A PERSPECTIVE REVIEW ON THE IMPORTANCE OF VETERINARY VACCINE RESEARCH AND DEVELOPMENT AND ITS INFLUENCE ON ANIMAL HEALTH AND DISEASE MANAGEMENT STRATEGIES

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ABSTRACT. Vaccine production processes have often been characterised by ambiguity, both for the public and, to some extent, for practitioners in the field. The selection of options for veterinary research extends beyond merely ensuring safety and efficacy. It also encompasses a careful evaluation of various factors, including the financial implications, the practicality of implementation, and the specific challenges encountered when introducing the vaccine to farmers. Additionally, considerations must be made regarding how effectively the vaccine can be administered to the targeted animals in real-world conditions. This comprehensive approach aims to ensure that the solutions developed are not only scientifically sound but also feasible and beneficial for those involved in animal husbandry. Therefore, this paper aims to elucidate the extensive and intricate journey of vaccine research and development, emphasising the economic and health ramifications associated with the improper use of veterinary vaccines, as well as its influence on both animal and human populations. By doing so, the paper seeks to enhance awareness of the significance of infection prevention. It begins by outlining the foundational aspects, including the types and requirements of veterinary vaccines and vaccination, and the necessity of vaccines for emerging and re-emerging animal diseases as well as the challenges of policies and guidelines on veterinary vaccine research and developments.

Keywords: vaccines, veterinary, animal, health, disease

INTRODUCTION

The use of animal vaccines plays a critical role in ensuring food security for millions by enabling farmers to produce food in an efficient, safe and economically viable manner (Capper, 2023; Robi *et al.,* 2024). Moreover, food safety and security represent a significant and pressing concern globally, stemming from challenges such as overpopulation, conflict, diseases affecting animals, plants, and humans, climate change, resource depletion and environmental degradation (Brooks *et al.,* 2022; Charlier *et al.,* 2022). It is imperative that long-term solutions for food production consider their effects on the environment, water and other resources, as well as on human and animal health, and that they promote sustainable agricultural practices (Zhang *et al.,* 2024).

Vaccination plays a vital role in protecting the health of animals, significantly contributing to the maintenance of high production standards in livestock as well as ensuring the well-being of companion animals (Rautenschlein and Schat, 2024). The effective development of vaccines and the successful implementation of vaccination programs necessitate a comprehensive understanding of the intricacies of the immune system (De la Fuente and Contreras, 2021). This system is a well-coordinated network involving various key components, each interacting with the others, achieving a delicate balance (Thomas *et al.,* 2022).

To create effective vaccines, it is essential to explore the various mechanisms through which immunity can be stimulated by different vaccine candidates. The intricacies of these mechanisms and their critical roles in health and disease have been highlighted by recent developments that have deepened our understanding of the innate and adaptive immune responses in animals (Pathak and Kim, 2024). The different cell types involved, signalling pathways, and the interaction between innate and adaptive immunity are some of the mechanisms that researchers are investigating to understand these immune responses. In addition to improving our understanding of basic immunological processes, this expanding corpus of research has important ramifications for the creation of vaccines, the prevention of disease, and therapeutic approaches in both human and veterinary medicine (Rautenschlein and Schat, 2024). However, many aspects of these complex systems remain unclear, highlighting the on-going need for further research and exploration in this critical area of animal health.

VETERINARY VACCINES AND VACCINATIONS

Vaccination is fundamentally based on the principle of introducing a vaccine, which contains an antigen, into a host, whether in an animal or a human (Hill *et al.,* 2021). This controlled administration is designed to stimulate the body's immune system, prompting it to recognise and respond to the specific pathogen without causing the disease itself (Thomas *et al.,* 2022). By doing so, the immune system develops the necessary defences, enabling it to recognise and respond more effectively to the actual infection if encountered in the future (Park *et al.,* 2024).

Veterinary vaccines and vaccinations are essential not only for protecting animal health but also for enhancing human health by ensuring a safer food supply (Chambers *et al.,* 2015). Vaccinations utilised on farms aim to maintain animal welfare by reducing pain, suffering, and the impact of various diseases (Meeusen *et al.,* 2007).

