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Nanotechnology: Current Applications, Safety Issues and Future Prospects in Veterinary Pharmacology and Toxicology

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Abstract— *Nanotechnology has emerged as one of the most promising advancements in modern pharmaceutical sciences due to its ability to manipulate materials at the nanoscale and enhance their interaction with biological systems. In veterinary pharmacology and toxicology, nanotechnology offers innovative solutions to overcome the limitations associated with conventional drug delivery systems, such as poor bioavailability, lack of target specificity, rapid elimination, systemic toxicity, and drug residue concerns in food-producing animals. Nanotechnology-based drug delivery systems improve therapeutic efficacy by enhancing drug solubility, stability, controlled release, and targeted delivery.*

Various nanocarriers, including liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, dendrimers, quantum dots, magnetic nanoparticles, nanoshells, and nanopores, have shown significant applications in veterinary therapeutics, diagnostics, oncology, vaccine delivery, and infectious disease management. These nanosystems improve the pharmacokinetic and pharmacodynamic properties of drugs while minimizing adverse effects.

Despite their advantages, nanotechnology-based products raise important safety and toxicological concerns. The unique physicochemical properties of nanoparticles may result in organ toxicity, immunotoxicity, reproductive toxicity, oxidative stress, and environmental hazards. Species-specific responses and long-term exposure effects further complicate safety evaluation in veterinary applications. Therefore, comprehensive nanotoxicological assessment and regulatory oversight are essential before widespread adoption.

The future prospects of nanotechnology in veterinary pharmacology and toxicology include the development of smart nanocarriers, nano-theranostics, nano-phytogenics, precision veterinary medicine, and environmentally safer nanomaterials. This review consolidates findings from multiple scientific studies to present a comprehensive overview of the current applications, safety issues, and future prospects of nanotechnology in veterinary pharmacology and toxicology (Alivisatos, 2004; McNeil, 2009; Patra et al., 2018).

Keywords— Nanotechnology; Veterinary pharmacology; Veterinary toxicology; Nanocarriers; Drug delivery systems; Nanotoxicology; Nanomedicine; Targeted drug delivery; Veterinary therapeutics; Nanosafety; Environmental toxicity.

I. INTRODUCTION

Veterinary pharmacology and toxicology form the foundation of effective disease prevention, treatment, and control in animals. The rational use of drugs in veterinary practice is essential not only for animal health and welfare but also for ensuring food safety and public health. Conventional drug formulations often face several limitations, including poor aqueous solubility, low bioavailability, non-specific distribution, rapid metabolism, and short biological half-life. These drawbacks frequently necessitate higher doses or repeated administration, increasing the risk of toxicity and drug residues in milk, meat, and eggs (Patel et al., 2017).

In recent years, advancements in pharmaceutical sciences have focused on the development of novel drug delivery systems to overcome these challenges. Among these advancements, nanotechnology has gained significant attention due to its ability to modify drug behaviour at the molecular and cellular levels. Nanotechnology involves the design, synthesis, and application of materials with dimensions typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physicochemical properties such as increased surface area, enhanced reactivity, altered optical behaviour, and improved interaction with biological membranes (Alivisatos, 2004).

In veterinary pharmacology, nanotechnology provides opportunities to enhance drug absorption, improve tissue targeting, prolong circulation time, and achieve controlled release. Nanocarriers protect drugs from premature degradation and facilitate site-specific delivery, thereby reducing systemic toxicity. In veterinary toxicology, nanotechnology offers tools to study toxicokinetics, minimize adverse drug reactions, and develop safer therapeutic formulations. Additionally, nanotechnology has expanded its applications beyond drug delivery to include diagnostics, imaging, vaccine development, and cancer therapy in animals (McNeil, 2009; Patra et al., 2018).

However, the increasing application of nanomaterials raises concerns regarding their safety. Due to their small size and high reactivity, nanoparticles may cross biological barriers and accumulate in vital organs. Understanding the toxicological implications of nanotechnology is therefore crucial for its safe and responsible application. This review aims to discuss the current applications of nanotechnology in veterinary pharmacology and toxicology, highlight associated safety issues, and explore future prospects in this rapidly evolving field.

II. DEFINITION AND CONCEPT OF NANOTECHNOLOGY

Nanotechnology is defined as the science and engineering of materials at the nanometer scale, typically between 1 and 100 nanometers, where unique physical, chemical, and biological properties emerge. At the nanoscale, materials exhibit increased surface-to-volume ratio, enhanced reactivity, and improved interaction with biological systems, making them suitable for pharmaceutical and biomedical applications (Alivisatos, 2004).

In the context of veterinary pharmacology and toxicology, nanotechnology refers to the application of nanoscale materials and systems for improving drug delivery, therapeutic efficacy, diagnostic accuracy, and safety evaluation in animals. Nanomaterials can be engineered to encapsulate drugs, vaccines, genes, or imaging agents and deliver them in a controlled and targeted manner. Surface modification of nanocarriers with polymers, ligands, or antibodies further enhances biocompatibility and specificity (Sapino et al., 2022).

