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Understanding poultry vaccine delivery systems in low-resource settings: a systems analysis from Uganda

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Abstract

Background

Vaccination is critical for preventing livestock diseases and is an important strategy for reducing antimicrobial use. However, in many low- and middle-income countries, vaccination performance is shaped by how delivery systems operate from importation to farm use. While constraints such as cold-chain failures, weak oversight, and poor handling are widely recognised, the structural mechanisms that sustain them remain poorly understood.

Methods

We conducted a qualitative systems mapping study of Uganda's poultry vaccine delivery system based on 37 key informant interviews with regulatory, commercial, and service-delivery actors. Using systems thinking and system dynamics approaches, we identified system bottlenecks, analysed their interactions, developed causal loop diagrams, and identified key leverage points within the system.

Results

The delivery system was highly import-dependent, with regulatory oversight concentrated at market entry and limited downstream control. Four interconnected bottlenecks were identified: weak post-market surveillance, cold-chain failures, cost pressures that discouraged investment in storage, transport, and quality assurance, and limited technical capacity at the point of administration. These constraints interact through reinforcing feedback processes linking delivery quality, perceived effectiveness, trust, demand, and reinvestment, thereby sustaining underperformance. Structural inequities in infrastructure, market access, and regulatory presence further exacerbated these challenges. Cold-chain integrity, post-market surveillance, upstream procurement decisions, and vaccine handling at the point of use emerged as key leverage points for intervention.

Conclusions

Vaccination underperformance in this setting was shaped by delivery-system dynamics rather than access alone. Strengthening key leverage points within the system offers a pathway to improve vaccination effectiveness, enhance poultry health, and reduce reliance on antimicrobials. More broadly, improving vaccination performance requires strengthening the governance and delivery systems that enable reliable disease prevention in livestock production.

1. Introduction

Vaccination is a highly scalable and cost-effective strategy for improving animal health and productivity, particularly in low- and middle-income countries (LMICs), where access to veterinary services and diagnostics is often limited [1]. By preventing infectious diseases, especially viral infections for which treatment options are limited, vaccination reduces infection pressure and the need for routine or prophylactic antimicrobial use [2, 3]. Consequently, livestock vaccination is a central component of One Health strategies to mitigate antimicrobial resistance (AMR) across the human–animal–environment interface [4].

Despite this potential, vaccination performance in many LMIC livestock systems remains inconsistent. This inconsistency stems not only from individual practices but also from deeper structural constraints within vaccine delivery systems, including weaknesses in governance, market organisation, infrastructure, and accountability. These constraints manifest as fragmented supply chains, limited downstream regulatory oversight, and procurement dynamics that prioritise short-term affordability over quality. Together, they shape how vaccines are accessed, handled, and used, often undermining effectiveness and reinforcing reliance on antimicrobials as substitutes for preventive disease control. Although vaccination is widely promoted in policy frameworks, implementation frequently fails to deliver consistent disease control or sustained reductions in antimicrobial use [5].

In Uganda, the commercial poultry sector is expanding rapidly in response to rising demand for affordable animal-source protein [6]. However, vaccine-preventable diseases, including Newcastle disease and infectious bursal disease, remain highly prevalent [7]. Following the decentralisation and privatisation of veterinary services in the 1980s, vaccine delivery has become dominated by private-sector actors [8]. While this shift has improved access, it has also led to uneven delivery conditions, with variability in availability, affordability, and quality across regions and production systems.

Vaccines for major poultry diseases are available, yet coverage remains low and inconsistent [9]. Distribution occurs primarily through fragmented private-sector channels with limited public oversight. Weak post-market surveillance, limited feedback from field-level experiences to regulatory authorities, and inconsistent cold-chain and handling practices undermine vaccine performance. These challenges contribute to the continued use of antimicrobials as substitutes for preventive vaccination [10–12].

Although vaccines are included in national and global AMR action plans, few studies have examined how underperformance in vaccination arises and persists through interactions among governance arrangements, market incentives, and perceptions of vaccine effectiveness. Existing research has largely focused on vaccine efficacy or behavioural barriers, with less attention to the institutional, logistical, and governance factors that shape delivery systems [13, 14]. While previous studies have identified cold-chain failures, weak regulatory oversight, and uneven access [15–20], the persistence of these constraints despite repeated interventions remains insufficiently explained.

Therefore, this study aimed to examine how structural constraints interact within poultry vaccine delivery systems, using Uganda as a case study of vaccine delivery in a low-resource setting. We conceptualised

the vaccination system as a dynamic network of actors, infrastructure, incentives, and institutions through which vaccines move from production and importation to effective use at the farm level.

Using qualitative systems mapping, we analysed interactions among governance, market, and service-delivery processes, identified feedback dynamics influencing vaccination performance, and highlighted potential leverage points for system improvement. By examining these interconnected mechanisms, this study provides insights relevant to strengthening animal vaccine delivery systems in settings facing similar challenges of fragmented supply chains, limited infrastructure, and evolving public–private service delivery arrangements.

2. Methods

2.1 Study design and conceptual approach

We conducted a qualitative systems mapping study in Uganda to examine how structural constraints shape the performance of poultry vaccine delivery. Uganda represents a rapidly expanding poultry production system where vaccine delivery is predominantly private-sector driven and operates through interconnected regulatory, commercial, and service-delivery actors. The study was guided by systems thinking and system dynamics principles, including feedback, endogenous causation, and structure–behaviour relationships [21, 22]. Data collection and analysis were informed by an integrated framework that combined supply chain performance theory[23], institutional analysis theory [24], and access and equity models [25].

2.2 Data sources and sampling

Participants were selected using a purposive sampling approach designed to capture perspectives across the key functional components of the poultry vaccine delivery system rather than to achieve statistical representation of individual stakeholder groups. A total of 37 key informant interviews were conducted across seven stakeholder categories representing regulatory, commercial, service-delivery, and system-support functions: regulatory authorities (n = 4), importers/manufacturers (n = 3), distributors (n = 5), retailers (n = 5), veterinary professionals and paraprofessionals involved in vaccine delivery (n = 8), district veterinary officers responsible for local animal health coordination (n = 5), and system support actors, including academia, NGOs, and industry experts (n = 7). The sampling strategy captured actors positioned along the vaccine pathway, from regulation and supply to last-mile delivery, enabling analysis of interactions and system-level factors influencing vaccination performance.

Data collection continued until sufficient information depth was achieved, with later interviews reinforcing previously identified themes, actor relationships, and system dynamics rather than generating substantially new concepts. The final sample size was considered appropriate for qualitative systems mapping, where the analytical focus was on understanding relationships among system components rather than estimating the prevalence of stakeholder perspectives.