Vaccination of animals against various diseases, coupled with the prompt diagnosis and treatment of illnesses when they occurred enables farmers to maintain the supply of essential food products. The implementation of vaccination programs has not only enhanced human health but also contributed significantly to food security by reducing disease outbreaks in livestock production (Du *et al.,* 2022; Laxminarayan *et al.,* 2024; Mkulo *et al.,* 2024). A thorough understanding of immunological principles and the development of advanced innovative vaccines have enabled effective vaccination strategies (Oladejo *et al.,* 2024).

Vaccinations administered over the past century have significantly reduced mortality and morbidity in millions of animals (Jorge and Dellagostin, 2017). These vaccinations are extensively utilised across various animal species to protect them against highly contagious and lethal diseases (Tizard, 2020; Lewis and Roth, 2021; Thomas *et al.,* 2022). For instance, vaccines such as those for rabies, parvovirus, distemper and kennel cough are commonly given to companion animals (Egberink *et al.,* 2022; Ellis *et al.,* 2022; Weidinger *et al.,* 2024). Additionally, in livestock and poultry sectors, species such as chickens, turkeys, pigs, and cattle are vaccinated against diseases including haemorrhagic septicaemia, swine fever, salmonellosis, Newcastle disease and infectious bronchitis (Lupini *et al.,* 2020; Francis, 2021; Liu *et al.,* 2023).

EMERGING AND RE-EMERGING ANIMAL DISEASES

Emerging infections refer to a category of diseases that has been recently identified and classified within a taxonomic framework (Paul-Pierre, 2009). The transformative effects of globalisation, climate change and the opening of previously isolated ecosystems have significantly altered the dynamics of endemic diseases (Roeder *et al.,* 2013; Melkikh, 2022). Furthermore, these changes have facilitated the emergence of new pathogenic agents that threaten animal health.

The emergence and re-emergence of infectious diseases can be attributed to a multitude of mechanisms, each playing a vital role in the behaviour of pathogens (Leeks *et al.,* 2021; Le *et al.,* 2022). One significant factor is the remarkable variability inherent in viruses, particularly RNA viruses. This variability gives rise to diverse populations of quasispecies, which enhances their ability to adeptly cross the boundaries between different species (Su *et al.,* 2020; Brandao *et al.,* 2022; Bi *et al.,* 2024).

Viruses possess an astonishing capacity for evolution that occurs at a rate far surpassing that of their host organisms (Koonin *et al.,* 2022; Schuster and Stadler, 2023). They utilise a number of complex strategies, including point mutations, to enable this rapid evolution. Their genetic material undergoes minor but profound changes as a result of these mutations, enabling slow adaptations that eventually produce amazing changes (Koonin *et al.,* 2022). Other methods include the deletions that remove segments of their genome and recombination that allows this virus to exchange genetic information with other viruses (Harvey and Holmes, 2022). Additionally, viruses with segmented genomes such as avian influenza virus (AIV), can undergo reassortment during co-infection of different strains, shuffling their genetic material in new combinations (Bi *et al.,* 2024). Some viruses can even acquire genes from their host cells, integrating them into their own genome (Schonrich *et al.,* 2017; Aylward and Moniruzzaman, 2022).

One significant source of diseases emergence is the opening of previously isolated ecosystems, which creates new interactions among unrelated species. These new interactions can reveal vulnerabilities, showing that a species once believed to be resistant to certain infections may actually be susceptible (Bi *et al.,* 2024).

The introduction of invasive or migratory species can significantly contribute to the emergence of new diseases within animal populations (Melkikh, 2022). Such introductions may result from either deliberate actions or accidental releases into non-native environments. These species can serve as new reservoirs for pathogens, facilitating the spread of infectious agents to local wildlife (Bansal *et al.,* 2022). As a result, they may disrupt established ecosystems and propagate diseases to animal populations with no prior exposure or immunity (Tyson-Pello and Olsen, 2020; Sultan *et al.,* 2022).

The movement of migratory species into livestock territories has produced a substantial rise in disease occurrence among the animals (Melkikh, 2022). The sudden arrival of these species disrupts the fragile ecosystem equilibrium which results in elevated risk levels among vulnerable animal groups. Consequently, enhancement of livestock diseases profoundly have adverse effects on production and cause distortions in value due to shocks in both domestic and international markets, leading to market inefficiencies (Hu *et al.,* 2022). The health and sustainability of commercial livestock product markets, along with their growth to meet demand and support smallholder farming systems, are jeopardised by livestock disease outbreaks (Melkikh, 2022). Moreover, the prevalence of livestock diseases can promote unsustainable and detrimental practices within the agricultural sector (Ekwem *et al.,* 2021; Akpan, 2024).