III. HISTORY OF NANOTECHNOLOGY

TABLE 1

HISTORICAL DEVELOPMENT OF NANOTECHNOLOGY AND ITS RELEVANCE TO VETERINARY PHARMACOLOGY AND TOXICOLOGY

Year/Period	Major Development	Relevance to Veterinary Pharmacology & Toxicology
1959	Richard Feynman proposed manipulation of matter at atomic level	Laid conceptual foundation for nanoscale drug design and targeted therapy
1974	Term "nanotechnology" coined by Norio Taniguchi	Formal beginning of nanoscale precision relevant to drug formulation
1980-1985	Development of STM and AFM techniques	Enabled characterization of nanodrug carriers used in pharmacology
1985	Discovery of fullerenes	Sparked interest in nanoscale materials with biological relevance
1990-1995	Development of liposomes as drug carriers	First nanocarriers applied for controlled drug delivery and toxicity reduction
Late 1990s	Expansion of nanotechnology into biomedical research	Adoption of nano-drug delivery concepts in veterinary medicine
Early 2000s	Polymeric nanoparticles and nanoemulsions developed	Improved pharmacokinetics and bioavailability of veterinary drugs
2005-2010	Emergence of nanotoxicology	Evaluation of nanoparticle-induced organ toxicity and safety
2010-2015	Targeted nanocarriers (SLNs, magnetic NPs) explored	Reduced systemic toxicity and drug residues in food animals
2015-2020	Use in veterinary oncology and vaccines	Improved cancer therapy and immune response in animals
2020-Present	Focus on precision veterinary medicine and nano-theranostics	Integration of pharmacology with safety, diagnostics and regulation

IV. NEED FOR NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

The urgent need for nanotechnology in veterinary science arises from the severe limitations of conventional medicine (Trif et al., 2023). Despite significant advances in veterinary therapeutics, conventional drug delivery systems continue to present multiple challenges that limit therapeutic success. Many veterinary drugs suffer from poor aqueous solubility, instability in gastrointestinal fluids, rapid first-pass metabolism, and non-specific tissue distribution. These limitations often result in reduced bioavailability and unpredictable therapeutic responses, particularly when the same drug is administered across different animal species with varying physiological characteristics. Standard diagnostic methods can often take days or weeks to identify a disease, during which time an entire herd may become infected, necessitating mass culling (Hill & Li, 2017). Nanotechnology addresses these needs by providing tools for early, on-site pathogen detection and "smart" delivery systems that release medications directly to diseased cells without harming healthy tissue (Woldeamanuel et al., 2021). It also offers a way to "re-life" old or toxic drugs by using nanocarriers to improve their solubility, half-life, and safety profiles (Woldeamanuel et al., 2021).

In food-producing animals, the use of higher or repeated drug doses increases the likelihood of drug residues in edible tissues such as milk, meat, and eggs. Residue persistence poses a serious concern for public health and may lead to the development of antimicrobial resistance. In addition, frequent handling and repeated dosing cause stress to animals, negatively affecting productivity and welfare. These challenges highlight the need for advanced drug delivery approaches that improve therapeutic efficiency while minimizing toxicity and residue-related risks (Patel et al., 2017).

Nanotechnology-based systems offer a promising solution to these limitations by improving drug solubility, protecting active molecules from enzymatic degradation, and enabling sustained and targeted drug release. By modifying pharmacokinetic behaviour, nanotechnology allows the use of lower drug doses while maintaining or enhancing therapeutic efficacy. This

approach is particularly valuable in veterinary pharmacology, where species-specific dosing and safety margins are critical considerations (Patra et al., 2018).

V. SCOPE OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

The scope of nanotechnology in veterinary pharmacology and toxicology extends beyond conventional drug delivery and encompasses multiple aspects of animal healthcare. Nanotechnology-based systems are increasingly used for targeted drug delivery, controlled release formulations, diagnostic imaging, vaccine development, cancer therapy, and toxicological assessment.

In veterinary pharmacology, nanocarriers improve drug absorption, enhance tissue targeting, and prolong circulation time, thereby optimizing pharmacokinetic and pharmacodynamic profiles. In veterinary toxicology, nanotechnology contributes to the development of safer drug formulations by reducing off-target toxicity and enabling detailed evaluation of toxicokinetic behaviour. Additionally, nanomaterials are used as tools to study cellular and molecular mechanisms of toxicity, providing insights into drug-tissue interactions and adverse effect pathways (McNeil, 2009).

The integration of nanotechnology supports the concept of precision veterinary therapeutics, where treatments are tailored based on disease condition, species, and physiological status of animals. This broad scope highlights the multidisciplinary nature of nanotechnology in veterinary pharmacology and toxicology.

VI. CLASSIFICATION OF NANOMATERIALS

Nanomaterials used in veterinary pharmacology and toxicology can be broadly classified into organic, inorganic, and hybrid nanomaterials based on their composition and functional properties.

