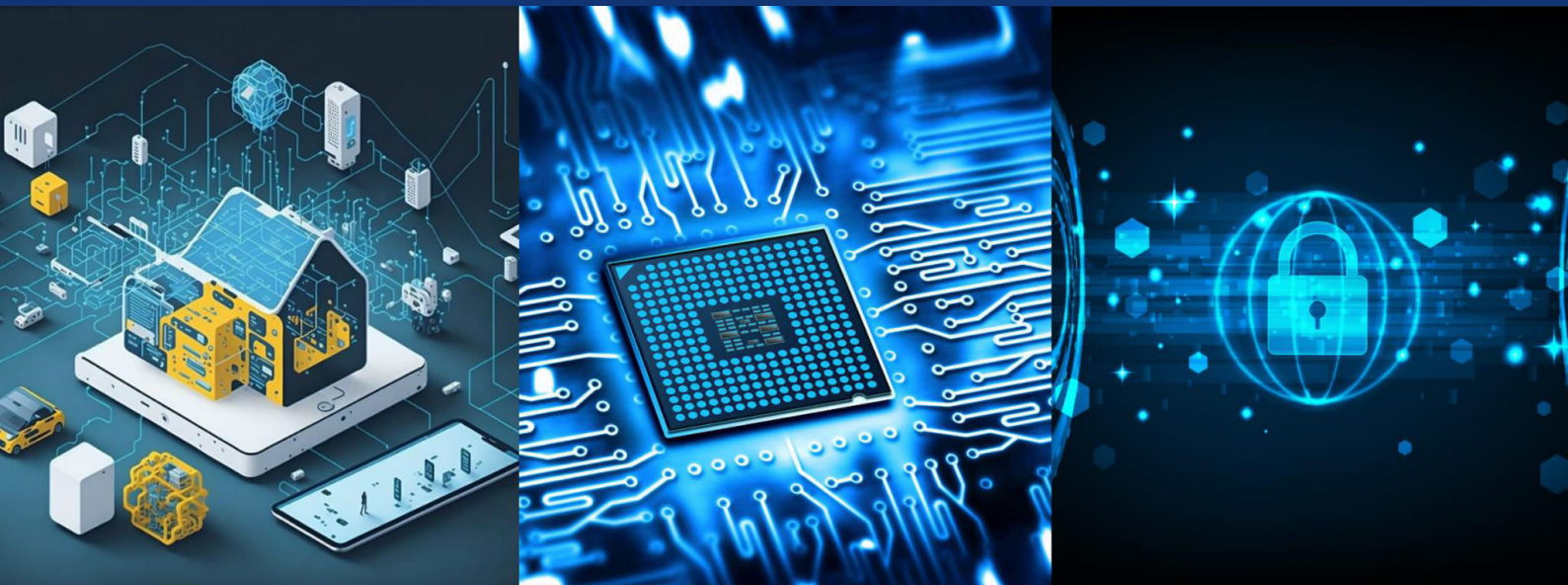
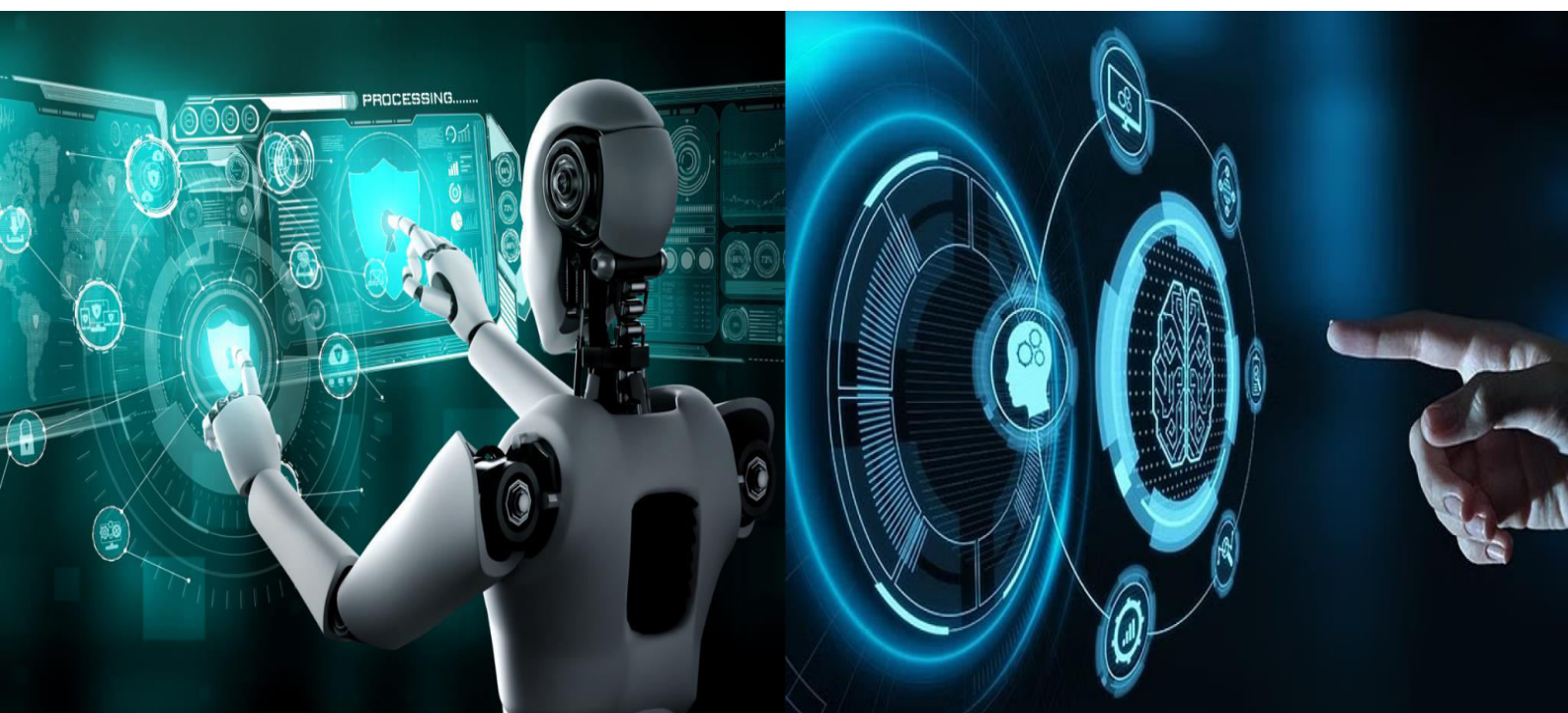




