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Strengthening Livestock Vaccine Distribution and Cold-Chain Preparedness in the United States: A One Health Imperative

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Strengthening Livestock Vaccine Distribution and Cold-Chain Preparedness in the United States: A One Health Imperative

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Abstract

The U.S. livestock industry, including cattle, pigs, chickens and numerous other species, is among the largest and most strategic elements of the nation's food system. Repeated instances of contagious livestock diseases such as FMD and HPAI have shown how they can disrupt markets, sever international trade agreements and produce a cascade of negative impacts on public health. Vaccines are universally accepted as a core component of disease prevention and emergency response, but for vaccines to be effective, they must be reliably distributed. This manuscript will provide a comprehensive review of all aspects of livestock vaccine delivery in the US such as the multi-layered, state-federal-private structure of vaccine delivery, persistent challenges in maintaining cold-chains to protect vaccines, geographic and workforce disparities that create inequality in emergency preparedness, new technologies and policies being developed to improve the delivery of vaccines and the broader One Health goals that position the preparedness of vaccines for animals as a national public health issue. Utilizing reports from the literature, assessment of agencies at the federal level and case study examples based on data collected during field-level observations, this report provides an extensive list of specific, actionable policy and research recommendations to address the gap between the potential use of a vaccine stockpile and the ability to deliver those vaccines to where they are needed in the field.

Abbreviations: US, United States; USDA, United States Department of Agriculture; APHIS, Animal and Plant Health Inspection Service; NVVB, National Veterinary Vaccine Bank; NADPRP, National Animal Disease Preparedness and Response Program; CDC, Centers for Disease Control and Prevention; HHS, Department of Health and Human Services; FMD, Foot-and-Mouth Disease; HPAI, Highly Pathogenic Avian Influenza; H5N1, Highly Pathogenic Avian Influenza A (H5N1); WOAH, World Organisation for Animal Health; OIE, World Organisation for Animal Health; IoT, Internet of Things; AI, Artificial Intelligence.

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1. Introduction

The United States has previously experienced severe livestock disease epidemics, and all evidence suggests that it is likely to face them again [1]. During 2014-2015 one single HPAI wave decimated commercial poultry farms in the United States killing more than 50 million birds and causing a disruption of egg and poultry supply chains for months and incurring economic losses in the hundreds of millions of dollars in farm communities everywhere [18]. The USDA has directly recognized this warning that these outbreaks can ruin livestock farmers and endanger the ability of Americans to get safe healthy and cheap food [1]. They are not only hypothetical issues but well established and persistent ones that need solid and continuous policy focus. Prevention and control of such crises have historically been greatly assisted by vaccination. According to the World

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Organization for Animal Health (OIE) the preeminent global body for animal health standards in general, and the OIE Terrestrial Animal Health Code specifically, well-executed immunization programs mitigate economic losses among farmers, safeguard human beings from zoonotic disease transmission and facilitate the smooth trade of animal derived products that are fit for consumption [2]. The United States has made significant efforts to strengthen preparedness, with Congress authorizing the establishment of the National Veterinary Vaccine Bank (NVVB) to maintain emergency stockpiles of vaccines for foot-and-mouth disease and other high-consequence animal diseases, while the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) has progressively expanded this stockpiling capacity over time [3].

Veterinary vaccines are thermolabile biologicals, and most of them need to be kept at a temperature in the range of 2 to 8 degree centigrade from manufacturing to administration [4]. Even a small disruption in this cold chain can lead to loss of efficacy of the vaccine. This can often remain undetectable as of loss of potency. Apart from maintaining cold chain, mass vaccination of animals during an active outbreak is logistically very demanding. Animals need to be identified and restrained, vaccination records need to be created and maintained and trained personnel and equipment need to be mobilized quickly over a large geographical area sometimes under emergency situations [5]. It has been observed that the State animal health agencies working as the operational link between the Federal vaccine reserves and the farm level often report to have limited resources relative to the extent of the response needed in such situations [6].