6.1 Organic Nanomaterials

Organic nanomaterials include liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, and dendrimers. These systems are generally biocompatible and biodegradable, making them suitable for drug delivery applications. Organic nanocarriers are widely explored for the delivery of antimicrobials, antiparasitic agents, anticancer drugs, and vaccines in veterinary practice.

6.2 Inorganic Nanomaterials

Inorganic nanomaterials include metallic nanoparticles, magnetic nanoparticles, quantum dots, and nanoshells. These materials possess unique optical, magnetic, and thermal properties that make them useful for diagnostic imaging, targeted therapy, and therapeutic monitoring. However, inorganic nanomaterials often raise greater safety concerns due to their persistence and potential for bioaccumulation.

6.3 Hybrid Nanomaterials

Hybrid nanomaterials combine the advantages of both organic and inorganic components to achieve improved functionality and safety. These systems are designed to enhance therapeutic efficacy while minimizing toxicity, thereby offering promising applications in veterinary pharmacology and toxicology (Sapino et al., 2022).

VII. TYPES OF NANOCARRIERS AND THEIR APPLICATIONS

7.1 Liposomes

Liposomes are spherical vesicular systems composed mainly of phospholipids and cholesterol, arranged as one or more concentric bilayers surrounding an aqueous core. Due to their structural similarity to biological membranes, liposomes exhibit excellent biocompatibility and are widely used as drug delivery systems in veterinary pharmacology. They are capable of encapsulating both hydrophilic drugs within their aqueous core and lipophilic drugs within the lipid bilayer, thereby increasing formulation flexibility.

In veterinary pharmacology, liposomes are extensively explored to improve drug stability, enhance bioavailability, and reduce systemic toxicity. Liposomal drug delivery modifies pharmacokinetic behaviour by prolonging circulation time and enabling passive targeting to organs such as the liver and spleen. This is particularly useful in the treatment of systemic infections and neoplastic conditions in animals. Liposomal formulations of amphotericin B have demonstrated reduced nephrotoxicity compared to conventional formulations, highlighting their importance in veterinary therapeutics (Patel et al., 2017).

Additionally, liposomes reduce drug exposure to non-target tissues, thereby minimizing adverse effects and improving safety margins. In food-producing animals, this contributes to reduced drug residues in edible tissues, supporting food safety regulations. Liposomes are also explored as vaccine adjuvants and carriers, enhancing antigen presentation and immune response in veterinary vaccines (Sapino et al., 2022).

7.2 Polymeric Nanoparticles

Polymeric nanoparticles are solid colloidal systems typically prepared from biodegradable and biocompatible polymers such as poly(lactic acid), poly(lactic-co-glycolic acid), and chitosan. Chitosan is valued for its mucoadhesive properties and ability to protect DNA or drug payloads from degradation (Mweetwa et al., 2022). These nanoparticles range in size from a few nanometers to several hundred nanometers and are designed to provide controlled and sustained drug release.

In veterinary pharmacology, polymeric nanoparticles play a crucial role in improving drug delivery efficiency by protecting drugs from enzymatic degradation and releasing them in a predictable manner. Sustained drug release reduces dosing frequency, which is advantageous in large animals and wildlife where repeated administration is difficult. Polymeric nanoparticles have been investigated for the delivery of antimicrobials, antiparasitic drugs, anti-inflammatory agents, and hormones in animals (Carvalho et al., 2020).

Surface modification of polymeric nanoparticles enables active targeting to specific tissues, thereby reducing off-target toxicity. This targeted approach is particularly relevant in veterinary toxicology, as it helps minimize systemic exposure and adverse effects. In food-producing animals, polymeric nanoparticles also aid in reducing drug residue levels by maintaining therapeutic efficacy at lower doses (Zhou et al., 2024).

7.3 Solid Lipid Nanoparticles

Solid lipid nanoparticles are lipid-based nanocarriers composed of physiologically compatible solid lipids stabilized by surfactants. Unlike liquid lipid systems, solid lipid nanoparticles remain solid at body temperature, providing better physical stability and controlled drug release.

In veterinary pharmacology, solid lipid nanoparticles are used to improve the delivery of poorly water-soluble drugs. They enhance oral bioavailability by increasing drug solubility and protecting the active ingredient from degradation in the gastrointestinal tract. Solid lipid nanoparticles have been explored for delivering antimicrobials, anticancer drugs, and nutraceuticals in poultry and livestock (Patra et al., 2018).

From a toxicological perspective, solid lipid nanoparticles are considered relatively safe due to their biodegradable lipid composition. Their ability to reduce peak plasma concentrations helps minimize dose-related toxicity. Additionally, these systems offer potential for reducing drug residues, making them suitable for use in food-producing animals.