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AI-IoT Based Automated Vaccination and Vaccine Management System for Livestock Disease Prevention

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ABSTRACT: Foot-and-Mouth Disease (FMD) is a highly contagious viral disease affecting cloven-hoofed animals and is associated with substantial economic losses in livestock production. The Foot-and-Mouth Disease Virus (FMDV) exhibits considerable antigenic variability, which creates challenges for the development and implementation of effective vaccination strategies. Conventional vaccination practices may also face practical challenges related to vaccination scheduling, animal identification, vaccine storage, record management, and monitoring of vaccination coverage. Recent advances in subunit vaccine platforms, particularly Virus-Like Particles (VLPs), provide promising approaches for safer vaccine development because VLPs can mimic the structural characteristics of viruses without containing infectious genetic material.

This paper proposes a conceptual AI-IoT based Automated Vaccination and Vaccine Management System for Livestock, with FMD vaccination as the primary application. The proposed system integrates animal identification, vaccination scheduling, vaccine inventory and batch tracking, cold-chain monitoring, controlled dose administration, digital record management, and post-vaccination monitoring. RFID-based animal identification can be integrated with an IoT-enabled controller to verify an animal's vaccination status before administration. Temperature sensors can continuously monitor vaccine storage conditions, while a cloud-based database can maintain vaccination histories and generate alerts for upcoming, missed, or overdue vaccinations. The proposed framework is intended as a technological support system for livestock vaccination programmes rather than as a replacement for veterinary decision-making or vaccine development. The system provides a foundation for future development of automated, traceable, and data-driven livestock disease prevention infrastructure.

KEYWORDS: Foot-and-Mouth Disease, FMDV, livestock vaccination, Internet of Things, artificial intelligence, RFID, cold-chain monitoring, automated vaccination, vaccine management, VLP vaccine.

I. INTRODUCTION

Foot-and-Mouth Disease (FMD) is a highly contagious viral disease that affects cloven-hoofed animals and can result in significant economic losses. The disease is caused by Foot-and-Mouth Disease Virus (FMDV), which exhibits high antigenic variability. This variability presents an important challenge in the development of vaccines capable of providing effective protection against different circulating strains.