The field of diseases is also changing quite a bit, which actually makes it much more important. The re-emergence of the very dangerous bird flu (HPAI) H5N1 from 2022 to 2024 was a wake-up call of how capricious and widespread these dangers might be. Within this time frame the virus was transmitted not only among commercialization flocks of chickens but also, surprisingly, into U. S. dairy herds where infections in farm workers were also subsequently documented [7]. The reach of this progress is not limited to agriculture. Once a livestock disease starts jumping to humans it is no longer just an agricultural problem but a possible public health crisis. These circumstances demonstrate the importance of the One Health approach, that health of humans, animals and the ecosystems within which they coexist is essentially linked and policy has to be designed considering this interconnectedness [8,9]. Optimizing the distribution of vaccines for livestock is thus not just a technical aspect of the agricultural system but a One Health concern with immediate consequences for food security, the economic and social sustainability of rural areas, the control and prevention of zoonoses and the lowering of the risk of pandemics.

Subsequently, this manuscript proceeds by examining five substantive areas, analyzing the systemic challenges that continue to undermine vaccine distribution, reviewing cold-chain innovations and infrastructure investments capable of addressing these limitations, exploring the One Health dimensions that give the issue its full scope and urgency, and concluding with a set of integrated policy and research recommendations.

2. Current Challenges in Livestock Vaccine Distribution

2.1. A Layered System Under Stress

The U.S. has an intrastate hierarchical process in place for distributing emergency livestock vaccines. Under normal conditions, APHIS deposits federally stockpiled doses to state departments of agriculture, who then work with certified veterinarians and animal health distributors, and ultimately individual producers [1]. This cascade of handoffs can work, because state agencies have greater familiarity with the local geography and producer networks that federal actors often lack, but every transfer point also creates opportunities for cold-chain breaches, communication failures or administrative delays. State-level warehousing remains subject to refrigeration standards and chain-of-custody documentation requirements, however the personnel that oversee these operations are not always sufficiently trained or resourced to respond to surges in demand [1].

A case study that we find particularly illustrative comes from a recent distribution pilot, in which APHIS collaborated with private animal health distributors to handle emergency vaccine logistics [1]. They provide not only capabilities that many state agencies lack, including bulk refrigerated warehousing space, temperature-monitored transportation fleets and advanced inventory management systems but also existing relationships with veterinary networks across the country. In comparison to a model relying exclusively on state-managed vaccine dose distribution [1], the pilot showed much faster doses delivered to veterinary practitioners. But incorporating private commercial actors into emergency public health infrastructure can be challenging. A formal arrangement would need to resolve, in careful negotiation, issues of liability, equitable access between different categories of producers, and the extent to which commercial supply-chain interests align with public health goals [9].

All vaccination-planning resources emphasize minimizing handling steps. As one guide for emergency vaccination explains, teams should minimize the transport of a vaccine to maintain its power [13]. But the existing vaccine distribution system which parcels vaccines from federal, state and distributor levels to a producer and then to elderly people multiplies transfer events. Each additional handoff increases the risk of cold-chain failure. Streamlining this structure by distinguishing steps that add real value from those that introduce unnecessary exposure is a fundamental task that preparedness planners have not yet systematically addressed.

2.2. Geographic Inequity and Rural Infrastructure Deficits

One of the most severe and least-acknowledged vulnerabilities in the U.S. livestock vaccine distribution system is fact that infrastructure across the agricultural landscape isn't uniform. Livestock operations cover a spectrum from the highly concentrated sectors of commercial poultry and swine in the Midwest and Southeast to the largest sparsely populated range cattle operations of the Mountain West and Great Plains.

For farms in isolated regions, an accredited veterinarian could be hours away and a reliable cold-storage facility even more so. During a disease emergency, where restrictions on movement may be implemented, roads may also be clogged with outbreak-response traffic and veterinary personnel are likely not only responsible for reporting the disease, but they may already have overextended resources [13] and these distances translate directly into delayed vaccination and wider spread of disease. Small and medium-scale producers have further disadvantages. Whereas large integrated enterprises manage on-site cold storage and dedicated relationships with veterinary services, smaller operations depend upon local feed cooperatives, county extension offices and community veterinarians the very channels that are most likely to be overwhelmed or disrupted during high-demand emergencies.