2.3 Data collection and management

Semi-structured key informant interviews were conducted between July and October 2025, using interview guides to explore vaccine supply and distribution pathways, regulatory oversight, pricing and procurement practices, cold-chain infrastructure, and vaccination service delivery. Interviews were audio-recorded, transcribed verbatim, and anonymised before analysis. Transcripts were imported into NVivo (Release 1.7.1) for coding. Data were organised by actor category and delivery-system position (upstream, midstream, downstream) to enable cross-interview comparison, and summary tables were maintained in Microsoft Excel to support synthesis and triangulation. Data preparation was iterative, with transcripts incorporated as interviews were completed and analytic memos updated throughout to document coding decisions, emerging patterns, and interpretive reflections. This process ensured consistency and traceability prior to formal qualitative analysis.

2.4 Systems analysis

2.4.1 Identification of bottlenecks

After coding the interview transcripts, the data were analysed to identify recurring challenges affecting system performance. Following discussions within the multidisciplinary author team, criteria were set to distinguish structural bottlenecks from isolated operational problems. Challenges were classified as system bottlenecks if they met three criteria: (i) they were reported by more than one stakeholder group, (ii) they disrupted the flow of vaccines, information, or regulatory accountability, and (iii) they contributed to persistent weaknesses in system performance rather than temporary or one-off disruptions.

This approach aligns with systems thinking and the health systems literature, which conceptualise bottlenecks as constraints that impede system functioning and the flow of resources among interconnected actors [26–28]. Identified bottlenecks were then reviewed across transcripts to confirm their recurrence across actor categories and delivery-system levels.

2.4.2 Development of causal loop diagrams (CLDs)

Building on the identified system bottlenecks, we developed CLDs to illustrate how these constraints interact and affect the performance of the poultry vaccine delivery system. Bottlenecks were translated into system variables by abstracting key processes, behaviours, and constraints from the data. These variables were then linked through causal relationships that reflect reported decision-making and interactions among actors [28, 29].

Bottlenecks were included in the CLD when they met two criteria: (i) they were part of a feedback loop and (ii) they contributed to observable patterns in system performance over time, with a focus on dominant feedback mechanisms.

2.4.3 Identification of critical control points (CCPs)

CCPs were identified through a systematic examination of the causal loop diagrams to pinpoint positions that exert disproportionate influence on system behaviour. Variables were assessed according

to their role within feedback structures across actors and stages of the vaccine delivery system, consistent with established system dynamics approaches [28].

Variables were classified as CCPs if they met three criteria: (i) they were structurally central to multiple feedback loops, (ii) they influenced upstream decision-making or downstream system responses, and (iii) they represented leverage points capable of altering system dynamics[26]. Identifying these high-influence positions within system structures aligns with approaches that derive intervention points from causal loop diagrams [29].

As this was a qualitative systems mapping study, no statistical hypothesis testing or power calculation was performed. Sample size was guided by purposive representation of key actors across the vaccine delivery system and the need to capture perspectives across regulatory, commercial, and service-delivery levels.

2.5 Ensuring trustworthiness and reflexivity

Credibility was strengthened through triangulation of interviews and documentary sources, and by maintaining a detailed audit trail of analytic decisions. Reflexive journaling and peer debriefing facilitated a critical examination of potential biases arising from the lead researcher's veterinary background. Consistent with the systems-oriented design, trustworthiness was further reinforced through iterative comparison of emerging system structures across data sources, with analysis focused on identifying system-level patterns, interactions, and feedback mechanisms rather than on individual accounts.

3. Results

Findings were drawn from 37 interviews with actors across the upstream, midstream, and downstream stages of Uganda's poultry vaccine delivery system. The distribution of participants across system levels and actor categories is presented in Supplementary Table S3.

3.1 Structural organisation and flow of poultry vaccines

The poultry vaccine delivery system was described as relatively coordinated upstream but increasingly fragmented downstream. Regulators, importers, and distributors consistently reported heavy reliance on imports, with most vaccines sourced from international private manufacturers, entering through Entebbe International Airport and supplied by private-sector distributors. Vaccines were initially stored in importer-operated cold rooms, concentrated mainly around Kampala, which served as distribution hubs supplying wholesale pharmacies and retail outlets serving downstream markets. Domestic production was reported to be limited largely to thermostable Newcastle disease vaccines. One respondent noted that local production remained insufficient to meet demand: "Locally, there is only one vaccine producer … they cannot meet local demand" *(Government regulatory actor, GRA01).* The overall structure of vaccine importation, distribution and delivery to end users is summarised in Fig. 1.

Delivery pathways included both formal and informal routes. Commercial distributors supplied retailers, who in turn supplied animal health workers and farmers. Several participants described informal sub-flows involving repackaging and resale outside formal regulatory channels. At the retail level, vaccines were reported to sometimes be reconstituted and dispensed in aliquots over extended periods. As one respondent explained, “a drug shop attendant may reconstitute a vaccine and sell it over several days, repeatedly drawing a few doses into a syringe for different customers.” *(Veterinary professional, VPP02)*

Large hatcheries and vertically integrated enterprises were reported to access specialised supply channels and maintain internal cold-chain systems. Respondents highlighted that as vaccines moved downstream, responsibility for storage, transport, and handling shifted from central actors to more decentralised actors with variable capacity.

3.2 Governance configuration and distribution of accountability

Governance of poultry vaccine delivery was described as shared between public regulatory institutions and private market actors (Fig. 2). The Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) was responsible for import approvals, while the National Drug Authority (NDA) oversaw product registration and inspections at points of entry. Respondents also noted that the NDA is responsible for post-market surveillance and inspections of drug shops and pharmacies, although many participants indicated that oversight was more limited further downstream, particularly at the retail level and at the point of use.

Private-sector actors largely carried out distribution, retail sales, and vaccine administration. District veterinary authorities were described as overseeing veterinary practice and disease reporting; however, supervision of downstream actors relied mainly on passive reporting and informal coordination rather than on routine inspection and enforcement. As one respondent summarised this boundary: “When the vaccines leave the drug shop outlet, it is far beyond our regulatory control.” *(Government regulatory actor, GRA03)*

3.3 System bottlenecks across the delivery pathway

Multiple bottlenecks were identified across the vaccine delivery system, including weak post-market surveillance, fragile cold-chain capacity, cost pressures that constrained investment in storage and quality assurance, and limited technical capacity at retail and at the point of administration (Table 1). These constraints were concentrated at downstream stages, particularly in distribution, retail handling, transport to farms, and on-farm administration, where they could affect vaccine quality and use.