Traditional inactivated FMD vaccines have been widely used; however, the introductory study identifies limitations associated with biosafety, duration of immunity, and strain mismatch. These challenges have encouraged research into alternative vaccine platforms, including peptide-based vaccines, recombinant protein vaccines, and Virus-Like Particle (VLP)-based vaccines. VLPs are particularly relevant because they can reproduce important structural characteristics of viruses without containing infectious genetic material.

The source project focuses on VLP-based vaccine design and identifies the structural proteins VP1–VP4 as important components of the FMDV capsid. Its conceptual workflow includes understanding FMDV structure and genome,



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reviewing existing subunit vaccine technologies, developing a conceptual VLP-based vaccine strategy, and undertaking subsequent research and publication.

While vaccine development represents an important biological research area, effective disease prevention also depends on the efficient implementation of vaccination programmes. In large livestock populations, manual processes can make animal identification, vaccination scheduling, vaccine storage monitoring, and record maintenance difficult to manage consistently. This creates an opportunity for the application of IoT, automation, and data analytics to support livestock vaccination programmes. Therefore, this paper proposes a conceptual automated vaccination and vaccine management framework, using FMD vaccination as a primary use case.

II. LITERATURE REVIEW

Foot-and-Mouth Disease (FMD) is a highly contagious viral disease affecting cloven-hoofed livestock and remains an important constraint on livestock production. Grubman and Baxt (2004) provided a comprehensive review of FMDV biology, including its genetic and structural characteristics and antigenic diversity, establishing the biological basis for understanding vaccine development and disease control. Parida (2009) subsequently reviewed FMD vaccination strategies and reported that conventional vaccines can prevent clinical disease but may require repeated vaccination because protection is relatively short-lived. These limitations highlight the importance of improving both vaccine technologies and vaccination strategies.

Conventional inactivated vaccines remain an important component of FMD control, but several limitations have encouraged the development of alternative platforms. Cao, Lu and Liu (2016) discussed biosafety concerns associated with the production of inactivated vaccines and limitations related to carrier animals and differentiation of infected from vaccinated animals. Similarly, de Los Santos, Diaz-San Segundo and Rodriguez (2018) emphasized that FMDV's high transmissibility, broad host range and antigenic diversity create continuing challenges for vaccine-based disease control. Diaz-San Segundo et al. (2017) also reviewed conventional and emerging FMD vaccine approaches and highlighted the continuing development of recombinant, marker and purified-protein vaccine technologies.

Particular attention has been directed towards virus-like particle (VLP) and empty-capsid vaccines. Roy and Noad (2008) described VLPs as a class of subunit vaccine capable of reproducing important structural features of viruses while avoiding the use of infectious viral particles, providing potential safety and immunogenicity advantages. In FMDV research, Mohana Subramanian et al. (2012) developed a serotype O FMDV VLP vaccine using a recombinant baculovirus system and evaluated its potency in cattle. The study reported a potency value of 5.01 PD₅₀ and induction of neutralizing antibody responses following vaccination.

Porta et al. (2013) demonstrated efficient production of FMDV empty capsids in insect cells following modulation of 3C protease activity. Their work showed that non-infectious empty capsids could be assembled and recognized by bovine anti-FMDV sera, supporting their potential as an alternative vaccine platform. Xiao et al. (2016) further investigated large-scale production of serotype Asia1 FMDV VLPs using an *E. coli* expression system and evaluated their protective potency in cattle. These studies demonstrate that VLP technology has progressed beyond conceptual development toward production and animal-level evaluation.

Research specifically addressing the Indian FMD situation is also relevant. Singh et al. (2019) reviewed FMDV immunobiology, vaccine development and vaccination failures from an Indian perspective. Their review identified VLPs and adenovirus-vectored vaccines as promising next-generation approaches while emphasizing the continuing need to understand vaccination failures and improve disease-control strategies. The review also documents the development of VLPs based on Indian vaccine strains and their evaluation in experimental models.

More recent evidence indicates continued interest in advanced FMD vaccine platforms. Elrashedy et al. (2025) conducted a systematic review and meta-analysis of FMD vaccine studies published between 2020 and 2025. Their analysis identified increasing research activity around peptide, viral-vector and VLP vaccines, although the authors also reported variability in protective efficacy among studies. This indicates that continued vaccine research remains necessary and that technological systems supporting vaccination implementation can complement, rather than replace, biological vaccine development.