7.4 Nanoemulsions

Nanoemulsions are kinetically stable colloidal dispersions consisting of oil and water phases stabilized by surfactants, with droplet sizes typically below 200 nm. Due to their small droplet size, nanoemulsions exhibit enhanced drug solubilization and improved absorption across biological membranes.

In veterinary pharmacology, nanoemulsions are widely studied for oral, topical, and parenteral drug delivery. They are particularly useful for delivering lipophilic drugs and phytogenic compounds. Nanoemulsions improve bioavailability and therapeutic efficacy while reducing variability in drug absorption. In poultry and livestock, nanoemulsions are explored for antimicrobial delivery, vaccine formulations, and feed additives (Youssef, 2019).

Nanoemulsions also contribute to reduced drug doses and lower systemic toxicity, making them relevant from a veterinary toxicology standpoint. However, surfactant selection and concentration must be carefully optimized to avoid irritation or toxicity.

7.5 Quantum Dots

Quantum dots are semiconductor nanocrystals that exhibit size-dependent optical and fluorescent properties. In veterinary pharmacology, quantum dots are mainly used as diagnostic and research tools rather than therapeutic carriers. Their strong fluorescence and photostability make them valuable for imaging, drug tracking, and studying pharmacokinetics in animal models. Quantum dots are semiconductor nanocrystals used as highly sensitive bio-imaging probes (Dhakad et al., 2017).

Quantum dots are used to visualize drug distribution, tissue targeting, and cellular uptake, thereby aiding in pharmacological and toxicological evaluation of new formulations. In veterinary oncology, quantum dots assist in tumour imaging and lymph node mapping, supporting early diagnosis and therapeutic monitoring (Alivisatos, 2004).

However, due to concerns related to heavy metal content and long-term toxicity, quantum dots are mainly restricted to experimental and diagnostic applications. Their safety profile remains an important area of research in veterinary toxicology.

7.6 Magnetic Nanoparticles

Magnetic nanoparticles, particularly superparamagnetic iron oxide nanoparticles, possess unique magnetic properties that allow them to be guided using external magnetic fields. In veterinary pharmacology, these nanoparticles are used for targeted drug delivery, diagnostic imaging, and hyperthermia-based cancer therapy.

Drug-loaded magnetic nanoparticles can be directed to specific tissues using an external magnetic field, resulting in localized drug accumulation and reduced systemic exposure. This targeted approach enhances therapeutic efficacy while minimizing adverse effects. In veterinary oncology, magnetic nanoparticles are explored for localized tumour treatment through magnetic hyperthermia (Ianiski et al., 2022).

From a toxicological perspective, superparamagnetic behaviour ensures that nanoparticles do not retain magnetization once the magnetic field is removed, reducing the risk of aggregation and vascular embolization. Nevertheless, long-term safety and iron overload concerns must be carefully evaluated.

7.7 Nanoshells

Nanoshells are nanostructures consisting of a dielectric core, usually silica, coated with a thin metallic layer. These systems are engineered to absorb near-infrared radiation and convert it into heat, enabling localized thermal destruction of diseased tissues.

In veterinary pharmacology, nanoshells are being investigated primarily for tumour therapy. Upon exposure to external infrared radiation, nanoshells produce localized heat, leading to selective tumour cell destruction without damaging surrounding healthy tissues. This photothermal therapy approach offers a minimally invasive alternative for cancer treatment in animals (Patra et al., 2018).

Although promising, nanoshell applications are still under experimental evaluation and their safety profile requires further investigation in veterinary toxicology.

7.8 Nanoparticles and Nanoporous Systems (Nanopores)

Nanopores are highly porous nanostructures that allow selective passage of small molecules such as oxygen, glucose, and insulin while preventing the movement of immune cells and antibodies. This selective permeability makes nanopores useful in immune-protected drug and cell delivery systems.

In veterinary pharmacology, nanopores are explored for controlled drug release and cell-based therapies. Encapsulation of pancreatic β-cells within nanoporous systems allows nutrient exchange while preventing immune rejection, offering a novel approach for managing insulin-dependent diabetes mellitus in animals.

Nanopore systems represent an advanced interface between pharmacology and biotechnology, with significant therapeutic potential. However, long-term biocompatibility and safety concerns remain areas of active research.

VIII. ADVANTAGES OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology provides significant advantages in veterinary pharmacology by improving the bioavailability of drugs that otherwise show poor solubility and limited absorption. Nano-sized drug carriers enhance dissolution rate and protect active pharmaceutical ingredients from chemical and enzymatic degradation, thereby improving systemic availability and therapeutic efficacy (Patra et al., 2018).

Targeted drug delivery is another major advantage of nanotechnology. Nanocarriers can be designed to selectively accumulate in diseased tissues through passive or active targeting mechanisms, reducing drug exposure to healthy tissues. This targeted approach enhances pharmacological efficacy while minimizing adverse effects, where dose margins are often narrow (Ianiski et al., 2022).