The cold-chain infrastructure problem extends beyond the last mile. Rural areas often face unreliable electricity, limited broadband connectivity for remote temperature monitoring systems, and restricted access to refrigeration technicians who can repair equipment quickly [14]. Addressing these challenges requires investment not only in vaccine logistics infrastructure itself but also in the rural electricity, connectivity, and technical services that support it.

2.3. Workforce Constraints and Documentation Burdens

Large-scale emergency vaccination of livestock is a very intensive labor process. Each animal should be individually identified (usually by official ear tags or other electronic identification devices) and physically subdued for injection, vaccination and recovery, all of which are recorded in a traceable database [13]. For a cattle operation that runs several thousand head across numerous pastures, this process multiplied by outbreak urgency and tightened timeframes can take weeks of concerted work. Call for CDR may seem bureaucratic, the need for documentation is imperative at post outbreak epidemiological tracing, international trade certification and liability management stage. They also introduce a hefty speed penalty in time-critical operations.

This system has a statutory bottleneck for example accredited veterinarians. Most jurisdictions require officially recognized vaccinations to be administered or directly supervised by an accredited veterinarian [1,11]. The rural U. S. is facing a well-documented and worsening shortage of large-animal veterinary practitioners, a work force gap identified by the National Academies of Sciences, Engineering, and Medicine as a significant threat to agricultural resilience [11]. Immediate contingency plans based on the premise that sufficient numbers of real-time accredited veterinary personnel are readily available may be unrealistic in areas most susceptible to extensive widespread outbreaks.

Portable cold-chain logistics represent another often-underprepared operational challenge. Field vaccination teams need to have portable refrigeration units that can maintain validated temperatures between 2–8°C for a full workday under many ambient conditions, be it a hot July afternoon in Texas or a frigid February morning in Minnesota [14]. The use of cooling units must be combined with temperature-logging devices, and the logging records must be preserved as chain-of-custody documentation. Pre-positioning sufficient supplies, holding units between emergencies and training teams to use them properly are thankless but essential parts of preparedness that most state emergency plans underfund (Table 1).

Table 1. Major challenges affecting livestock vaccine distribution in the United States.

Challenge	Description	Impact on Vaccine Delivery
Cold-chain maintenance	Veterinary vaccines must be stored between 2–8 °C throughout manufacturing, storage, transport, and field use	Temperature deviations can reduce vaccine potency and effectiveness [4,12]
Multi-level distribution system	Vaccines move through federal, state, distributor, and veterinary channels before reaching producers	Multiple transfer points increase the risk of delays and cold-chain breaches [1,14]
Rural infrastructure gaps	Remote livestock operations may lack nearby cold-storage facilities and veterinary services	Slower vaccination response during outbreaks [16,17]
Veterinary workforce shortages	Limited number of large-animal veterinarians in rural areas	Reduced capacity for large-scale emergency vaccination campaigns [11]
On-farm storage limitations	Many farms use domestic refrigerators not designed for vaccine storage	Temperature fluctuations may compromise vaccine efficacy [13]

3. Opportunities for Strengthening Cold-Chain Infrastructure

3.1. Technology-Enabled Monitoring and Inventory Management

Modern monitoring technology deployed at various points throughout the distribution network is arguably the most immediate and cost-effective method for improving cold-chain reliability. If installed in refrigerated storage units and shipping containers, smart data loggers and Internet of Things (IoT) sensors can continuously record temperature and humidity, send data to centralized

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dashboards in real time, and issue automated alerts when readings come close to or exceed safe thresholds [2]. These are not experimental tools, these were commercially developed and widely deployed in the distribution of human pharmaceuticals. However, there is a gap in their systematized implementation and incorporation into veterinary vaccine logistics, as monitoring practices are not uniform between states or distributors (Table 2).

