers, 16: 196.
Lange A., Grzenia A., Wierzbicki M., Strojny-Cieslak B., Kalińska A., Gołębiewski M., Radzikowski D., Sawosz E., Jaworski S. (2021). Silver and copper nanoparticles inhibit biofilm formation by mastitis pathogens. Animals, 11: 1884.
Lee L.C., Gadegaard N., De Andrés M.C., Turner L.A., Burgess K.V., Yarwood S.J., Wells J., Salmeron-Sanchez M., Meek D., Oreffo R.O., Dalby M.J. (2017). Nanotopography controls cell cycle changes involved with skeletal stem cell self-renewal and multipotency. Biomaterials, 116: 10–20.

Li D., Fu D., Kang H., Rong G., Jin Z., Wang X., Zhao K. (2017). Advances and potential applications of chitosan nanoparticles as a delivery carrier for the mucosal immunity of vaccine. Curr. Drug Deliv., 14: 27–35.

Liao J., Peng H., Liu C., Li D., Yin Y., Lu B., Zheng H., Wang Q. (2021). Dual pH-responsive-charge-reversal micelle platform for enhanced anticancer therapy. Mater. Sci. Eng. C, 118: 111527.

Lin L.C.W., Huang C.Y., Yao B.Y., Lin J.C., Agrawal A., Algaissi A., Chang Y.C. (2019). Viromimetic STING agonist-loaded hollow polymeric nanoparticles for safe and effective vaccination against Middle East respiratory syndrome coronavirus. Adv. Funct. Mater., 29: 1807616.

Liu D., Hong Y., Li Y., Hu C., Yip T.C., Yu W.K., Zhu Y., Fong C.C., Wang W., Au S.K., Wang S., Yang M. (2020). Targeted destruction of cancer stem cells using multifunctional magnetic nanoparticles that enable combined hyperthermia and chemotherapy. Theranostics, 10: 1181–1196.

Liu H., Tang W., Li C., Lv P., Wang Z., Liu Y., Zhang C., Bao Y., Chen H., Meng X., Song Y. (2015). CdSe/ZnS quantum dots-labeled mesenchymal stem cells for targeted fluorescence imaging of pancreas tissues and therapy of type 1 diabetic rats. Nanoscale Res. Lett., 10: 265.

Liu J., Liu Z., Pang Y., Zhou H. (2022). The interaction between nanoparticles and immune system: application in the treatment of inflammatory diseases. J. Nanobiotechnol., 20: 127.

Ma X., Luan Z., Li J. (2023). Inorganic nanoparticles-based systems in biomedical applications of stem cells: opportunities and challenges. Int. J. Nanomed., pp. 143–182.

Madhusoodan A.P., Das K., Mili B., Kumar K., Kumar A., Saxena A.C., Singh P., Dutt T., Bag S. (2019). *In vitro* proliferation and differentiation of canine bone marrow derived mesenchymal stem cells over hydroxyl functionalized CNT substrates. Biotechnol. Rep., 24: e00387.

Malik S., Muhammad K., Waheed Y. (2023). Emerging applications of nanotechnology in healthcare and medicine. Molecules, 28: 6624.

Malyugina S., Skalickova S., Skladanka J., Slama P., Horky P. (2021). Biogenic selenium nanoparticles in animal nutrition: a review. Agriculture, 11: 1244.

Manessis G., Gelasakis A.I., Bossis I. (2022). Point-of-care diagnostics for farm animal diseases: from biosensors to integrated lab-on-chip devices. Biosensors, 12: 455.

Mansour H., Aboamer A.A., Agamy R., Ali S.M., Mohamed M.Y., Abd El-Aziz M.E., Darwish A.M., Khalil W.K.B., Farag I.M (2025). Effect of zinc oxide and selenium nanoparticles on milk production efficiency and related gene expression in Egyptian Baladi goats. Egypt. J. Chem., 68: 445–454.

Mehanna M.M., Mneimneh A.T. (2021). Formulation and applications of lipid-based nanovehicles: spotlight on self-emulsifying systems. Adv. Pharm. Bull., 11: 56.

Mili B., Das K., Kumar A., Saxena A.C., Singh P., Ghosh S., Bag S. (2018). Preparation of NGF encapsulated chitosan nanoparticles and its evaluation on neuronal differentiation potentiality of canine mesenchymal stem cells. J. Mater. Sci. Mater. Med., 29: 1–13.

Mitchell M.J., Billingsley M.M., Haley R.M., Wechsler M.E., Peppas N.A., Langer R. (2021). Engineering precision nanoparticles for drug delivery. Nat. Rev. Drug Discov., 20: 101–124.