The significance of livestock disease in production, along with its impact on public health and market stability, underscores the necessity for government intervention through response and eradication programs (Ankers and Bengoumi, 2020; Amenu *et al.,* 2023). This situation also highlights the importance of implementing trade bans and restrictions to mitigate risks associated with such diseases.

ENDEMIC AND EXOTIC ANIMAL DISEASES

The subset of animal pathogens identified by the World Organisation for Animal Health (WOAH, founded as OIE) as high-risk biological threats is characterised by their highly transmissible nature, enabling them to spread rapidly across borders and inflict significant socio-economic and public health repercussions (Khurana *et al.,* 2021; Durrwald *et al.,* 2022; Sailleau *et al.,* 2022). These pathogens are also classified as high-risk agents for deliberate introduction into non-endemic countries for similar reasons (Dixon *et al.,* 2020). These biological agents include pathogens that affect animals, and in certain instances, zoonotic pathogens that have been eradicated in numerous countries but continue to persist in many developing regions (Karpagam and Ganesh, 2020). The effects of these pathogens can vary a lot depending on the specific environments where they naturally exist or have been introduced (Debnath *et al.,* 2021). This shows how important it is to understand local conditions to effectively manage their impact.

Many researchers have studied and written about the significant impact of infectious diseases on livestock and poultry. These studies also explore zoonotic diseases, showing the close links between animal health and human well-being (Bach *et al.,* 2023). Each piece of research offers important insights into how these diseases affect farming, animal care, and public health, emphasising the need to understand and control these pathogens in our food systems (Bosch-Camos *et al.,* 2022; Bach *et al.,* 2023). These studies examine the diverse characteristics of animal diseases, including the range of hosts affected, modes of transmission and the potential for spread. They further assess the consequences for production and survival, as well as the costs associated with prevention and control in different geographical contexts (Kang *et al.,* 2024).

The impact of an outbreak involving a known biological agent is always significant but can vary greatly depending on factors like location, population density, local healthcare systems, and the environment (McElwain and Thumbi, 2017). For example, urban areas might see faster spread because people live closer together, while rural areas may face challenges due to slower access to medical care. Cultural attitudes and public awareness about health also play a big role in how well response efforts work, ultimately affecting how much the outbreak impacts a specific region. Relevant comparisons and contrasts regarding the effects on animal health, economic stability, food security and safety, and public health within these diverse contexts have been previously documented (McElwain and Thumbi, 2017).

The impact of animal disease on food safety and security, economic and human health has prompted a growing interest in the integration of economics and epidemiology (Kappes *et al.,* 2023). Policy formulation is increasingly informed not only by considerations of supply, market price fluctuations, and trade, but also by the implications for public health (Debnath *et al.,* 2021). There is a major lack of knowledge about how animal diseases are spread within livestock value chains and their economic effects, especially considering the differences between high- and low-income countries (Rajala *et al.,* 2021). To effectively assess the impacts of animal disease burdens, it is essential to obtain accurate and relevant data, as well as institutional information related to veterinary practices, health monitoring, and regulatory policies that segmented across all stakeholders and economies involved in these value chains (Kappes *et al.,* 2023).

REDUCING DISEASE AND MORTALITY

The development of vaccines has revolutionised animal husbandry, leading to lower mortality rates and improvements in the production of healthy livestock (Coppo *et al.,* 2013; Carpenter *et al.,* 2022). This increase in animal production has played a crucial role in mitigating food insecurity by providing communities with essential nutrients and economic stability (Werling *et al.,* 2024).

Despite these advancements, challenges persist. Climate change has intensified conditions favourable to disease vectors and pathogens, increasing the risk of new animal diseases emerging (Carlson *et al.,* 2022; Philips *et al.,* 2024). The transmission of such emerging infectious diseases, particularly at the animal-human interface, poses a critical risk to global health, threatening to trigger epizootics and pandemics that could affect animal populations and human communities worldwide (Debnath *et al.,* 2021).