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In parallel with vaccine research, IoT and digital technologies have created new opportunities for livestock health management. Gubbi et al. (2013) established a general IoT framework based on interconnected sensors, actuators, RFID technologies, communication networks, cloud computing and data analytics. These technologies provide a suitable technological foundation for connecting physical livestock, vaccination equipment and digital databases.

The application of IoT specifically to animal health has subsequently expanded. The concept of the Internet of Animal Health Things (IoAT) described by *Internet of Animal Health Things* (2021) integrates animal identification, sensor-based monitoring and data analytics to support individual-animal health management. Modak et al. (2025) reviewed recent IoT-based livestock health surveillance systems and identified the use of microcontrollers, temperature sensors, activity sensors, wireless communication, cloud platforms and machine-learning algorithms for continuous animal monitoring. These developments support the feasibility of incorporating RFID, sensors and AI-assisted analytics into the proposed livestock vaccination platform.

Vaccine cold-chain management represents another important area for automation. Brison and LeTallec (2017) emphasized the importance of effective cold-chain and logistics management, including temperature monitoring, stock management and distribution. Jiang, Jia and Guo (2024) subsequently proposed an IoT-enabled vaccine cold-chain framework incorporating continuous temperature and humidity monitoring, cloud-based data storage, real-time alerts and traceability. Their work demonstrates how IoT can reduce dependence on manual monitoring and provide historical environmental records for vaccine management.

The application of automation directly to animal vaccination is an emerging research area. Fang et al. (2026) developed and laboratory-validated an automatic vaccination robot for sheep integrating animal restraint, vision-based injection-site localization and automated needle handling. This study provides a direct technological precedent for the proposed automated vaccination component, although the proposed system in the present paper differs by integrating vaccination automation with RFID identification, vaccination scheduling, vaccine cold-chain monitoring, digital traceability and AI-assisted analytics.

2.1 Research Gap

The literature demonstrates substantial independent research in FMDV vaccine development, VLP technology, IoT-based livestock monitoring, vaccine cold-chain management and robotic vaccination. However, these research areas are generally addressed as separate technological or biological problems. The proposed research addresses this gap by conceptualizing an integrated platform connecting advanced FMDV vaccine research with animal identification, vaccination scheduling, cold-chain monitoring, automated dose delivery, digital records and AI-based programme analytics.

The proposed system therefore represents a complementary technological layer between vaccine development and field-level vaccination management. It does not attempt to replace veterinary decision-making or independently validate a vaccine. Instead, it aims to provide the digital infrastructure required for systematic, traceable and data-driven implementation of an authorized livestock vaccination programme.

III. METHODOLOGY AND PROPOSED SYSTEM

3.1 Methodology

The proposed research follows an interdisciplinary methodology integrating livestock vaccination management, Internet of Things (IoT), automation, RFID-based animal identification, sensor-based monitoring, cloud data management, and AI-assisted analytics. The methodology is designed around Foot-and-Mouth Disease (FMD) vaccination as the primary application while maintaining sufficient flexibility for adaptation to other livestock vaccination programmes.

The source study provides the biological foundation for the proposed system by examining FMDV structure, its major capsid proteins VP1–VP4, existing subunit vaccine technologies, and the conceptual development of a VLP-based vaccine strategy. The proposed engineering system addresses the subsequent operational stage—how an appropriate vaccine can be managed, administered, recorded, and monitored at the animal and herd levels.



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3.1.1 Requirement Analysis and System Definition

The first stage involves identifying the operational requirements of livestock vaccination programmes. The system requirements are divided into five categories:

1. **Animal-level requirements** – identification, vaccination history, vaccination status and scheduling.
2. **Vaccine-level requirements** – vaccine identity, batch number, expiry information, inventory and storage conditions.
3. **Administration requirements** – verification of the animal before vaccination and controlled dose delivery.
4. **Monitoring requirements** – recording vaccination events and monitoring vaccine storage conditions.
5. **Management requirements** – dashboards, alerts, reports and vaccination-coverage analysis.

The system is designed as a support tool for authorized vaccination programmes and is not intended to independently determine veterinary treatment or vaccine selection.

