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Nano-Adjuvants: A Promising Approach For Next-Generation Veterinary Vaccine

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Key Points

- **Enhanced antigen delivery:** Nano-adjuvants can improve antigen protection, uptake by antigen-presenting cells, processing, and presentation to immune cells.
- **Multiple nanoplatforms:** Polymeric particles, lipid nanoparticles, biomimetic systems, protein nanoparticles, and inorganic or hybrid systems offer different delivery and immune-stimulation properties.
- **Targeted and controlled responses:** Nanomaterials can support lymph-node targeting, controlled antigen release, and systemic or mucosal immune responses.

Abstract

Nano-adjuvants are nanomaterial-based vaccine formulations developed to enhance antigen delivery, immunogenicity, targeting, and controlled release. Their physicochemical properties, including particle size, surface chemistry, composition, shape, and solubility, influence their interaction with immune cells and tissues. Nano-adjuvants can facilitate antigen uptake by antigen-presenting cells, support lymph-node delivery, protect sensitive vaccine components, and promote systemic or mucosal immune responses. Various platforms, including polymeric particles, lipid nanoparticles, biomimetic systems, self-assembling protein nanoparticles, and inorganic or hybrid systems, are being investigated for veterinary applications. Their potential extends across poultry and livestock diseases; however, safety, reproducibility, stability, scalability, cost-effectiveness, and regulatory acceptance remain important considerations. With appropriate design and validation, nano-adjuvants could contribute significantly to next-generation veterinary vaccination strategies.

Keywords: Nano-adjuvants, Veterinary vaccines, Nanomaterials, Antigen delivery, Immunogenicity, Mucosal immunity, Nanovaccines, Animal health

INTRODUCTION

Adjuvant

A vaccine must generate an immune response of sufficient magnitude, quality and duration to provide protection. Adjuvants are added when an antigen alone does not stimulate adequate immunity and can influence the type and persistence of the response.

This is particularly important for purified and subunit vaccines. Such vaccines can have good safety characteristics but may be comparatively weakly immunogenic. A suitable adjuvant can improve antigen recognition and help the immune system respond more efficiently.

Nano-Adjuvant

A nano-adjuvant is a nanomaterial-based formulation designed to enhance vaccine immunogenicity, antigen delivery, or both.

Depending on composition, it may carry antigen inside the particle, display antigen on its surface, deliver an immunostimulatory component, or combine several functions

The important point is that "nano" is not itself a mechanism. Particle size, surface chemistry, composition, shape, deformability, solubility and other physicochemical properties determine how a nanomaterial interacts with cells and tissues

Antigen Delivery To Immunity

After vaccination, nanoplatforms can facilitate contact between antigen and antigen-presenting cells (APCs), including dendritic cells.

APCs capture and process antigen and present antigen-derived peptides to T cells, linking innate and adaptive immunity (He et al., A useful sequence is: antigen protection/loading → delivery to APCs → uptake and processing → presentation to T cells → B- and T-cell responses → immune memory and protection. The exact pathway depends on the nanomaterial, antigen and route (He et al., 2025; Dai et al., 2026).

Nanoparticle design can influence lymphatic transport and lymph-node access, important sites where antigen-presenting cells interact with lymphocytes and adaptive responses develop.

What Makes Nanoparticles Different ?

Nanoscale systems offer a high surface area and can organize antigen molecules at high density or in an ordered presentation. Such multivalent presentation can improve recognition and immunogenicity for selected vaccine designs (He *et al*., 2025).

Nanoparticles may also protect sensitive vaccine components from premature degradation, an advantage for antigens or nucleic-acid-based components vulnerable to enzymatic or environmental degradation (He *et al.*, 2025).

However, more uptake is not automatically better. The biological outcome depends on how the material is sensed, processed and cleared. Rational design and careful characterization are therefore central to nano-adjuvant development (Ren *et al.,* 2023; Dai *et al.*)

Major Nano-Adjuvant Platforms

Polymeric nanomaterials. Polymeric particles can encapsulate or associate with antigens and can be designed for controlled delivery (He *et al.*, 2025).

Lipid nanoparticles. Lipid-based systems are important delivery platforms and can be tuned for interaction with biological membranes and intracellular delivery (He *et al*., 2025).

Biomimetic nanomaterials.Virus-likeparticles, cell-membrane-coated nanoparticles and extracellular-vesicle-based systems reproduce selected biological features (He *et al*., 2025).

Self-assembling protein nanoparticles. Protein building blocks can form ordered nanoscale structures that present antigens in a multivalent fashion (He *et al*., 2025).Inorganic, hybrid and composite systems. These can provide distinct physical and chemical properties and may combine delivery, stability and immune-stimulation functions; safety and biological persistence require evaluation (Dai *et al*., 2026).