Table 2. Technologies and strategies for strengthening veterinary vaccine cold-chain systems.

Technology/Strategy	Description	Potential Benefit
IoT temperature sensors	Smart sensors monitor temperature and humidity continuously in storage and transport	Real-time alerts help prevent vaccine degradation [2]
GPS-enabled refrigerated transport	Refrigerated vehicles with live tracking and temperature logging	Allows rapid intervention if cold-chain conditions deviate [11]
Cloud-based inventory management	Digital platforms track vaccine stock levels, locations, and expiration dates	Improves distribution efficiency during outbreaks
Regional vaccine depots	Pre-positioned vaccine stockpiles located near livestock production regions	Reduces transportation time and cold-chain exposure [1]
Portable field refrigeration units	Mobile cooling devices used by vaccination teams during field operations	Maintains temperature stability during on-farm vaccination [12]
IoT temperature sensors	Smart sensors monitor temperature and humidity continuously in storage and transport	Real-time alerts help prevent vaccine degradation [2]

Cloud-based inventory management systems offer a complementary solution. If vaccine stock levels, lot numbers, expiration dates, and current locations throughout the distribution network were visible in real time to APHIS and state coordinators they could make informed decisions during fast-moving emergencies such as redirecting shipments to hot spots or preventing doses that are about to expire from being wasted in transit or storage [11]. GPS-oriented cooled transport paired with no-cost live temperature dashboards would enable logistics coordinators to determine and address deviances before they endanger an entire shipment. This technology infrastructure to make it work is already possible. What is still needed is more policy commitment and funding to encourage standardization of its adoption across the veterinary vaccine distribution network.

3.2. Regional Pre-Positioning and Public-Private Distribution Hubs

The second significant opportunity for improvement comes from the physical geography of vaccine storage. The current model, centered on federal stockpiling and subsequent reliance on state storage facilities, creates a distance between vaccine and the farm. Developing a series of regional distribution points, pre-stocked with priority vaccines for the diseases prevalent in the surrounding livestock populations, would significantly reduce the time to distribute vaccine and minimize exposure to the elements during transport [1].

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The Iowa FMD distribution exercise, as noted in the U.S. Animal Health Association documents, demonstrates the effectiveness of a regional distribution model. By using a commercial distributor's regional warehouse and distribution system, the planners were able to achieve vaccine dispersal times greater than the federal or state systems could hope to attain [1]. This could be developed by the USDA through cooperative agreements with the major animal health distributors, effectively creating permanent livestock vaccine depots in regions of the country where the demand for vaccine would likely be the greatest, such as the Corn Belt, the Southern Plains, the Southeast poultry belt, and California's Central Valley. This structural improvement aligns directly with the preparedness principle of minimizing vaccine transport [13].

3.3. Thermostable and Next-Generation Vaccine Platforms

Perhaps the greatest promise for long-term solutions to the problems of the cold chain can be found in the technology of the vaccines. Researchers at various institutions have been working on thermostable vaccines, including lyophilized, encapsulated, and polymer-stabilized vaccines that retain potency at room temperature for long periods of time [2]. Such vaccines would have tremendous potential for animal diseases in remote areas, as they would eliminate the last mile problem for vaccine delivery. Vaccines could be distributed by means such as animal health clinics, feed stores, mail delivery, and even animal health workers, none of whom would require the infrastructure for a traditional vaccine.

New delivery systems for vaccines are also in development. Researchers at Kansas State have developed a system in which HPAI antigens are expressed in mealworms, which are ingested by the chicken. This system essentially allows for the use of chicken feed as a vaccine delivery system [5]. Other platforms under investigation include microneedle patches for transcutaneous delivery, an aerosol spray for respiratory delivery within poultry farms, and an oral vaccine bait modelled on successful wildlife rabies programs [2]. In a review on recent progress in veterinary vaccinology, Raut et al. highlight the advantage of thermostable vaccines with innovative delivery systems and optimized antigens through the use of AI to reduce logistical constraints on cold-chain storage while advancing the goals of One Health [2]. Federal investment to bring these platforms from research to approval and integration into the stockpile should be considered a preparedness priority rather than a research question.