The primary bottlenecks were as follows:

1. Cold-chain integrity. Constraints included unreliable electricity supply, limited refrigeration capacity, and prolonged storage and transport times. These conditions were reported to create risks for

maintaining appropriate temperature control throughout the supply chain. As one respondent noted, “The biggest challenge we have is the maintenance of the cold chain.” *(Drug shop retailer, DSR03)* Another added, “Over 80% of districts face electricity outages.” *(Government regulatory actor, GRA01)*

2. Governance-related constraints. Weak post-market surveillance, delayed recognition of vaccine performance issues, and limited feedback from the field to regulators were identified as key governance gaps. One respondent stated, “We don’t have a monitoring system for vaccine effectiveness.” *(Government regulatory actor, GRA02)*
3. Market dynamics. High logistics costs and price-sensitive demand were reported to shape sourcing and distribution decisions among importers, distributors, and retailers. These pressures were linked to reduced investment in storage infrastructure across the retail, transport, and supply chains, particularly in remote areas. As one respondent observed, actors were “not quality focused, they are price focused… they are looking for cheap vaccines.” *(Importer, ILP02)* Another added, “The biggest problem now is the cost of vaccines… access is no longer a problem in many areas.” *(Industry expert, IE01)*
4. Technical capacity at service delivery. Gaps in vaccine handling and administration, along with inconsistent adherence to recommended protocols, were reported across both drug shops and farm-level use. These challenges reflected limited technical capacity among personnel at the last mile. As one respondent noted, “the people at the drug shops are sometimes not well trained… they don’t know the biology of vaccines, how to handle them, yet farmers rely on them for advice.” *(District veterinary authority, DVA03)*

At the farm level, these constraints were further compounded by farmer-led transport and administration practices, often carried out with inadequate knowledge of storage and handling requirements, thereby increasing the risk of improper vaccine handling and administration. One respondent explained, “Most farmers transport and administer the vaccine themselves… yet they don’t understand the proper storage and administration guidelines.” *(Veterinary professional, VPP05)*

Table 1
System-level bottlenecks in the poultry vaccine delivery system.

System domain	Bottleneck	System consequence	Reported by
Governance	Regulatory oversight concentrated at market entry, with weak downstream enforcement	Quality assurance and accountability weaken beyond importation	Regulators, district authorities, industry actors
	Weak post-market surveillance and feedback systems	Failure detection, learning, and corrective action are weakened	Regulators, district authorities, academia
Supply system	High logistics costs and price-sensitive demand shaping procurement decisions	Cost pressures discourage investment in storage, transport, and quality assurance	Importers, industry actors
	Fragile downstream cold-chain capacity	Temperature-control failures may reduce vaccine potency before use	Importers, distributors, retailers
	Fragmented last-mile distribution networks	Uneven availability and handling conditions shift risk downstream	Distributors, retailers, district authorities
Service delivery	Limited technical capacity at the point of sale and vaccine administration	Inconsistent preparation, dosing, and protocol adherence	Retailers, veterinarians
	Post-retail handling and farm transport failures	Vaccine potency may be compromised between retail sale and on-farm use	Retailers, veterinarians

3.4 Interactions among system bottlenecks

Participants described these bottlenecks as interacting across multiple stages of the delivery pathway rather than occurring in isolation. Governance constraints, particularly weak downstream enforcement and limited post-market surveillance, were linked to storage, transport, and retail practices.

Within the supply chain, fragmented last-mile distribution and limited cold-chain capacity coincided with inconsistent storage and handling conditions, particularly at the retail and point-of-use levels. Procurement decisions were often described as prioritising price and short-term affordability over quality assurance and longer-term returns. High logistics costs were also linked to reduced investment in storage, transport, and handling capacity.

At the last mile, particularly at drug shops and on farms, limited technical capacity was reported alongside upstream cold-chain and transport problems. Vaccines exposed to suboptimal conditions earlier in the chain were sometimes administered with inconsistent preparation and dosing practices.

3.5 Feedback dynamics in the delivery system

Causal loop diagrams, derived from recurrent relationships reported in interviews, identified several feedback mechanisms linking delivery conditions, governance processes, market dynamics, and system outcomes (Fig. 3). Three reinforcing loops (R1–R3) and one balancing loop (B1) were identified.

The first reinforcing loop (R1: delivery quality loop) links delivery conditions, vaccine effectiveness, user confidence, demand, and reinvestment. Failures in cold-chain integrity, together with limited handling capacity at the point of administration, were reported to reduce vaccine effectiveness. This, in turn, was linked to perceived vaccine failure, lower confidence in vaccination, and reduced demand. Lower demand and sales were further associated with reduced investment in storage, transport, and service-delivery capacity.

The second reinforcing loop (R2: governance and system learning loop) links surveillance capacity, failure detection, corrective action, delivery failures (failures in vaccine delivery processes), perceived vaccine failure, and disease outbreaks. Limited surveillance capacity reduced the likelihood of timely detection and corrective action. Delivery failures were associated with perceived vaccine failure and ongoing disease outbreaks, which in turn reinforced weaknesses in surveillance and response systems.

The third reinforcing loop (R3: cost–quality trade-off loop) links price pressure, sourcing decisions, delivery capacity, and vaccine performance. Price pressure in the vaccine market, together with the costs of importation, storage, and distribution, created incentives to minimise procurement and delivery costs by adopting low-cost sourcing strategies and reducing investment in handling and quality assurance. Reduced delivery capacity was linked to lower vaccine effectiveness and increased perceived vaccine failure. Participants also reported that purchasing decisions were influenced by trust, prior experience with the vaccine brand, and perceptions of affordability.

A balancing loop (B1: outbreak response loop) was identified in response to disease outbreaks. Increased disease incidence was associated with heightened risk perception and higher vaccine demand and uptake.

Perceived vaccine failure appeared across multiple loops, linking delivery conditions, vaccine performance, demand dynamics, and user responses across the delivery system.

3.6 Critical control points in the delivery system

Using the causal loop diagrams and predefined systems criteria, four critical control points (CCPs) were identified within the vaccine delivery system (Fig. 3). These CCPs were points at which multiple feedback processes converged.

1. CCP1: Cold-chain integrity at the distribution and retail levels, linking temperature control, storage, transport, and vaccine potency before administration.
2. CCP2: Post-market surveillance capacity and feedback mechanisms linking failure detection, reporting, and corrective action.