Nanotechnology also enables controlled and sustained release of drugs. Sustained release formulations maintain therapeutic drug concentrations over prolonged periods, reducing dosing frequency. This is highly beneficial in veterinary practice, especially in livestock and poultry, where repeated handling and administration cause stress and economic loss (Carvalho et al., 2020).

From a veterinary toxicology perspective, nanotechnology contributes to reduced systemic toxicity. By lowering peak plasma concentrations and restricting off-target distribution, nanoformulations decrease dose-related adverse effects. Reduced toxicity also helps minimize drug residues in animal-derived food products, improving food safety and public health protection (Patel et al., 2017).

In addition, nanotechnology enhances diagnostic and therapeutic capabilities in the veterinary field. Nanomaterials such as quantum dots and magnetic nanoparticles facilitate advanced imaging, drug tracking, and cancer therapy. Nano-vaccines and nano-adjuvants improve antigen delivery and immune response, leading to better disease prevention strategies in animals (Sapino et al., 2022).

IX. DISADVANTAGES AND LIMITATIONS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Despite its advantages, nanotechnology presents several limitations and safety concerns in veterinary pharmacology and toxicology. One of the major disadvantages is nanotoxicity. Due to their small size and large surface area, nanoparticles may induce oxidative stress, inflammation, and cellular damage. Accumulation of nanoparticles in vital organs such as the liver, kidneys, lungs, and spleen has been reported, raising concerns about long-term toxicity (Singh, 2019).

Another important limitation is the lack of comprehensive safety and species-specific toxicity data. Most toxicological studies are conducted in laboratory animals, and extrapolation of these results to different veterinary species is challenging due to physiological and metabolic differences. This uncertainty complicates risk assessment and safe dose determination in veterinary toxicology (Chrishtop et al., 2021).

Environmental toxicity is also a growing concern associated with nanotechnology. Nanomaterials may enter the environment through animal excreta, pharmaceutical waste, or agricultural runoff. The persistence and accumulation of nanoparticles in soil and aquatic ecosystems may adversely affect microorganisms, plants, and non-target organisms. The long-term environmental impact of veterinary nanoproducts remains insufficiently understood (McNeil, 2009).

Economic and technical constraints further limit the widespread application of nanotechnology in veterinary practice. The development and manufacturing of nano-based formulations require specialized equipment, skilled personnel, and high production costs. These factors restrict large-scale commercialization and field-level application, particularly in developing countries (Carvalho et al., 2020).

Regulatory and ethical challenges also represent major disadvantages. Currently, standardized regulatory guidelines for approval, quality control, and post-marketing surveillance of nanotechnology-based veterinary products are limited. Ethical concerns related to animal welfare, environmental safety, and long-term exposure further emphasize the need for cautious implementation of nanotechnology in veterinary pharmacology and toxicology (Sapino et al., 2022).

X. EXPANDED CURRENT APPLICATIONS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology has revolutionized veterinary pharmacology by enabling precise control over drug delivery, improving therapeutic outcomes, and reducing toxicological risks. The application of nanotechnology is largely driven by the need to optimize pharmacokinetic behaviour of drugs, minimize adverse effects, and address issues such as antimicrobial resistance and drug residues in food-producing animals. Recent reviews have highlighted the broad applications of nanotechnology in the veterinary field, including drug delivery, diagnostics, oncology, vaccine development, and safety evaluation. These applications demonstrate the growing role of nanotechnology in improving therapeutic efficacy and reducing toxicological risks in veterinary practice (Bilgili & Uysal, 2019).

10.1 Advanced Drug Delivery Applications in Veterinary Pharmacology

Nanotechnology-based drug delivery systems play a crucial role in modifying absorption, distribution, metabolism, and excretion of veterinary drugs. Nanocarriers enhance drug dissolution rate and membrane permeability, thereby improving oral

and parenteral bioavailability. This is particularly relevant for drugs with poor aqueous solubility, such as antiparasitic agents and anticancer drugs. Nanoparticles also protect drugs from degradation in the gastrointestinal tract and during first-pass metabolism, leading to more predictable therapeutic responses (Patra et al., 2018).

Targeted drug delivery represents a major advancement enabled by nanotechnology. Surface modification of nanocarriers with ligands or antibodies allows selective accumulation of drugs at disease sites such as tumours, inflamed tissues, or infected organs. This targeted approach reduces off-target exposure and systemic toxicity, which is a major concern in veterinary pharmacology. In companion animals undergoing long-term therapy, targeted nanocarriers improve treatment efficacy while reducing adverse drug reactions (Ianiski et al., 2022).

Sustained and controlled drug release achieved through nanotechnology reduces dosing frequency and improves animal compliance. This application is especially beneficial in livestock and poultry, where repeated handling causes stress and economic loss. Controlled-release nanoformulations maintain therapeutic drug concentrations over extended periods, improving disease management and productivity (Patel et al., 2017).