Mondal T., Das K., Singh P., Natarajan M., Manna B., Ghosh A., Singh P., Saha S.K., Dhama K., Dutt T., Bag S. (2022). Thin films of functionalized carbon nanotubes support long-term maintenance and cardio-neuronal differentiation of canine induced pluripotent stem cells. Nanomedicine, 40: 102487.

Moniruzzaman M., Kim D., Kim H., Kim N., Chin S., Karthikeyan A., Han K., Min T. (2023). Evaluation of dietary curcumin nanospheres as phytobiotics on growth performance, serum biochemistry, nutritional composition, meat quality, gastrointestinal health, and fecal condition of finishing pigs. Front. Vet. Sci., 10: 1127309.

Mukherjee S., Togla O., Mukherjee A. (2022). Nanotechnology in animal breeding and reproduction. Recent Adv. Appl. Nanotechnol. Livest. Prod. Manag., The Agriculture Publication, Jaipur, pp. 142–174.

Najafi A., Daghigh-Kia H., Mehdipour M., Mohammadi H., Hamishehkar H. (2022). Comparing the effect of rooster semen extender supplemented with gamma-oryzanol and its nano form on post-thaw sperm quality and fertility. Poult. Sci., 101: 101637.

Natarajan M., Singh P., Mondal T., Kumar K., Das K., Dutt T., Bag S. (2021). *In vitro* propagation and cardiac differentiation of canine induced pluripotent stem cells on carbon nanotube substrates. Tissue Cell, 71: 101571.

Neculai-Valeanu A.S., Ariton A.M., Mădescu B.M., Rîmbu C.M., Creangă Ş. (2021). Nanomaterials and essential oils as candidates for developing novel treatment options for bovine mastitis. Animals, 11: 1625.

Noah N.M., Ndangili P.M. (2022). Nanosensor arrays: innovative approaches for medical diagnosis. In: Nanosensors for Futuristic Smart and Intelligent Healthcare Systems. CRC Press, pp. 350–386.

Osorio H.M., Castillo-Solís F., Barragán S.Y., Rodríguez-Pólit C., Gonzalez-Pastor R. (2024). Graphene quantum dots from natural carbon sources for drug and gene delivery in cancer treatment. Int. J. Mol. Sci., 25: 10539.

Pandey V., Haider T., Agrawal P., Soni S., Soni V. (2022). Advances in natural polymeric nanoparticles for the drug delivery. In: Advanced Drug Delivery Systems. IntechOpen: London, UK.

Pati R., Shevtsov M., Sonawane A. (2018). Nanoparticle vaccines against infectious diseases. Front. Immunol., 9: 2224.

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

Prządka P., Buczak K., Frejlich E., Gąsior L., Suliga K., Kiełbowicz Z. (2021). The role of mesenchymal stem cells (MSCs) in veterinary medicine and their use in musculoskeletal disorders. Biomolecules, 11: 1141.

Przybyszewska A., Barbosa C.H., Pires F., Pires J.R.A., Rodrigues C., Galus S., Souza V.G.L., Alves M.M., Santos C.F., Coelhoso I., Fernando A.L. (2023). Packaging of fresh poultry meat with innovative and sustainable ZnO/pectin bionanocomposite films – a contribution to the bio and circular economy. Coatings, 13: 1208.

Rahman H.S., Othman H.H., Abdullah R., Edin H.Y.A.S., Al-Haj N.A. (2022). Beneficial and toxicological aspects of zinc oxide nanoparticles in animals. Vet. Med. Sci., 8: 1769–1779.

Reddy P.R.K., Yasaswini D., Reddy P.P.R., Zeineldin M., Adegbeye M.J., Hyder I. (2020). Applications, challenges, and strategies in the use of nanoparticles as feed additives in equine nutrition. Vet. World, 13: 1685–1696.

Reddy P.R.K., Yasaswini D., Reddy P.P.R., Kumar D.S., Elghandour M.M., Salem A.Z.M. (2023). Nanotechnology in veterinary sector: current applications, limitations and future perspective. In: Handbook of Green and Sustainable Nanotechnology: Fundamentals, Developments and Applications. Springer, pp. 1541–1567.

Remião M.H., Segatto N.V., Pohlmann A., Guterres S.S., Seixas F.K., Collares T. (2018). The potential of nanotechnology in medically assisted reproduction. Front. Pharmacol., 11: 994.

Ricles L.M., Nam S.Y., Trevino E.A., Emelianov S.Y., Suggs L.J. (2014). A dual gold nanoparticle system for mesenchymal stem cell tracking. J. Mater. Chem. B, 2: 8220–8230.