Controlled Release

A nanocarrier can be designed so antigen is not released all at once.Controlled or sustained exposure may help maintain antigen availability and coordinate antigen delivery with immune activation (Dai *et al*., 2026).

The desired release profile depends on the antigen, nanomaterial, route and immune mechanism. Release behaviour should therefore be experimentally characterized rather than assumed from the material alone (Dai *et al*., 2026).

Route of Administration

Veterinary nanovaccines can be investigated through injection, oral and nasal administration, depending on disease and desired immune response (He *et al*., 2025). The route changes where antigen first encounters the immune system, so a nanomaterial that works well for injection may not behave identically by oral or intranasal delivery (Dai *et al*., 2026).

Mucosal Immunity

Many animal pathogens enter through respiratory or gastrointestinal mucosal surfaces. Protection at these sites can therefore be highly relevant to disease prevention (Dai *et al*., 2026). Nanomaterials can help protect antigens and facilitate delivery to mucosal tissues, encouraging research into oral and intranasal nano-vaccine formulations (Dai *et al*., 2026).

For poultry, this is especially interesting because important respiratory and enteric infections can circulate efficiently within dense flocks.

Mucosal formulations must nevertheless address antigen stability, delivery and dosing consistency (Dai *et al*., 2026).

Applications Across Veterinary

Species Research is not limited to poultry. Nanomaterial vaccine systems have been explored for diseases including foot-and-mouth disease, porcine epidemic diarrhoea, pseudorabies and bordetellosis (He *et al*., 2025).

The 2026 review emphasizes selection according to target species, pathogen, vaccine type and delivery route rather than assuming one nanomaterial is optimal for every application (Dai *et al*., 2026).

SELECTION OF NANO-ADJUVANT

The first consideration is the antigen and immune response required.

A formulation intended mainly to improve stability may differ from one designed for mucosal delivery, lymph-node targeting or cellular immunity (Dai *et al*., 2026).

Particle size, surface charge, chemical structure, shape, deformability, solubility and composition can influence uptake, trafficking and immune recognition (Ren *et al*., 2023).

A rational sequence is: define disease and target response → select antigen and route → select compatible nanoplatform → characterize formulation → test immunogenicity and safety → evaluate protection and practical feasibility (Ren et al., 2023; Dai et al., 2026).

Safety: A stronger immune response is not useful if accompanied by unacceptable toxicity or excessive inflammation. The potential and toxicity of adjuvants must therefore be balanced carefully (Nooraei *et al.*, 2023).

Nanoparticle behaviour can change with size, shape, surface charge, composition and concentration. These properties can influence cellular uptake and immune activation, so safety cannot be inferred from the material name alone (Ren *et al.*, 2023).

From Laboratory To Farm

A nano-adjuvant must be reproducible from batch to batch. Small changes in particle size, composition or surface characteristics can alter biological behaviour, making manufacturing control essential (Dai et al., 2026).

Other practical questions include shelf stability, storage conditions, dose consistency, production cost and compatibility with existing vaccination programmes. These factors can determine whether a laboratory formulation is useful in the field (Dai et al., 2026).

For veterinary use, interdisciplinary collaboration is valuable.

Nanotechnology, immunology, veterinary medicine, formulation science, animal trials and regulatory evaluation need to work together (Ren et al., 2023).

Scope Of Nano-Adjuvants

Future nano-adjuvants are moving toward rationally designed platforms matched to the pathogen, antigen, animal species, route and desired immune response (Dai *et al*., 2026).

Important directions include lymph-node targeting, mucosal vaccination, cross-presentation, controlled release and multifunctional platforms combining delivery and immune stimulation (Dai *et al.*, A deeper understanding of nano–immune interactions may make it possible to predict how physicochemical properties influence immunity. High-dimensional and

multiomics approaches have been proposed to help understand and optimize these interactions (Ren *et al*., 2023).

For poultry and livestock, successful future systems are likely to combine immune protection with safety, stability, affordability and simple field application—not merely the smallest particle size or highest laboratory response (He *et al*., 2025; Dai *et al*., 2026).

Conclusion

Nano-adjuvants are versatile tools for next-generation veterinary vaccines. They can provide antigen delivery, protection, controlled release, targeting and immune stimulation within engineered nanoscale platforms (He *et al*., 2025; Dai *et al*., 2026).

Their potential extends across poultry and livestock diseases and includes systemic and mucosal vaccination. However, nano-adjuvants are not automatically superior simply because they are nanoscale; performance depends on material selection, formulation and biological evaluation (Nooraei *et al*., 2023; Ren *et al*., 2023).

The path from laboratory concept to routine veterinary use requires evidence for efficacy, safety, reproducibility, stability, scalability, cost-effectiveness and regulatory acceptability. With these requirements addressed, nano-adjuvants could become an important part of future animal-health vaccination strategies (Dai et al., 2026).

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