10.2 Applications in Antimicrobial and Antiparasitic Therapy

Nanotechnology has shown significant potential in improving antimicrobial and antiparasitic therapy. Nanoformulated antibiotics exhibit enhanced penetration into infected tissues and biofilms, increasing antimicrobial efficacy. This is particularly important in the treatment of chronic infections and intracellular pathogens, where conventional antibiotics show limited effectiveness.

Nanotechnology also plays a role in addressing antimicrobial resistance. By improving drug targeting and reducing required doses, nanocarriers minimize selective pressure on microorganisms. Nano-phytogenics and nano-antimicrobials are being explored as alternative therapeutic strategies to reduce reliance on conventional antibiotics, thereby contributing to antimicrobial stewardship in veterinary practice (Sapino et al., 2022).

10.3 Diagnostic and Imaging Applications in Veterinary Toxicology

Nanotechnology has enhanced diagnostic and imaging capabilities in the veterinary field. Quantum dots and magnetic nanoparticles are used as imaging probes due to their superior optical and magnetic properties. These nanomaterials facilitate early disease detection, tumour localization, and real-time monitoring of drug distribution in animal tissues (Alivisatos, 2004). In disease diagnostics, the use of genosensors and biochips allows for the simultaneous detection of thousands of disease biomarkers (Prasad et al., 2021).

In veterinary toxicology, imaging-based nanotechnology applications help in evaluating drug biodistribution, organ accumulation, and toxicokinetic behaviour. These tools provide valuable insights into mechanisms of drug-induced toxicity and support the development of safer formulations.

10.4 Applications in Veterinary Vaccines and Immunotherapy

Nanotechnology has significantly improved vaccine delivery and immunotherapy in the veterinary field. Nanocarriers act as antigen carriers and adjuvants, enhancing antigen stability and immune response. Nano-vaccines improve antigen uptake by antigen-presenting cells and prolong immune stimulation, resulting in enhanced protection against infectious diseases.

Nanotechnology-based vaccines are particularly useful in poultry and livestock, where effective mass vaccination strategies are required. Improved vaccine efficacy reduces disease incidence, antimicrobial usage, and economic losses in animal production systems (Sapino et al., 2022).

10.5 Applications in Feed Additives, Nutraceuticals, and Growth Promotion

Nanotechnology is increasingly applied in the formulation of feed additives and nutraceuticals in veterinary practice. Nanoformulated vitamins, minerals, and phytogenic compounds exhibit improved absorption and bioavailability compared to conventional formulations. These applications enhance growth performance, immune function, and disease resistance in animals.

From a veterinary toxicology perspective, nanoformulations allow precise dose control and reduce the risk of toxicity associated with overdosing of micronutrients. However, long-term exposure studies are essential to ensure safety and environmental compatibility (Youssef, 2019).

10.6 Role of Nanotechnology in Toxicological Research and Risk Assessment

In veterinary toxicology, nanotechnology serves both as a therapeutic tool and a subject of safety evaluation. Nanomaterials are used to study cellular and molecular mechanisms of toxicity, oxidative stress, and inflammatory responses. At the same time, the toxicological effects of nanomaterials themselves are evaluated under the discipline of nanotoxicology.

Nanotechnology-based tools enable detailed assessment of toxicokinetics, species-specific responses, and environmental impact. These studies support the development of regulatory guidelines and safer nanotechnology-based veterinary products (Singh, 2019).

XI. Safety Issues and Nanotoxicological Concerns of Nanotechnology in Veterinary Pharmacology and Toxicology

Although nanotechnology offers numerous advantages in veterinary pharmacology, its application raises important safety and toxicological concerns. The unique physicochemical properties of nanomaterials, such as extremely small size, high surface area, surface charge, and increased reactivity, influence their interaction with biological systems in ways that differ significantly from conventional drugs. These properties may result in unintended biological effects, making safety evaluation a critical component of nanotechnology-based veterinary products. Extremely small particles can become highly reactive and hazardous by increasing the production of reactive oxygen species (ROS), which leads to oxidative stress and cellular damage (Alghuthaymi et al., 2021).

11.1 General Factors Influencing Nanotoxicity

The toxicological behaviour of nanomaterials depends on several factors, including particle size, shape, surface chemistry, dose, route of administration, and duration of exposure. Smaller nanoparticles are more likely to cross biological barriers such as the gastrointestinal epithelium, blood-brain barrier, and placental barrier. Surface charge and coating also influence cellular uptake, biodistribution, and clearance. In veterinary pharmacology, these factors complicate dose standardization across species with different physiological and metabolic characteristics (McNeil, 2009).

11.2 Organ-Specific Toxicity

One of the major safety concerns in veterinary toxicology is organ-specific accumulation of nanoparticles. Following systemic exposure, nanoparticles tend to accumulate in organs involved in detoxification and clearance, particularly the liver, kidneys, lungs, and spleen. Accumulation in the liver may cause hepatotoxicity through oxidative stress, inflammation, and disruption of normal metabolic processes. Renal accumulation may lead to nephrotoxicity, especially with prolonged exposure or repeated dosing (Singh, 2019).