3. CCP3: Market sourcing and procurement decisions, linking vaccine selection to incentives for investment in quality assurance, storage, and transport.
4. CCP4: Handling practices at the last-mile service-delivery interface, linking vaccine preparation, dosing, administration, and realised effectiveness at the point of use.

3.7 Structural inequities in access and delivery conditions

Participants described unequal access and delivery conditions across geographic areas and stakeholder groups. Cold-chain facilities and distribution networks were concentrated mainly in urban and peri-urban centres. By contrast, farmers in rural areas rely on longer delivery routes, often travelling long distances to urban outlets to access vaccines.

Differences in market position further shaped access to vaccines. Large integrated producers were described as operating within more controlled supply systems, including internal cold-chain capacity. In contrast, small-scale farmers and retailers relied on less reliable distribution channels and faced practical constraints, such as unsuitable pack sizes, long travel distances, and limited cold storage. These factors were reported to restrict access to properly handled vaccines for smaller producers. As one participant noted, “the vaccines are packaged in sizes of 500 or 1000 doses… it becomes very hard for a farmer of 10–30 birds.” *(District veterinary authority, DVA01)*

4. Discussion

This study identified interconnected governance, market, infrastructure, and service-delivery constraints that shape the performance of Uganda’s poultry vaccine delivery system. Poultry vaccination underperformance in Uganda is best understood as a delivery-system failure, rather than a problem of access, adoption, or product efficacy alone. The delivery system is organised so that coordination and oversight are concentrated upstream, while responsibility for vaccine quality is fragmented downstream, where capacity, infrastructure, and supervision are more limited. As vaccines move through distribution, retail, and on-farm use, small losses in quality accumulate across stages, shaping effectiveness at the point of use [30]. Vaccination performance is therefore shaped less by availability alone and more by the organisation and operation of the delivery system.

These structural patterns underpin the feedback processes observed within the system. Rather than being isolated constraints, challenges such as cold-chain failures and weak oversight are interconnected and reinforce one another. By tracing these interactions, this study shows how delivery-system weaknesses are reproduced over time through reinforcing feedback dynamics, sustaining persistent underperformance.

Reinforcing feedback processes linking delivery conditions, perceived effectiveness, demand, and reinvestment play a central role in shaping system behaviour. Declines in delivery quality may reduce both vaccine potency and perceived effectiveness, potentially lowering confidence in vaccination and demand for vaccination services. System actors perceived that reduced confidence and demand could

limit incentives for reinvestment in infrastructure and service capacity, thereby further weakening delivery conditions over time [31]. In this way, perceptions of vaccine performance and willingness to invest in vaccination are shaped by delivery-system conditions. Similar dynamics have been observed in livestock and public health systems, where cold-chain failures contribute to perceived vaccine ineffectiveness, reduced uptake, and persistent low-performance states [10, 11, 32].

The system has limited capacity to correct itself when problems arise, largely due to weaknesses in governance and system learning. Weak post-market surveillance, delayed detection of delivery failures, and poor accountability constrain timely corrective action, allowing quality failures and coordination challenges to persist [30, 33]. As a result, these reinforcing dynamics are not effectively corrected, allowing poor performance to persist and become normalised within the system [26].

In this context, sustained underperformance within a predominantly private-sector delivery system underscores the limits of market mechanisms in ensuring quality. Information asymmetries may constrain end users' ability to assess vaccine quality and handling conditions, while fragmented accountability across the delivery chain weakens incentives for quality assurance. As a result, poor performance is not consistently reflected in demand or pricing, and competition tends to emphasise price rather than quality, discouraging investment in infrastructure and service capacity. Collectively, these characteristics indicate a form of market failure in which private provision alone is insufficient to ensure consistent and effective vaccination performance.

Similar dynamics have been documented in livestock and public health systems, where market-based delivery has been linked to persistent quality gaps stemming from weak accountability and underinvestment in public goods [34, 35]. In these settings, improving delivery performance has required stronger regulatory oversight, public investment in cold-chain infrastructure, and enhanced surveillance and system stewardship [36].

These dynamics indicate that improving vaccination performance requires focusing on a limited number of critical leverage points rather than relying on isolated downstream interventions. In feedback-driven systems such as vaccine delivery, interventions at such points can influence multiple processes simultaneously, shaping delivery conditions, perceived effectiveness, trust, and reinvestment [26]. This analysis identifies cold-chain integrity, post-market surveillance, upstream sourcing decisions, and on-farm vaccine administration as key leverage points within the system.

Cold-chain integrity is critical, as it directly links storage and transport conditions to vaccine potency. Strengthening this component requires improved temperature monitoring, adherence to storage standards, and sustained investment in reliable cooling infrastructure across distribution and retail stages. In resource-constrained settings, decentralised energy solutions, including solar-powered refrigeration, have demonstrated potential to stabilise temperatures and improve vaccine preservation [37].

Strengthening post-market surveillance and feedback mechanisms is equally important but must be aligned with existing institutional capacity. Building on current reporting and supervisory structures within veterinary and public health systems can enable earlier detection of delivery failures and more timely corrective action. Relevant lessons can be drawn from human immunisation programmes, where routine reporting, supervision, and cold-chain monitoring are embedded within service delivery through coordinated public-sector stewardship and investment [38, 39].

Addressing market incentives is also essential. Shifting competition away from price alone towards quality requires the enforcement of standards, certification mechanisms, and procurement practices that prioritise reliability of delivery. At the service-delivery interface, improving vaccination outcomes depends on strengthening technical capacity through training, supervision, and standardised protocols for vaccine handling and administration, particularly among frontline providers such as agrovet attendants and paraprofessionals [40].

Collectively, these interventions target system positions where change can influence multiple feedback processes simultaneously, making them more effective than isolated or downstream actions.

These system dynamics are not experienced equally. Delivery failures create uneven outcomes across actors, reflecting differences in their position within the system. Large, vertically integrated producers and hatchery operations with direct supply channels and internal cold-chain systems are relatively insulated from delivery risks, whereas small-scale actors depend on dispersed, weakly regulated markets, in which quality, costs, and risks are passed downstream [17]. Unequal access to infrastructure, technical capacity, and regulatory presence further limits the ability of actors located farther from centres of market and institutional power to respond to or recover from these challenges [12, 41]. System structure, therefore, not only shapes overall performance but also determines how risk and vulnerability are distributed across actors.

These structural constraints may influence broader disease prevention and management practices within poultry production systems. System actors perceived that unreliable vaccine delivery and inconsistent vaccination outcomes could weaken confidence in vaccination as a preventive strategy. In such contexts, weaknesses in vaccination systems may increase dependence on reactive disease management approaches, including antimicrobial use [42].