3.4. Training, Coordination, and Operational Readiness

Technology and infrastructure development are crucial but not in isolation. The human system also needs development in terms of training programs, communication systems, inter-agency coordination mechanisms, and educating producers. The USDA’s National Animal Disease Preparedness and Response Program (NADPRP) has funded a number of training grants for emergency responders and producers. This has had a positive effect in building capacity [11]. However, it is observed that there is a lack of emphasis on teaching aspects of cold chain management in such programs. This is an area that needs to be covered in greater detail because it is an area that is identified as a problem during an emergency response situation.

Extension services at the state level, commodity groups, veterinary groups, etc., can also be instrumental in providing practical information to producers regarding vaccines. Joint tabletop exercises among federal, state, and private sector participants are essential in stress-testing a distribution system to identify problem areas before they are revealed in a real-life emergency response situation. The level of understanding regarding role definitions, communication systems, and decision-making authority that is achieved in these exercises cannot be done in an emergency response situation.

4. Implications for One Health and National Preparedness

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The 2022-2024 HPAI H5N1 outbreak is an example that clearly illustrates this principle. From wild birds as an avian influenza, it expanded to poultry flocks and, in an outcome that caught the attention of infectious diseases experts around the globe, to the U. S. dairy cattle herds [7]. Subsequent human cases resulted from the infection of dairy farm workers. The CDC responded by activating One Health protocols, and the possibility that a new influenza strain could adapt to mammalian transmission changed an issue that was at first a poultry industry problem into a broader public health issue in short order [3,7]. A more efficient vaccine delivery system for dairy cattle could have kept the H5N1 virus confined to animal populations. Another area where WOAH has identified One Health benefits from strong animal vaccination programs is in the area of zoonotic diseases. Vaccinated herds are healthier, reducing the need for prophylactic antibiotic use and directly contributing to efforts to slow antimicrobial resistance, which WHO identifies as one of the greatest human health threats of the twenty-first century [6]. Vaccination programs also reduce the necessity for mass culling operations, which carry environmental costs such as carcass disposal, soil contamination, and disruption to local communities.

On the international level, WOAH maintains global vaccine banks and emergency response systems that can provide member countries with priority access to vaccine doses in the event of an emergency under pre-negotiated agreements [9]. The U.S. is part of these agreements and benefits from them, but the ability to access and utilize these international resources depends on the existence of an effective system to get the doses from the federal level to farms in the affected area. The CDC's National One Health Zoonotic Disease Framework for 2025-2029 outlines the goals for an integrated surveillance system, emergency response, and food security across sectors [8]. The state of readiness in livestock vaccine distribution is relevant to each of these goals. It helps to more quickly contain animal disease outbreaks before they are transmitted to humans, provides valuable surveillance data through coverage and identification, and helps to protect the food systems that are key to the nutrition security of the U.S. population.

5. Policy and Research Priorities

5.1. Federal Investment in Distribution Infrastructure

The most obvious policy suggestion is the most basic one as well such as the level of investment in infrastructure should be equivalent to the level of investment in vaccine stockpiling. The recent Farm Bill provided over $6 million in funding for the procurement of foot-and-mouth disease vaccines for the national bank [11]. Although this is a positive move, the stockpile is only as good as the infrastructure through which it is distributed. The level of investment in infrastructure should be equivalent to the level of investment in vaccine stockpiling. APHIS should set standards for infrastructure, including the need for temperature monitoring, backup power, and chain of custody, and apply them equally to all participants in the emergency distribution network, both public and private sectors.

5.2. Formalizing and Governing Public-Private Distribution Partnerships

The obvious benefits of this capacity in the private sector strongly support the formalization of cooperative agreements between APHIS, state animal health agencies, and major animal health distributors [1]. However, if not governed properly, it may result in systems that are more geared towards efficiency than equity. It must be in the form of performance contracts with clear standards for cold chain compliance, provisions to ensure equitable access for small and geographically isolated producers, clear reporting mechanisms, and clear liabilities. The human pharmaceutical distribution partnerships developed during the COVID-19 pandemic response, especially those with retail pharmacies and logistics companies, are an imperfect yet relevant precedent from which valuable lessons can be derived by those charged with veterinary preparedness.