Pulmonary toxicity is of concern when nanoparticles are inhaled or reach the lungs through systemic circulation. Nanoparticles deposited in the lungs may induce inflammation, fibrosis, and impaired respiratory function. In food-producing animals, organ accumulation raises additional concerns regarding the persistence of nanomaterials and their potential transfer into edible tissues.

11.3 Immunotoxicity

Nanomaterials may interact with the immune system and alter immune responses. Depending on their composition and surface properties, nanoparticles can either stimulate or suppress immune function. Immunostimulation may lead to unintended inflammatory responses, while immunosuppression can increase susceptibility to infections. Such effects are particularly important in the veterinary field, where immune competence directly influences disease resistance and vaccine efficacy (Chrishtop et al., 2021).

Nanoparticles used as vaccine carriers or adjuvants must be carefully evaluated to ensure that immune modulation is beneficial rather than harmful. Uncontrolled immune activation may lead to hypersensitivity reactions or autoimmune-like responses in animals.

11.4 Oxidative Stress and Cellular Toxicity

A common mechanism underlying nanotoxicity is the induction of oxidative stress. Nanoparticles can generate reactive oxygen species (ROS), leading to lipid peroxidation, protein denaturation, and DNA damage. Oxidative stress may result in cellular

apoptosis or necrosis, contributing to tissue damage. In veterinary toxicology, oxidative stress-related toxicity is a major concern, particularly with inorganic nanomaterials such as metallic nanoparticles and quantum dots (Singh, 2019).

11.5 Reproductive and Developmental Toxicity

Reproductive and developmental toxicity is an emerging concern associated with nanotechnology. Certain nanoparticles have been reported to cross the placental barrier and reach fetal tissues, potentially affecting fetal development. In breeding animals, such effects may result in reduced fertility, embryonic loss, or developmental abnormalities. The long-term impact of nanoparticle exposure on reproductive performance in livestock and companion animals remains inadequately understood and requires further investigation (Patra et al., 2018).

11.6 Neurotoxicity

Due to their small size, some nanoparticles may cross the blood-brain barrier and interact with the central nervous system. Neurotoxicity may manifest as behavioural changes, altered neurotransmission, or neuronal damage. Although data on neurotoxicity in veterinary species are limited, this potential risk necessitates caution, particularly when nanotechnology-based drugs are intended for systemic use.

11.7 Environmental and Ecotoxicological Concerns

Environmental toxicity is a significant safety issue associated with nanotechnology. Nanomaterials may enter the environment through animal excreta, pharmaceutical waste, or agricultural runoff. Once released, nanoparticles may persist in soil and water, affecting microorganisms, plants, and aquatic organisms. Environmental accumulation of nanomaterials may disrupt ecosystems and indirectly affect animal and human health (McNeil, 2009).

In veterinary toxicology, environmental safety is closely linked to food safety. The potential for nanomaterials to bioaccumulate in the food chain raises concerns regarding long-term exposure of humans and animals to nanomaterial residues.

11.8 Species-Specific Toxicity

One of the major challenges in veterinary nanotoxicology is species-specific variability in toxic responses. Differences in anatomy, physiology, metabolism, and drug handling among species make it difficult to extrapolate safety data from laboratory animals to livestock, poultry, or companion animals. A nanomaterial considered safe in one species may exhibit toxic effects in another. Therefore, species-specific toxicity studies are essential for safe veterinary application (Ianiski et al., 2022).

11.9 Regulatory and Risk Assessment Challenges

Currently, regulatory frameworks for nanotechnology-based veterinary products are limited and not well standardized. Conventional toxicity testing methods may not adequately predict the safety of nanomaterials due to their unique properties. Risk assessment strategies must therefore be adapted to account for nanoparticle-specific behaviour, including long-term exposure and environmental impact. The lack of clear regulatory guidelines remains a major barrier to the clinical translation of nanotechnology in veterinary pharmacology and toxicology (Sapino et al., 2022).

XII. FUTURE PROSPECTS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology is expected to play an increasingly important role in the future of veterinary pharmacology and toxicology by enabling safer, more effective, and precision-based therapeutic strategies. Continuous advancements in nanoscience, material engineering, and biological understanding are likely to expand the scope of nanotechnology beyond conventional drug delivery into integrated therapeutic, diagnostic, and safety-oriented applications.

12.1 Precision Veterinary Pharmacology

One of the most promising future prospects of nanotechnology is its contribution to precision veterinary pharmacology. Nanotechnology-based drug delivery systems can be tailored according to species, disease condition, age, and physiological status of animals. Such individualized treatment approaches improve therapeutic outcomes while minimizing adverse effects. Precision drug targeting using ligand-modified nanocarriers is expected to reduce systemic exposure and improve pharmacodynamic efficiency, especially in chronic diseases and cancer therapy in companion animals (Ianiski et al., 2022).