From a One Health perspective, efforts to reduce antimicrobial resistance often assume that preventive systems are functional and accessible. The present findings challenge this assumption, showing that vaccine delivery systems often perform inconsistently, particularly in fragmented, private-sector-dominated contexts where both public and private sector capacity to ensure quality and effective implementation is constrained. As a result, efforts to reduce antimicrobial use through vaccination alone are unlikely to achieve sustained impact in many low- and middle-income settings. These dynamics help explain why antimicrobial use persists even where vaccines are available.

Effective One Health strategies must therefore extend beyond behaviour change to include strengthening the systems that underpin reliable disease prevention [43]. Without addressing the system dynamics that degrade delivery quality over time, efforts to promote vaccination are unlikely to achieve sustained reductions in antimicrobial use [5].

These findings should be interpreted in light of several limitations. The study was based on qualitative data from key informant interviews and therefore reflects stakeholder perspectives, which may be influenced by reporting bias. Although participants represented multiple functions within the poultry vaccine delivery system, the findings were not intended to provide statistically representative estimates of practices across all contexts. Instead, the study aimed to identify system structures, interactions, and feedback mechanisms influencing vaccination performance. The causal loop diagrams represent conceptual models derived from stakeholder insights and were not parameterised to quantify effect sizes or simulate alternative intervention scenarios. The study focused on Uganda; however, several mechanisms identified, including fragmented delivery networks, cold-chain constraints, and public–private coordination challenges, may be relevant to animal health systems facing similar structural constraints. Finally, the study did not directly measure vaccine efficacy, disease outcomes, or antimicrobial use, and future research integrating systems modelling with quantitative performance indicators could further evaluate these relationships.

5. Conclusions

Vaccination performance in Uganda's poultry sector is shaped primarily by how the delivery system is organised and operates, rather than by vaccine availability or farmer behaviour alone. Fragmented downstream systems, uneven governance, and market-driven incentives interact through reinforcing feedback processes that influence delivery quality, perceived effectiveness, and demand. These dynamics help explain the persistent underperformance of vaccination and continued reliance on antimicrobials despite vaccine availability.

Improving vaccination outcomes requires targeting key leverage points within the delivery system, particularly cold-chain integrity, post-market surveillance, sourcing practices, and vaccine handling at the point of use. Strengthening these areas offers a practical pathway to improve vaccination effectiveness, enhance disease prevention, and reduce dependence on antimicrobials.

More broadly, efforts to address antimicrobial resistance must recognise that successful preventive interventions depend not only on technologies such as vaccines, but also on the governance, infrastructure, and delivery systems that enable them to perform effectively. Strengthening these underlying systems is essential for achieving sustainable One Health outcomes.

Abbreviations

AMR
Antimicrobial resistance

CCP
Critical control point
CGIAR
Consultative Group on International Agricultural Research
CLD
Causal loop diagram
ILRI
International Livestock Research Institute
IREC
Institutional Research Ethics Committee
KII
Key informant interview
LMIC
Low- and middle-income countries
MAAIF
Ministry of Agriculture, Animal Industry and Fisheries
NDA
National Drug Authority
NGO
Non-governmental organisation
SAAF
Sustainable Animal and Aquatic Foods
UNCST
Uganda National Council for Science and Technology
VCDR
Vector Control Division Research Ethics Committee

Declarations

Ethics approval and consent to participate

Ethical approval was obtained from the International Livestock Research Institute (ILRI) Institutional Research Ethics Committee (ILRI-IREC-2025-23), which provided institutional ethical oversight for the study. Additional ethical and regulatory approval for research conducted in Uganda was obtained from the Vector Control Division Research Ethics Committee (VCDR-2025-78) and the Uganda National Council for Science and Technology (UNCST; A655ES).

All methods were performed in accordance with the relevant institutional guidelines and regulations and the ethical principles governing research involving human participants.

Written informed consent was obtained from participants interviewed in person. For interviews conducted virtually, verbal informed consent was obtained before the interview commenced, consistent

with the approved consent procedures. All participants were informed about the purpose of the study, the voluntary nature of participation, the measures taken to protect confidentiality, and their right to withdraw at any time without consequence.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and analysed in the current study are not publicly available due to confidentiality considerations regarding qualitative interview data; however, they are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

D.A.: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualisation, Project administration, Writing – original draft, Writing – review & editing.

D.M.M.: Conceptualization, Methodology, Investigation, Supervision, Project administration, Writing – review & editing.

W.E.: Methodology, Investigation, Writing – review & editing.

A.M.B.: Conceptualization, Methodology, Supervision, Writing – review & editing.

T.K.J.: Conceptualization, Methodology, Supervision, Writing – review & editing.

A.M.: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

All authors read and approved the final manuscript.

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Authors' information

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References

1. Bett, B. *Vaccine delivery pathways in low- and middle-income countries: Livestock sector perspectives* (ILRI, 2020).
2. Hasso-Agopsowicz, M. et al. *The role of vaccines in reducing antimicrobial resistance: A review of potential impact of vaccines on AMR and insights across 16 vaccines and pathogens* Vol. 42, S1–8 (Vaccine. Elsevier;, 2024).
3. Hoelzer, K. et al. Vaccines as alternatives to antibiotics for food producing animals. Part 2: new approaches and potential solutions. *Vet. Res. Springer*. **49**, 1–15 (2018).
4. World Health Organization, UNEP United Nations Environment Programme. *World Organisation for Animal Health. Implementing the global action plan on antimicrobial resistance: first quadripartite biennial report* (World Health Organization, 2023).
5. Laxminarayan, R. et al. *Unlock the potential of vaccines in food-producing animals* Vol. 384, 1409–1411 (Science. American Association for the Advancement of Science, 2024).
6. Tainika, B., Şekeroğlu, A., Duman, M. & Şentürk, E. Poultry Production in Uganda: Challenges and Opportunities. (2019).
7. Byaruhanga, J. et al. Retrospective study on cattle and poultry diseases in Uganda. *Int. J. Vet. Sci. Med. Elsevier*. **5**, 168–174 (2017).
8. Ilukor, J., Birner, R., Rwamigisa, P. B. & Nantima, N. *The provision of veterinary services: who are the influential actors and what are the governance challenges? A case study of Uganda* Vol. 51, 408–434 (Cambridge University Press, 2015).
9. Bikaako, W. et al. Breaking institutional barriers to enhance women's participation in and benefit from the Peste des Petits Ruminants and Newcastle Disease vaccine value chains for Sembabule district of Uganda. Plos One. Public Library of Science San Francisco, CA USA; ;17:e0270518. (2022).
10. Bakkabulindi, P. et al. Improving the last mile delivery of vaccines through an informed push model: Experiences, opportunities and costs based on an implementation study in a rural district in Uganda. *PLOS Glob Public. Health*. https://doi.org/10.1371/journal.pgph.0002647 (2024).
11. Bessell, P. R. et al. An analysis of the impact of Newcastle disease vaccination and husbandry practice on smallholder chicken productivity in Uganda. Prev Vet Med. Elsevier; ;177:104975. (2020).
12. Dione, M. M., Amia, W. C., Ejobi, F., Ouma, E. A. & Wieland, B. Supply Chain and Delivery of Antimicrobial Drugs in Smallholder Livestock Production Systems in Uganda. *Front. Vet. Sci.* **8**, 611076. https://doi.org/10.3389/fvets.2021.611076 (2021).
13. International Development Research Centre (IDRC). Livestock Vaccine Innovation Fund [Internet]. (2023). https://www.idrc.ca/en/initiative/livestock-vaccine-innovation-fund
14. World Organisation for Animal Health (WOAH). Accelerating action against antimicrobial resistance: Closing the gaps in the animal health sector (High-Level AMR Resolution) [Internet]. (2025).