5.3. Expanding Veterinary Workforce Capacity

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Closing the rural veterinary workforce gap is a long-term challenge that requires sustained policy attention. In the short term, USDA and state governments should encourage greater utilization of the Veterinary Medicine Loan Repayment Program and extend eligibility for USDA grants to rural practitioners willing to work in rural shortage areas [11]. Participation in interstate veterinary compacts should be incentivized, enabling credentialed out-of-state veterinarians to provide emergency services across state lines without the lengthy delays associated with relicensure. In the case of emergency vaccination services, graduated scope of practice standards enabling qualified livestock producers or veterinary technicians to administer particular vaccines under remote supervision could greatly enhance operational capacity without compromising safety standards.

5.4. Investing in Thermostable and Novel-Delivery Vaccine Research

Federal research and development investments in thermostable vaccine formulations and novel delivery systems for high-priority animal pathogens, conducted through the USDA's National Institute of Food and Agriculture, Agricultural Research Service, and in partnership with the NIH, are essential. According to Raut and co-authors, thermostability research, innovative delivery systems, and AI-based antigen design are an exciting area of research that holds promise to revolutionize the deplorability of veterinary vaccines. The regulatory process for veterinary vaccine platforms, which is slower and less well-resourced than that for human pharmaceuticals, should be reviewed and modernized by the USDA's Center for Veterinary Biologics to ensure that new technologies are integrated into the stockpile in a timely fashion.

5.5. Institutionalizing One Health Coordination in Preparedness Planning

Additionally, emergency preparedness exercises at the national, state, and regional levels regarding animal disease outbreaks should always include the participation of human health agencies. A simulated HPAI or FMD outbreak should include the CDC, state health departments, hospitals, and environmental health departments as participants rather than as passive observers. This is the only way that the communication that is key to whether or not the One Health approach is able to function in real time, rather than as a theoretical construct on paper, is developed. Data systems used for animal disease surveillance, human disease surveillance, and environmental surveillance should be fully integrated across the animal and human health and environmental sectors.

6. Conclusion

Significant investments have been made in livestock disease preparedness in the U. S. over the last two decades. The National Veterinary Vaccine Bank program, NADPRP training grants, and expanded surveillance and response efforts by APHIS are notable successes in improving basic preparedness levels [4,10,11]. However, it must be noted that measuring preparedness levels by volume does not accurately portray the situation. More important than this question is the unaddressed question of whether vaccines in federal stockpiles will be delivered undamaged and in a timely fashion to farms in the critical hours after the start of a rapidly escalating outbreak.

These are not trivial issues with the operational systems. They are systemic issues that could very well determine the success or failure of efforts to contain FMD within a county or allow it to spread across multiple counties before efforts to limit transmission can be initiated. The stakes are very high indeed, with losses running in the billions of dollars and, in some cases, human lives.

The One Health framework emphasizes an integrated perspective on these risks. Animal disease outbreaks are not isolated events. They affect the people who work with animals, the surrounding communities, the consumers who rely on stable food supplies, and, in situations such as the recent HPAI H5N1 spillover into dairy cattle and human farm workers, the broader public health system [3,7,8]. Strengthening livestock vaccine distribution is therefore simultaneously an agricultural

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investment, a rural economic investment, and a public health investment aligned with the missions of USDA, CDC, and HHS alike.

The path forward is clear like modernize cold-chain monitoring technology, pre-position regional distribution infrastructure, formalize and govern private-sector partnerships, close the rural veterinary workforce gap, accelerate the development of thermostable vaccines, and institutionalize genuine One Health coordination in emergency preparedness exercises. None of these steps is technically unattainable and they require political will, sustained funding, and recognition that preparedness is not a one-time expenditure but an ongoing operational commitment [1,2,4,11].