Therefore, it is increasingly urgent to focus on the development of novel vaccines to effectively prevent diseases in animals. This proactive approach is essential for protecting not only animal health but also public health on a global scale (Kaasschieter *et al.,* 1992). In addition, vaccines play a critical role in the prevention of diseases that could necessitate antibiotic intervention (Hoelzer *et al.,* 2018). A common objective within the agricultural sector is to maintain the health of animals while minimising the reliance on antibiotics (Lubroth *et al.,* 2007). This approach ensures that antibiotics remain accessible for responsible use in alleviating animal suffering when necessary (Micoli *et al.,* 2021). Overuse of antibiotics can lead to the development of antibiotic-resistant pathogens, posing significant risks to both human and animal health (Hoelzer *et al.,* 2018). Vaccination is instrumental in reducing the reliance on antibiotics, thereby mitigating resistance risks and preserving their effectiveness for essential treatments (Buchy *et al.,* 2020).

PROTECTING PUBLIC HEALTH

Veterinary vaccines are integral to the protection of public health, particularly in the prevention of zoonotic diseases. Notable zoonotic diseases include tuberculosis (Ugochukwu *et al.,* 2020), avian influenza (Kang *et al.,* 2024) and the novel coronavirus (Ertuk *et al.,* 2021), all of which pose significant threats to human health.

By effectively controlling these diseases at their animal source, veterinary vaccines significantly mitigate the risk of human outbreaks, thereby contributing to the safety and health of populations (Busch *et al.,* 2021; Lerch *et al.,* 2022). This is especially important considering that animals are primary sources of essential food products, such as eggs, milk, meat and other protein-rich commodities. Healthy animal populations help ensure safer food for consumers, showing the important connection between veterinary interventions and public health (MacPhillamy *et al.,* 2022; Davis *et al.,* 2024).

ECONOMIC DRIVERS AND OPPORTUNITIES

Animals play a vital role in human society by providing not only essential food sources and clothing but also a diverse array of value-added products that enhance the human daily existence. As human diets and lifestyles evolved, there has been a notable increase in the consumption and utilisation of animal products, reflecting changing preferences and nutritional needs (Kiiza *et al.,* 2023).

However, alongside these benefits, infectious diseases affecting animals pose a significant and escalating threat to global animal health and welfare (Roth and Sandbulte, 2021). Effectively managing and controlling these diseases is paramount as it directly impacts animal health, ensures food security, and helps to alleviate rural poverty that often relies on livestock and animal production for income (Campbell *et al.,* 2018; Alhaji *et al.,* 2020; Brooks *et al.,* 2022).

At present, veterinary vaccines are only available for a limited number of diseases that impact animal health. A manufacturing process that maximises safety even when working in low containment conditions should be one of the ideal features for animal vaccines. This method guarantees that the vaccines can be produced without requiring a large infrastructure, while also reducing the chance of contamination (Farnos *et al.,* 2020). Furthermore, it is essential that these vaccines have a strong ability to produce a large number of doses effectively (Roth, 2011).

In order to maintain the vaccines' accessibility and financial viability for broad use in veterinary clinics and agricultural settings, this scalability must be balanced with an economical production model (Koppu *et al.,* 2022). In the end, these vaccines' overall efficacy and uptake in preserving animal health will be improved by their affordability, scalability, and safety. Achieving widespread usage hinges on their affordability, making it accessible for farmers and pet owners alike to obtain these vital vaccines (Nuvey *et al.,* 2023). This accessibility not only encourages vaccination but also strengthens overall community health by reducing the risk of disease transmission between animals and humans (Lewis and Roth, 2021; Davis *et al.,* 2024).

A truly optimal vaccine would not only exhibit high efficacy but also facilitate a rapid onset of immunity after just a single dose. Besides that, it will have an amazing feature to provide cross protection from different strains of pathogens. Protection is the most important thing, hence, the vaccine should be safe for many different animal species and work well with all age groups (Koppu *et al.,* 2022). Additionally, it should play a crucial role in preventing the transmission of viruses to both susceptible animals and humans, ensuring comprehensive health protection (Carpenter *et al.,* 2022; Zhang *et al.,* 2023).