12.2 Nano-Theranostics

Nano-theranostics, which combine diagnostic and therapeutic functions within a single nanoplatform, represent a major advancement. The term "theranostics" refers to the integration of therapeutic and diagnostic capabilities within a single system. These systems allow simultaneous disease diagnosis, targeted drug delivery, and monitoring of therapeutic response. In veterinary oncology, nano-theranostic systems enable real-time tumour imaging along with localized treatment, improving treatment accuracy and prognosis. The integration of pharmacology and diagnostics is expected to transform disease management strategies in animals (Patra et al., 2018).

12.3 Development of Safer and Biodegradable Nanocarriers

Future research in veterinary pharmacology and toxicology is expected to focus on the development of safer, biodegradable, and environmentally friendly nanomaterials. Organic and polymer-based nanocarriers with minimal long-term accumulation and reduced toxicity are likely to replace persistent inorganic nanomaterials. Emphasis will be placed on surface modification and controlled degradation to improve clearance and minimize organ accumulation, addressing major concerns in veterinary toxicology (Sapino et al., 2022).

12.4 Nano-Phytogenics and Alternative Therapeutics

Nano-phytogenics represent an emerging and promising area in veterinary pharmacology. Nanoformulation of plant-derived bioactive compounds enhances their stability, bioavailability, and therapeutic efficacy. These nano-phytogenic compounds are expected to serve as safer alternatives to conventional antibiotics, growth promoters, and chemotherapeutic agents. Their use may significantly contribute to reducing antimicrobial resistance and drug residues in food-producing animals, which is a major goal of veterinary toxicology and public health (Youssef, 2019).

12.5 Future Role in Vaccine Development and Immunotherapy

Nanotechnology is expected to revolutionize veterinary vaccines and immunotherapy. Nano-vaccines with improved antigen delivery and immune stimulation can provide long-lasting immunity with fewer booster doses. Future vaccine formulations may incorporate nanocarriers that enhance mucosal immunity, which is particularly important in poultry and livestock. Improved vaccine safety and efficacy will reduce dependence on antimicrobial therapy and contribute to better disease control strategies (Sapino et al., 2022).

12.6 Advances in Nanotoxicology and Risk Assessment

The future of nanotechnology in veterinary toxicology will involve the development of advanced nanotoxicological evaluation methods. Improved *in vitro* and *in vivo* models, along with computational toxicology and predictive risk assessment tools, will enhance understanding of nanoparticle behaviour in biological systems. Species-specific toxicity data and long-term exposure studies will be prioritized to ensure safe veterinary application. Regulatory frameworks are expected to evolve to incorporate nanoparticle-specific safety testing and environmental impact assessment (Singh, 2019).

12.7 Environmental Safety and Sustainable Veterinary Practice

Environmental sustainability will be a key focus in the future application of nanotechnology. Research efforts will aim to minimize environmental release and persistence of nanomaterials. Development of eco-friendly nanomaterials and biodegradable formulations will reduce environmental contamination and food chain accumulation. These advancements will support sustainable veterinary practice and align with global food safety and environmental protection goals (McNeil, 2009).

12.8 Translation to Field-Level Veterinary Practice

In the future, efforts will be directed toward translating nanotechnology-based products from laboratory research to field-level veterinary practice. Cost-effective manufacturing, scalable production methods, and simplified delivery systems will be essential for widespread adoption, particularly in livestock and poultry sectors. Collaboration between researchers, regulatory agencies, and veterinary professionals will play a crucial role in the successful implementation of nanotechnology in routine veterinary care.

XIII. CONCLUSION

Nanotechnology has emerged as a transformative tool in veterinary pharmacology and toxicology by offering innovative solutions to the limitations of conventional drug delivery systems. The application of nanotechnology has significantly

improved drug bioavailability, targeting efficiency, controlled release, and therapeutic efficacy across different veterinary species. Nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, magnetic nanoparticles, nanoshells, and nanopores have demonstrated promising applications in drug delivery, diagnostics, oncology, vaccine development, and feed supplementation.

From a veterinary toxicology perspective, nanotechnology has contributed to a better understanding of drug-tissue interactions, toxicokinetics, and safety evaluation. However, the unique physicochemical properties of nanomaterials also raise concerns regarding organ toxicity, immunotoxicity, reproductive toxicity, neurotoxicity, and environmental impact. Species-specific responses and long-term exposure effects further emphasize the need for comprehensive safety evaluation and risk assessment before widespread veterinary application.

Future prospects of nanotechnology in veterinary pharmacology and toxicology are highly promising, particularly in the areas of precision veterinary medicine, nano-theranostics, nano-phytogenics, and environmentally safer nanomaterials. Advances in nanotoxicology, regulatory frameworks, and sustainable manufacturing are expected to facilitate safer and more effective use of nanotechnology in veterinary practice. With responsible application, appropriate regulation, and continued research, nanotechnology has the potential to significantly enhance animal health, productivity, food safety, and environmental sustainability.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The authors alone are responsible for the content and writing of this article.

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