Rios T.B., Maximiano M.R., Feitosa G.C., Malmsten M., Franco O.L. (2024). Nanosensors for animal infectious disease detection. Sens. Bio-Sens. Res., 43: 100622.

Saadeldin I.M., Khalil W.A., Alharbi M.G., Lee S.H. (2020). The current trends in using nanoparticles, liposomes, and exosomes for semen cryopreservation. Animals, 10: 2281.

Santos-Jimenez Z., Guillen-Gargallo S., Encinas T., Berlinguer F., Veliz-Deras F.G., Martinez-Ros P., Gonzalez-Bulnes A. (2020). Use of propylene-glycol as a cosolvent for GnRH in synchronization of estrus and ovulation in sheep. Animals, 10: 897.

Sawutdeechaikul P., Cia F., Bancroft G.J., Wanichwecharungruang S., Sittplangkoo C., Palaga T. (2019). Oxidized carbon nanosphere-based subunit vaccine delivery system elicited robust Th1 and cytotoxic T cell responses. J. Microbiol. Biotechnol., 29: 489–499.

Sekimukai H., Iwata-Yoshikawa N., Fukushi S., Tani H., Kataoka M., Suzuki T., Nagata N. (2020). Gold nanoparticle-adjuvanted S pro-

tein induces a strong antigen-specific IgG response against severe acute respiratory syndrome-related coronavirus infection, but fails to induce protective antibodies and limit eosinophilic infiltration in lungs. Microbiol. Immunol., 64: 33–51.

Semeano A.T., Tofoli F.A., Corrêa-Velloso J.C., de Jesus Santos A.P., Oliveira-Giacomelli Á., Cardoso R.R., Pessoa M.A., da Rocha E.L., Ribeiro G., Ferrari M.F.R., Pereira L.V., Teng Y.D., Petri D.F.S., Ulrich H. (2022). Effects of magnetite nanoparticles and static magnetic field on neural differentiation of pluripotent stem cells. Stem Cell Rev. Rep., 18: 1337–1354.

Shafi B.U.D., Kumar R., Jadhav S.E., Kar J. (2020). Effect of zinc nanoparticles on milk yield, milk composition and somatic cell count in early-lactating Barbari does. Biol. Trace Elem. Res., 196: 96–102.

Shahin M.A., Khalil W.A., Saadeldin I.M., Swelum A.A., El-Harairy M.A. (2020). Comparison between the effects of adding vitamins, trace elements, and nanoparticles to SHOTOR extender on the cryopreservation of dromedary camel epididymal spermatozoa. Animals, 10: 78.

Shen W.B., Plachez C., Tsymbalyuk O., Tsymbalyuk N., Xu S., Smith A.M., Michel S.L., Yarnell D., Mullins R., Gullapalli R.P., Puche A. (2016). Cell-based therapy in TBI: magnetic retention of neural stem cells in vivo. Cell Transplant., 25: 1085–1099.

Shivanna A.T., Shalumon K.T., Chen J.P. (2019). Applications of magnetic liposomes in cancer therapies. Curr. Pharm. Des., 25: 1490–1504.

Siddharth S. (2022). Stem cell biology: an overview. In: Biotechnological Advances for Microbiology, Molecular Biology, and Nanotechnology, pp. 297–310.

Sreekanth K., Sharath K.P., Midhun Dominic C.D., Radhakrishnan E.K. (2024). Microbial load reduction in stored raw beef meat using chitosan/starch-based active packaging films incorporated with cellulose nanofibers and cinnamon essential oil. Meat Sci., 216: 109552.

Sun X., Gamal M., Nold P., Said A., Chakraborty I., Pelaz B., et al. (2019). Tracking stem cells and macrophages with gold and iron oxide nanoparticles: the choice of the best suited particles. Appl. Mater. Today, 15: 267–279.

Teng Z., Sun S., Luo X., Zhang Z., Seo H., Xu X., Huang J., Dong H., Mu S., Du P., Zhang Z., Guo H. (2021). Bi-functional gold nanocages enhance specific immunological responses of foot-and-mouth disease virus-like particles vaccine as a carrier and adjuvant. Nanomedicine, 33: 102358.

Tewari A., Jain B., Brar B., Prasad G., Prasad M. (2021). Biosensors: modern tools for disease diagnosis and animal health monitoring. In: Biosensors in Agriculture: Recent Trends and Future Perspectives, pp. 387–414.

Thwala L.N., Ndlovu S.C., Mpofu K.T., Lugongolo M.Y., Mthunzi-Kufa P. (2023). Nanotechnology-based diagnostics for diseases prevalent in developing countries: current advances in point-of-care tests. Nanomaterials, 13: 1247.