The cost of underinvestment will be evident the next time a highly contagious livestock disease moves faster than the distribution network designed to contain it. This scenario is not speculative, it is a matter of when, not if. The case for acting now, while there is still time to build capacity rather than scramble, has never been more compelling.

References

1. U.S. Animal Health Association. USAHA resolutions and recommendations on animal disease preparedness. USAHA Annual Meeting Proceedings. 2024.
2. Raut R, Shrestha R, Adhikari A, Fatima A, Naeem M. Revolutionizing veterinary vaccines overcoming cold chain barriers through thermostable and novel delivery technologies. Applied Microbiology. 2025;5(3):83. Available from: https://doi.org/10.3390/applmicrobiol5030083
3. Centers for Disease Control and Prevention. National One Health zoonotic disease framework 2025–2029. U.S. Department of Health and Human Services. 2024. Available from: https://www.cdc.gov/onehealth
4. U.S. Department of Agriculture Animal and Plant Health Inspection Service. National Veterinary Stockpile and countermeasures bank program overview. USDA APHIS Veterinary Services. 2023. Available from: https://www.aphis.usda.gov/animal_health/emergency_management/nvs.shtml
5. Kansas State University AgriLife Research. Mealworm based edible vaccine protects poultry flocks from highly pathogenic avian influenza. KSU News Service. 2025 Apr. Available from: https://www.k-state.edu/today/
6. World Organisation for Animal Health. State of the world's animal health 2025 the role of vaccination in disease prevention and trade facilitation. WOAH Technical Publication. 2025.
7. U.S. Department of Agriculture Animal and Plant Health Inspection Service. Secure our herds highly pathogenic avian influenza H5N1 in dairy cattle situation update. USDA APHIS Animal Health Updates. 2024 Dec.
8. Centers for Disease Control and Prevention. National One Health framework protecting people animals and the environment 2025–2029. CDC One Health Office. 2025. Available from: https://www.cdc.gov/onehealth/basics/index.html
9. World Organisation for Animal Health. Global vaccine banks and international emergency preparedness WOAH mechanisms and partner country access. WOAH Information Document. 2024.
10. U.S. Department of Agriculture Animal and Plant Health Inspection Service. 22.2 million awarded for animal disease preparedness research and response infrastructure. USDA Office of Communications news release. 2024 Nov.
11. U.S. Department of Agriculture Animal and Plant Health Inspection Service. Farm bill funding bolsters livestock disease readiness NADPRP grants and FMD vaccine bank allocations. USDA Office of Communications news release. 2024 Oct.
12. Young M, Costa R, Shirima G, Lobo Q, Tounkara K, Farrell P, Alders R. Veterinary cold chain manual: ensuring effective vaccines. 2016.
13. Williams PD, Paixão G. On-farm storage of livestock vaccines may be a risk to vaccine efficacy: a study of the performance of on-farm refrigerators to maintain the correct storage temperature. BMC veterinary research. 2018 Apr 19;14(1):136.
14. U.S. Department of Agriculture APHIS. *Vaccination for Contagious Diseases: Handling and Transportation Guidelines (FAD PReP/NAHEMS)*. USDA; 2023.

 doi:10.20944/preprints202603.1410.v1

15. Acharya KP, Phuyal S, Lopes BS. Overcoming vaccine cold chain challenges in Nepal's animal health sector: innovative strategies for effective immunisation. Vaccine. 2025 Nov 20;67:127857.
16. World Organisation for Animal Health (WOAH). Guidelines for emergency vaccination and vaccine logistics in animal disease control. Paris: WOAH; 2023.
17. Food and Agriculture Organization of the United Nations (FAO). Cold chain management for veterinary vaccines and biologicals. FAO Animal Production and Health Manual. Rome: FAO; 2022.
18. Economic Research Service, U.S. Department of Agriculture. *The 2014-15 highly pathogenic avian influenza outbreak significantly impacted turkey and egg producers* [Internet]. Washington (DC): USDA; 12 Jan 2018