https://www.woah.org/en/document/accelerating-action-against-amr-closing-gaps-in-the-animal-health-sector/

15. Acosta, D., Hendrickx, S. & McKune, S. The livestock vaccine supply chain: Why it matters and how it can help eradicate peste des petits Ruminants, based on findings in Karamoja, Uganda. *Vaccine Elsevier*. **37**, 6285–6290 (2019).
16. Chemuliti, J., Ogolla, K., Mbogoh, S., Mochabo, K. & Kibore, B. *Practices and trends in last-mile delivery of poultry vaccines in rural areas in developing countries: the case of Newcastle disease vaccine delivery in Bungoma County, Kenya. bioRxiv* 2021–2002 (Cold Spring Harbor Laboratory, 2021).
17. Jaime, G., Hobeika, A. & Figuié, M. Access to Veterinary Drugs in Sub-Saharan Africa: Roadblocks and Current Solutions. *Front. Vet. Sci. [Internet]*. 10.3389/fvets.2021.558973 (2022). https://www.frontiersin.org/journals/veterinary-science/articles/8-2021.
18. Nuvey, F. S. et al. Access to vaccination services for priority ruminant livestock diseases in Ghana: Barriers and determinants of service utilization by farmers. Prev Vet Med. Elsevier; ;215:105919. (2023).
19. Raut, R., Shrestha, R., Adhikari, A., Fatima, A. & Naeem, M. Revolutionizing Veterinary Vaccines: Overcoming Cold-Chain Barriers Through Thermostable and Novel Delivery Technologies. *Appl. Microbiol. MDPI*. **5**, 83 (2025).
20. Tizard, I. R. Production, assessment, and regulation of vaccines. (2021). https://api.semanticscholar.org/CorpusID:225032495
21. Hanger-Kopp, S., Lemke, L. K. G. & Beier, J. What qualitative systems mapping is and what it could be: integrating and visualizing diverse knowledge of complex problems. *Sustain. Sci. Springer*. **19**, 1065–1078 (2024).
22. Kiekens, A., Dierckx de Casterlé, B. & Vandamme, A-M. Qualitative systems mapping for complex public health problems: A practical guide. PloS One. Public Library of Science San Francisco, CA USA; ;17:e0264463. (2022).
23. Rai, P. & Bera, S. *Prioritizing performance objectives of vaccine supply chain for future pandemics. J Humanit Logist Supply Chain Manag* (Emerald Publishing Limited, 2025).
24. McKune, S. et al. Studying a gender responsive vaccine system: retrospective analysis of best methods. *Front. Sustain. Food Syst. Front. Media SA*. **7**, 1176101 (2023).
25. Peterson, A., Charles, V., Yeung, D. & Coyle, K. *The health equity framework: a science-and justice-based model for public health researchers and practitioners. Health Promot Pract* Vol. 22, 741–746 (Sage Publications Sage CA, 2021).
26. Meadows, D. *Thinking in systems: International bestseller* (chelsea green publishing, 2008).
27. Peters, D. H. The application of systems thinking in health: why use systems thinking? *Health Res. Policy Syst. Springer*. **12**, 51 (2014).
28. Sterman, J. D. *Business dynamics: systems thinking and modeling for a complex world* (Irwin/McGraw-Hill, 2000).

29. Hovmand, P. S. Community Based System Dynamics. 1st ed. New York, NY: Springer New York; 2014. (2014). https://doi.org/10.1007/978-1-4614-8763-0
30. De Savigny, D. & Adam, T. *Systems thinking for health systems strengthening* (World Health Organization, 2009).
31. Waweru, K. M. et al. *Socio-economic and structural barriers in Newcastle disease vaccines uptake by smallholder women farmers in Southeastern Kenya* Vol. 18, e0283076 (Plos One. Public Library of Science San Francisco, CA USA, 2023).
32. Enahoro, D. et al. Strategies to upgrade animal health delivery in village poultry systems: perspectives of stakeholders from northern Ghana and central zones in Tanzania. *Front. Vet. Sci. Front. Media SA*. **8**, 611357 (2021).
33. Rwashana, A. S., Nakubulwa, S., Nakakeeto-Kijjambu, M. & Adam, T. Advancing the application of systems thinking in health: understanding the dynamics of neonatal mortality in Uganda. *Health Res. Policy Syst.* **12**, 36. https://doi.org/10.1186/1478-4505-12-36 (2014).
34. Channa Sjoblom, M., Herrera, C. & de Alencar Paixao, L. G. Apr. Public–private collaboration in health: from market failure to public value [Internet]. World Bank Blogs. 2026 [cited 2026 Apr 5]. (2026). https://blogs.worldbank.org/en/latinamerica/public-private-collaboration-health. Accessed 5.
35. Lubroth, J. et al. *Veterinary vaccines and their use in developing countries* Vol. 26, 179 (Rev Sci Tech-Off Int Epizoot. OIE OFFICE INTERNATIONAL DES EPIZOOTIES, 2007).
36. Alders, R. G. Making Newcastle disease vaccines available at village level. *Vet. Rec*. **174**, 502–503 (2014).
37. Haidari, L. A. et al. The economic and operational value of using drones to transport vaccines. *Vaccine Elsevier*. **34**, 4062–4067 (2016).
38. Juneja, S., Wadi, F., Kannure, M. & Singh, S. K. Strengthening immunization systems through effective supply chains: insights from global effective vaccine management initiative. *IJPSR* **1**, 387–394 (2025).
39. World Health Organization. *Quality immunization services: a planning guide* (World Health Organization, 2022).
40. Ozawa, S. et al. Defining hard-to-reach populations for vaccination. *Vaccine Elsevier*. **37**, 5525–5534 (2019).
41. Implementation of WOAH standards: the Observatory Annual Report. First Edition, 2022 [Internet]. WOAH. (2022). Dec https://doi.org/10.20506/obs.3339
42. Rushton, J. *The Economics of Animal Health and Production [Internet]* (CABI, 2009). https://books.google.dk/books?id=iCyABkjkRJ0C
43. Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO). World Organisation for Animal Health (WOAH), United Nations Environment Programme (UNEP). One Health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals,

Plants and the Environment [Internet]. Rome, Italy: FAO; https://www.fao.org/documents/card/en/c/cc2289en/ (2022).