Usman K.A.S., Maina J.W., Seyedin S., Conato M.T., Payawan L.M. Jr, Dumée L.F., Razal J.M. (2020). Downsizing metal–organic frameworks by bottom-up and top-down methods. NPG Asia Mater., 12: 58.

Veclin C., Desmet C., Pradel A., Valsesia A., Ponti J., El Hadri H., Maupas T., Pellerin V., Gigault J., Grassl B., Reynaud S. (2022). Effect of the surface hydrophobicity–morphology–functionality of nanoplastics on their homoaggregation in seawater. ACS ES&T Water, 2: 88–95.

Vo-Van Q.B., Duong T.H., Le T.K.A. (2023). Biosynthesis of silver nanoparticles using curcumin against the bovine mastitis bacteria. J. Cent. Eur. Agric., 24: 505–512.

Walewska M., Małek A., Taciak B., Wojtalewicz A., Wilk S., Wojtkowska A., Zabielska-Koczywąs K., Lechowski R. (2023). PEG-liposomal doxorubicin as a potential agent for canine metastatic osteosarcoma – *in vitro* and *ex ovo* studies. J. Vet. Res., 67: 297.

Wang K., Lu X., Lu Y., Wang J., Lu Q., Cao X., Yang Y., Yang Z. (2022). Nanomaterials in animal husbandry: research and prospects. Front. Genet., 13: 915911.

Wang M., Yang X., Zhang P., Cai L., Yang X., Chen Y., Jing Y., Kong J., Yang X., Sun F.L. (2016). Sustained delivery growth factors with polyethyleneimine-modified nanoparticles promote embryonic stem cells differentiation and liver regeneration. Adv. Sci., 3: 1500393.

Wang X., Bai R. (2023). Advances in smart delivery of magnetic field-targeted drugs in cardiovascular diseases. Drug Deliv., 30: 2256495.

Weeratunga P., Harman R.M., Van de Walle G.R. (2023). Induced pluripotent stem cells from domesticated ruminants and their potential for enhancing livestock production. Front. Vet. Sci., 10: 1129287.

Williams A., Bennison J.J., Mackenzie A.M., Sinclair L.A. (2024). Feeding nanoparticles of copper oxide coated with lysine with or without added antagonists affects the copper status but not the performance of Holstein dairy cows. J. Dairy Sci., 107: 9277–9288.

Wu L., Wang C., Li Y. (2022). Iron oxide nanoparticle targeting mechanism and its application in tumor magnetic resonance imaging and therapy. Nanomedicine, 17: 1567–1583.

Xie S., Ying Z., Xiu Z., Sun Y., Yang Q., Gao H., Wu Y. (2024). Zinc oxide nanoparticles improve lactation and metabolism in dairy goats by modulating the rumen microbiota. Front. Microbiol., 15: 1483680.

Yang Y., Xing R., Liu S., Qin Y., Li K., Yu H., Li P. (2020). Chitosan, hydroxypropyltrimethyl ammonium chloride chitosan and sulfated chitosan nanoparticles as adjuvants for inactivated Newcastle disease vaccine. Carbohydr. Polym., 229: 115423.

Ying Z., Xie S., Xiu Z., Sun Y., Yang Q., Gao H., Fan W., Wu Y. (2025). Under heat stress conditions, selenium nanoparticles promote lactation through modulation of rumen microbiota and metabolic processes in dairy goats. Sci. Rep., 15: 9063.

Younis S., Zia R., Tahir N., Bukhari S.Z., Khan W.S., Bajwa S.Z. (2022). Nanosensors for animal health monitoring. In: Nanosensors for Smart Agriculture. Elsevier, pp. 509–529.

Yuan Y.G., Peng Q.L., Gurunathan S. (2017). Effects of silver nanoparticles on multiple drug-resistant strains of *Staphylococcus aureus* and *Pseudomonas aeruginosa* from mastitis-infected goats: an alternative approach for antimicrobial therapy. Int. J. Mol. Sci., 18: 569.

Zhao C., Song X., Jin W., Wu F., Zhang Q., Zhang M., Shen J. (2019). Image-guided cancer therapy using aptamer-functionalized cross-linked magnetic-responsive Fe_3O_4@carbon nanoparticles. Anal. Chim. Acta, 1056: 108–116.

Zorkina Y., Abramova O., Ushakova V., Morozova A., Zubkov E., Valikhov M., Melnikov P., Majouga A., Chekhonin V. (2020). Nanocarrier drug delivery systems for the treatment of neuropsychiatric disorders: advantages and limitations. Molecules, 25: 5294.

Received: 23 IX 2024
Accepted: 12 VIII 2025