POLICY AND SUPPORTING NATIONAL ERADICATING PROGRAMMES

Vaccine research and developments require collaboration between the multi discipline of human medicine, veterinary medicine, public health and environmental sciences (Kefaloudi *et al.,* 2022; Allam *et al.,* 2023).

Emerging zoonotic diseases, which account for a staggering more than 60% of all newly identified illnesses, are predominantly linked to infections originating in animals (Rahman *et al.,* 2020). This alarming trend highlights an urgent need for the development of innovative vaccines aimed at preventing and controlling these diseases effectively (Olawade *et al.,* 2024). Such vaccines are crucial not only for protecting animal health but also for thwarting the potential transmission of pathogens from animals to humans (Ahmed *et al.,* 2022).

To address this complex challenge, it is essential to enhance our understanding of how diseases can jump across species barriers. This calls for dedicated efforts in research to unravel the intricacies of cross-species disease transmission (Brooks *et al.,* 2022). Additionally, there is a pressing need for the creation of advanced diagnostic methods that can quickly and accurately identify these emerging threats. Moreover, improving our grasp of the immune mechanisms that confer protection against these diseases is vital. This knowledge will inspire new innovative ways of speeding the vaccine discovery process, which may be a viable link between humans and animals health (Akkermans *et al.,* 2020; Thornton *et al.,* 2024). Embracing such innovative approaches is not only feasible but also critically important in our fight against emerging infectious diseases (Hu *et al.,* 2022).

The One Health approach encompasses the study of emerging zoonotic diseases, which are newly identified diseases affecting animals that have the potential to cause widespread outbreaks and pandemics, as well as the ability to infect human populations (Dadar *et al.,* 2021; Haselbeck *et al.,* 2021). Despite the notable advancements in microbial genetics and genomics in recent years, the understanding of how these zoonotic agents persist in their natural environments and how they react to environmental changes which are often driven by human activities remains limited. There is a pressing need to enhance our detection capabilities and response strategies for emerging zoonotic agents, especially those that manifest rapidly and can spread across vast geographical areas (Schweizer *et al.,* 2021). In the upcoming section, we will delve into a range of both well-established and newly emerging One Health pathogens, highlighting their significance and the challenges they present (Hill, 2011; Kulpa-Eddy *et al.,* 2011).

Equally important is the regulatory process that ensures vaccines meet required safety and efficacy standards (Gifford *et al.,* 2011; Roth, 2011; Woodland, 2011; Ghattas *et al.,* 2021). It is essential that this process strikes a balance, providing the necessary oversight to protect consumers while also avoiding an increase in the costs associated with licensing and production (Busch *et al.,* 2021). If these costs become excessively high, there is a risk that the vaccine recipient will find the vaccines unaffordable, undermining the very purpose of regulation in promoting animal and public health, and accessibility (Ugochukwu *et al.,* 2020; Rajala *et al.,* 2021).

PREDOMINANT FACTORS INFLUENCING FUTURE TRENDS OF VETERINARY VACCINES RESEARCH AND DEVELOPMENTS

Omics Technologies

Omics technologies (genomics, transcriptomics, proteomics, metabolomics, etc.) represent a transformative approach to vaccine design, based on a detailed understanding of the molecular interactions between the immune system and the pathogens (De la Fuente and Contreras, 2021; Cwiklinski and Dalton, 2022; Dai and Shen, 2022). The substantial volume of data produced to elucidate host-pathogen interactions necessitates the development and validation of biologically robust models to effectively interpret and apply this knowledge to the design and implementation of vaccines (De la Fuente *et al.,* 2018; De la Fuente and Contreras, 2023).

Consequently, omics technologies offer insights into the molecular pathways and gene expression profiles associated with host cellular responses to pathogens, facilitating the identification, modelling, and prediction of the dynamics inherent in host-pathogen interactions (Cwiklinski and Dalton, 2022). Omics-based approaches offer significant benefits for both the research and development of veterinary vaccines (Kules *et al.,* 2016).

Additionally, the advent of omics technologies has sparked a revitalised interest in the research and development of vaccines targeting animal diseases (Cwiklinski and Dalton, 2022). These advanced methodologies allow for the design, evaluation, and refinement of candidate vaccines to be accomplished in a remarkably reduced time frame compared to traditional approaches (De la Fuente and Contreras, 2021). This efficiency not only accelerates the process but also enhances the potential for creating effective vaccines that can better protect animal populations from various diseases (De la Fuente and Contreras, 2023; Yennamalli and Onteru, 2025).