Figures

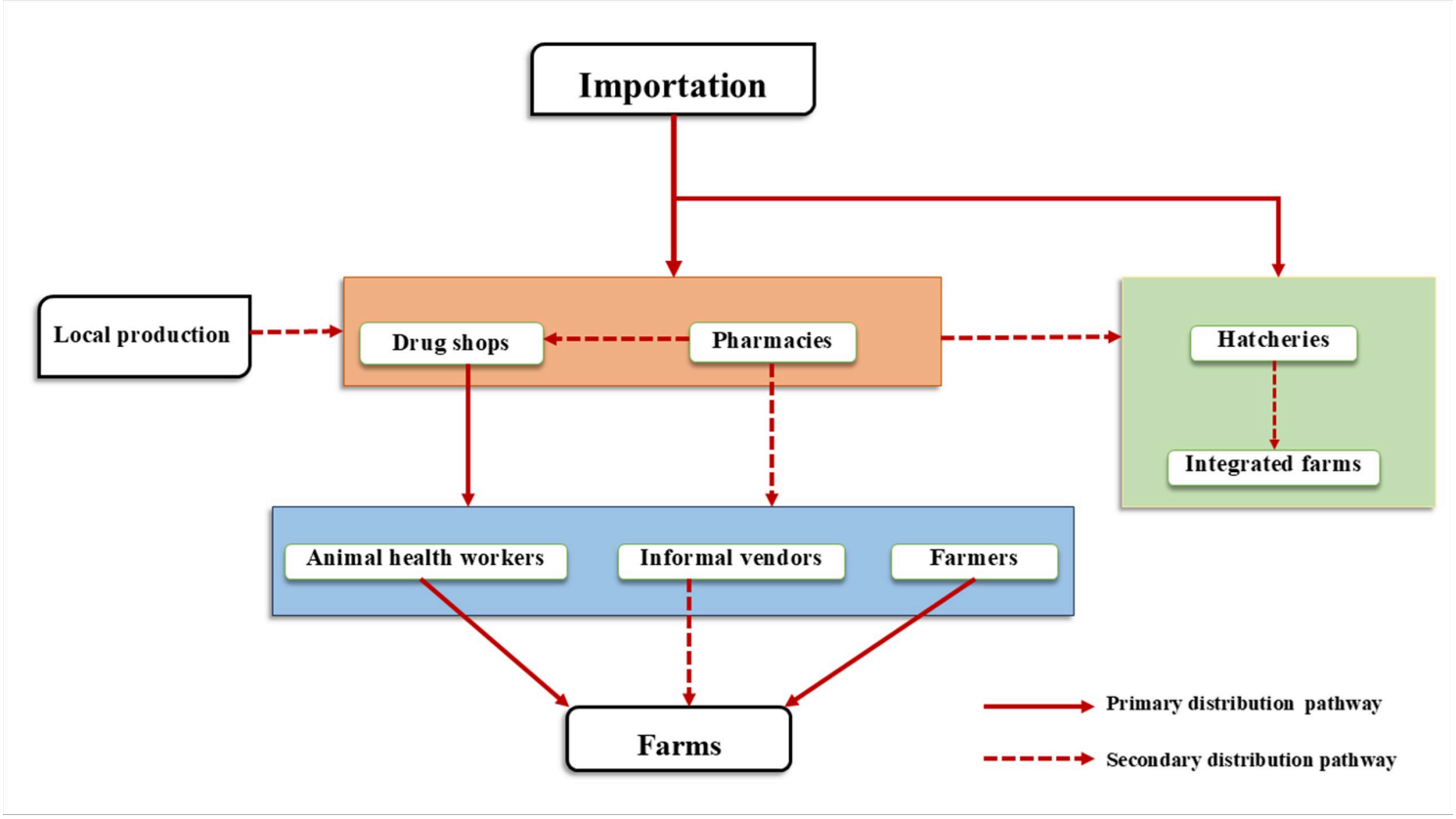


Figure 1

Structural and logistical flow of poultry vaccines from importation to end use.