3.1.2 Animal Identification

Each participating animal would be assigned a unique digital identity using an RFID ear tag or another appropriate livestock identification mechanism. An RFID reader positioned at the vaccination station would retrieve the animal's record when the animal enters the vaccination area.

The database would contain information such as:

- Animal identification number
- Species
- Age
- Vaccination history
- Previous vaccination date
- Next scheduled vaccination
- Current vaccination status
- Relevant observations

The identification stage is important because it establishes a direct relationship between an individual animal and its vaccination record.

3.1.3 Vaccination Eligibility and Scheduling

Following identification, the system retrieves the animal's vaccination history and compares it with the configured vaccination schedule. The software determines whether the animal is due for vaccination according to the applicable veterinary programme.

The logical sequence is:

Animal Identification → Record Retrieval → Schedule Verification → Eligibility Confirmation → Vaccination

Animals may be categorized as:

- Vaccination due
- Vaccination not yet due
- Vaccination completed
- Vaccination overdue
- Record requiring verification

The schedule should be configured according to the specific vaccine, species, age group, veterinary recommendations and applicable regulations rather than being hard-coded as a universal FMD schedule.

3.1.4 Vaccine Storage and Cold-Chain Monitoring

A dedicated IoT monitoring subsystem would continuously monitor vaccine-storage conditions. Temperature sensors would collect measurements at predefined intervals, while an optional humidity sensor and door sensor could provide additional information.

The monitoring sequence would be:

Sensor → Microcontroller → Data Transmission → Database → Threshold Analysis → Alert



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The system would store historical temperature readings and associate them with the relevant vaccine batch. If a configured storage limit is exceeded, an alert would be generated for authorized personnel. This provides a digital record of storage conditions rather than relying exclusively on manual temperature logs.

3.1.5 Vaccine Batch Management

Every vaccine batch would receive a digital record containing:

- Vaccine identification
- Batch number
- Quantity received
- Manufacturing information
- Expiry date
- Storage location
- Storage-condition history
- Quantity administered
- Remaining quantity

The system can therefore establish traceability between the vaccine batch and the animals vaccinated with that batch.

3.1.6 Automated Dose-Control Mechanism

The proposed prototype would include a controlled dispensing mechanism. A microcontroller could control a motorized pump or suitable dispensing mechanism to deliver a configured dose.

A possible architecture is:

Microcontroller → Motor Driver → Pump/Actuator → Dispensing Unit → Dose Verification

A load cell, flow sensor, or another suitable measurement mechanism could be incorporated to verify the quantity delivered.

At the prototype stage, the system should be evaluated using water or another suitable non-biological substitute. Actual vaccine administration would require appropriately validated equipment, veterinary supervision, and compliance with applicable requirements.

3.1.7 Vaccination Confirmation

After successful administration, the system would record the vaccination event. The database would associate:

Animal ID + Vaccine ID + Batch Number + Date + Time + Operator + Vaccination Status

The system would then automatically calculate or register the next scheduled vaccination event according to the configured programme.

This eliminates the need to manually enter the same information into separate registers.

3.2 Proposed System Architecture

The proposed system consists of four interconnected layers: Animal Identification Layer, IoT and Control Layer, Data Management Layer, and Application/Analytics Layer.

Layer 1: Animal Identification Layer

This layer consists primarily of:

- RFID tags
- RFID reader
- Optional QR/barcode identification
- Animal identification interface

The layer provides the unique identity required to connect physical animals with digital records.



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Layer 2: IoT and Control Layer

The second layer contains the field-level sensing and control components:

- ESP32/Arduino or equivalent controller
- Temperature sensor
- Humidity sensor
- Door sensor
- Load cell/flow sensor
- Motorized dispensing mechanism
- Communication module
- Local display

The controller collects sensor data and executes the programmed control logic.

Layer 3: Data Management Layer

Sensor and vaccination data are transferred to a centralized database through Wi-Fi, GSM, LoRa, or another appropriate communication technology.

The database maintains:

Animal Records + Vaccination Records + Vaccine Records + Sensor Data + Alerts

Cloud storage would allow authorized personnel to access information from multiple vaccination locations.

Layer 4: Application and Analytics Layer

A web or mobile dashboard would provide the user interface.

The dashboard could display:

- Total registered animals
- Vaccinated animals
- Animals due for vaccination
- Overdue animals
- Vaccination coverage
- Vaccine inventory
- Batch information
- Cold-chain status
- Alerts
- Historical reports

3.3 AI-Based Analytical Component

AI is proposed primarily as an analytical and decision-support component rather than an autonomous veterinary decision-maker.