Empowering the Vaccine Research Community and Talents Development

The vaccine research community plays a crucial role in promoting public health and enhancing global food security (Capper, 2023). To achieve these goals, it is essential to implement well-structured health monitoring and regulatory policies that foster collaboration across various sectors. This includes the creation of advanced programs such as the One Health initiative that is designed to promote the integration of animal and human health efforts. From the acknowledgment of the inescapable linkage of the human and animal ecosystems, these programs aim at providing an overall well-being that will affect every living being as well as their habitats (Hu *et al.,* 2022).

Moreover, establishing effective communication mechanisms and platforms is vital for improving interactions between health authorities and local research communities (Fawzy and Helmy, 2019). By facilitating communication strategies, it can help prevent the emergence and spread of diseases that affect both animal and human populations (Overgaauw *et al.,* 2020). Such proactive measures are important to build a resilient health framework that protects the communities and nurtures a sustainable environment.

The continuous advancement of expertise in vaccine research is essential for effectively responding to both emerging and re-emerging diseases, as well as zoonotic diseases that can be transmitted from animals to humans (Pike *et al.,* 2010). To achieve this goal, a comprehensive strategy focused on promotion and integration is necessary. This strategy should involve the establishment of professional training programs aimed at cultivating the talents and skills of individuals in the field (Schembri *et al.,* 2015). By enhancing the biosecurity practices within both smallholder and industrial farming systems, we can significantly reduce the risk of infectious diseases emerging and spreading (Alarcon *et al.,* 2021; Fountain *et al.,* 2023). These training initiatives will equip workers with the knowledge and techniques needed to implement preventive measures and control strategies, ultimately protecting public health and agricultural systems (Ouyang *et al.,* 2023; Zhang *et al.,* 2024).

Enhance Veterinary Vaccinology Networking and Coordination

Veterinary vaccinology integrates the expertise from various disciplines and organisations, spanning local, national, and global initiatives, to enhance the health of animals and, by extension, protect human health (Allam *et al.,* 2023). This approach acknowledges the intricate interdependence between animal and human populations and recognises the significant threat posed by emerging and re-emerging infectious diseases that can impact livestock, public health, and global food security (Brooks *et al.,* 2022).

The implementation of veterinary vaccines plays a crucial role in mitigating the risk of disease transmission between animals and humans (Chambers *et al.,* 2015). By effectively reducing the prevalence of both emerging and re-emerging infectious diseases, this field translates ground breaking advances in health science into practical strategies and policies (Li H *et al.,* 2021; Alders, 2024). These efforts are vital not only in protecting animal welfare but also in promoting overall community health and ensuring food security for the growing global population (Meeusen *et al.,* 2007; Roth and Sandbulte, 2021).

In addition, the establishment and execution of a comprehensive global and national surveillance system for emerging infectious diseases provides timely alerts regarding the emergence of pathogens in targeted high-risk areas (Perez *et al.,* 2011; Kumar *et al.,* 2021). This proactive approach enhances the management of animal diseases, which may have significant implications for both socio-economic conditions and public health outcomes (Singh *et al.,* 2024).

Integrating Vaccinology Research Through the Multidisciplinary Approach

The emergence and re-emergence of infectious diseases pose significant challenges to public health and global food security, necessitating a multidisciplinary approach to mitigate their impacts (Hu *et al.,* 2022; Allam *et al.,* 2023). Current vaccine research is increasingly focused on epizootic and zoonotic diseases, emphasising the importance of preventing the transmission of emerging infectious diseases at the interface between animals and humans (Pike *et al.,* 2010).

It is critically important to protect both animal and human populations from epizootics and pandemics. Emerging and re-emerging pathogens can significantly impact food safety and security, therefore, it is essential to propose strategies for enhancing vaccinology research by integrating multidisciplinary approaches in the development of new vaccine design methodologies (Dungu *et al.,* 2018; Fefferman *et al.,* 2023). Furthermore, fostering open discussions and communication regarding the opportunities and risks associated with vaccine research is crucial for advancing this field effectively (Fawzy and Helmy, 2019).