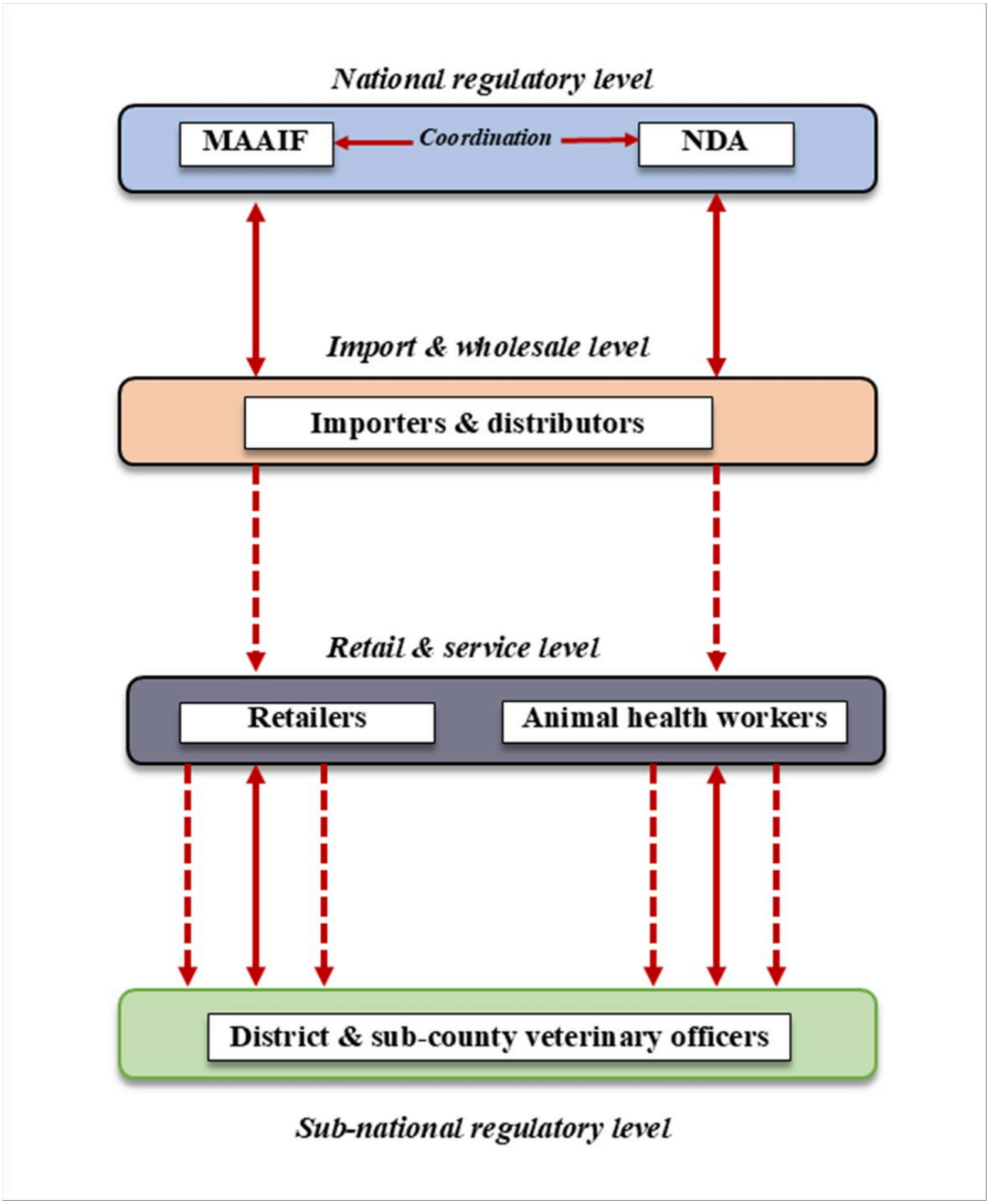


Figure 2

Schematic representation of the poultry vaccine delivery system showing regulatory and operational levels. Solid lines indicate formal coordination and reporting relationships, while dashed lines represent indirect or limited interactions among actors.

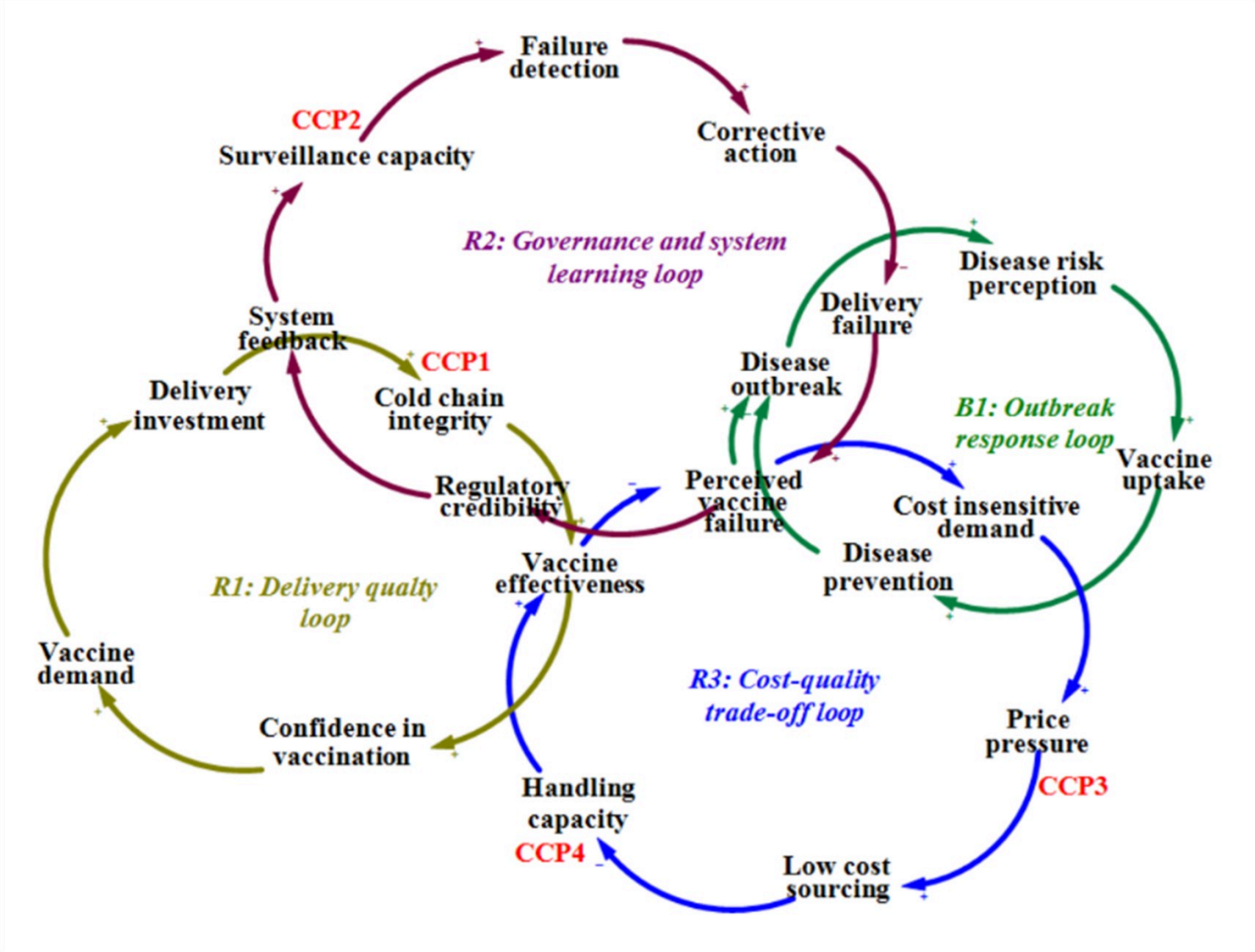


Figure 3

Causal loop diagram illustrating the main feedback structures identified in poultry vaccine delivery. Reinforcing loops (R1–R3) connect delivery quality, governance, system learning, and cost–quality trade-offs, while balancing loop (B1) depicts outbreak-related demand responses. Critical control points (CCP1–CCP4) indicate key leverage positions within the system.

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