Moreover, this research initiative, which is inherently multidisciplinary and collaborative, must incorporate both basic and applied research pertaining to food production (Potter and Babiuk, 2001; Gonzalez *et al.,* 2024). It is imperative that this research seamlessly integrates and balances the various inputs required for crop and livestock production while simultaneously protecting human health, animal welfare and environmental integrity (Pastoret *et al.,* 2000; Sleeman *et al.,* 2017). Additionally, efforts must be directed toward the conservation of non-renewable resources. The success of this endeavour hinges on the equitable sharing and implementation of resources, technologies and knowledge across all nations, thereby fostering a collective international commitment to enhance food production practices (Swayne, 2012; Mumtaz *et al.,* 2021).

FUTURE PERSPECTIVE IN VETERINARY VACCINE RESEARCH OPPORTUNITIES

Despite the remarkable progress achieved in the field of vaccinology, numerous intricate parts remain to be solved. A significant hurdle lies in the limited understanding of host-pathogen interactions, which play a crucial role in determining immune responses (Hill *et al.,* 2021; Hernaez and Alcami, 2024; Kalugotla *et al.,* 2024). The variability in immunological reactions under diverse conditions adds another layer of complexity. The difficulties in precisely modulating protective responses in light of antigenic variability serve as undeniable obstacles that must be addressed in the ongoing effort to enhance vaccine efficacy (Li K *et al.,* 2021).

Enhanced surveillance capabilities can be achieved by developing more effective diagnostic tests, particularly those that can be rapidly deployed in the field (Gifford *et al.,* 2021). It is crucial that these tests are not only cost-effective but also rigorously validated to ensure high sensitivity and specificity, allowing for accurate and reliable detection in various environments (Hobbs *et al.,* 2021). This improvement in diagnostic testing can significantly contribute to more timely and efficient monitoring of health threats.

Moreover, the combination of human and animal surveillance data aims to create a comprehensive and near real-time overview of the current situation. This integrated approach allows for the monitoring of health trends and potential outbreaks by analysing information from both populations simultaneously, thereby enhancing operational awareness and response capabilities (Pley *et al.,* 2021; Hutchinson *et al.,* 2024).

Improvements of current vaccines are necessary, particularly platform vaccines that have undergone rigorous validation to ensure their purity, potency, and safety. These innovative vaccines have the capability to incorporate genetic material from newly identified pathogens, allowing them to be swiftly manufactured (Ghattas *et al.,* 2021; Verma and Awasthi, 2024). This adaptability enables a rapid response to emerging infectious threats, making these vaccines a vital tool in veterinary and public health defence.

Gaining a deeper insight into the mechanisms underlying the development and spread of rapidly emerging diseases can help identify potential strategies to disrupt the transmission of these infections. By deciphering the biological processes and environmental factors that contribute to their emergence, we can develop targeted interventions aimed at preventing outbreaks and protecting animal and human health.

Comprehensive outreach strategies that emphasise clarity and timely communication are crucial to build a stronger connection with the community (Figueroa *et al.,* 2022). Improvement in the connection will help inform the public and encourage participation in activities designed to improve public health outcomes and promote animal welfare. This can be achieved through a range of communication avenues including workshops, social media campaigns, and information sessions (Garcia *et al.,* 2023). Ultimately, this step will help to educate the public leading to concerted efforts between health authorities, local organisations and members of the community to effectively implement much needed health programmes (Baker *et al.,* 2024).

CONCLUSION

In conclusion, this review highlights the importance of veterinary vaccine research and development and its influence toward the animal as well as public health and disease management strategies. For a vaccination strategy to be successful it must be built on a solid understanding of the immune system, their interdependence, and the delicate regulation involved. In addition, effective policies and regulations governing vaccine production should be taken into account.

Recent understanding of the various factors contributing to the advancement in veterinary vaccine research and development for both animals and humans will address several critical considerations including the need of enhancing our knowledge of current veterinary vaccine technologies, implementing effective vaccination strategies and strengthening policies and supporting guidelines on vaccine research in animals. These actions will enable a comprehensive study of pathogenicity, transmission dynamics, and disease prevalence to facilitate effective responses to potential future outbreaks of new animal diseases, particularly within economically important animal populations.

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