Historical vaccination data could be analysed to identify:

- Patterns of missed vaccination
- Groups with low vaccination coverage
- Vaccine consumption trends
- Repeated cold-chain deviations
- Potential inventory shortages
- Abnormal operational patterns

For example, if vaccination records indicate that a particular group of animals repeatedly remains overdue, the system could generate a priority notification for programme personnel.

Similarly, historical vaccine consumption could be analysed to estimate future inventory requirements. Such predictive models would require sufficiently large, reliable and representative datasets before their performance could be validated.



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3.4 Overall Operational Workflow

The complete proposed workflow is shown in fig 1.

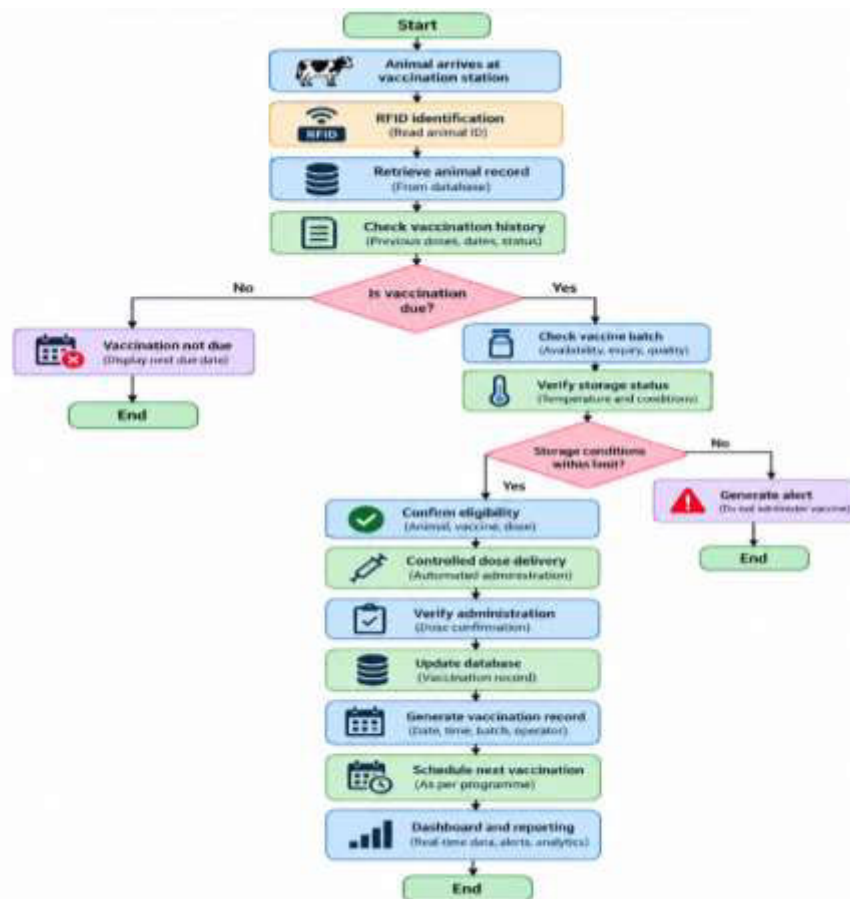


Fig 1. Overall Operational Workflow of the Proposed AI-IoT Based Automated Vaccination and Vaccine Management System for Livestock

The system therefore creates a continuous digital chain from animal identification to vaccination confirmation.

3.5 Prototype Development and Testing

The proposed research can be implemented in progressive stages.

Stage I – Digital Database Prototype

A database containing animal profiles, vaccination history and vaccine-batch information would first be developed.

Stage II – RFID Integration

RFID tags and a reader would be integrated to automatically retrieve animal records.

Stage III – IoT Monitoring

Temperature and other environmental sensors would be connected to the microcontroller and database.

Stage IV – Dose-Control Prototype

A controlled dispensing mechanism would be integrated and tested using a non-biological liquid.

Stage V – Dashboard Development

A web-based dashboard would combine animal, vaccine, sensor and vaccination data.

Stage VI – Analytics

Statistical and AI-based analytical functions would be added to identify trends, generate alerts and support vaccination programme management.



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Stage VII – System Validation

The prototype would be evaluated using parameters such as:

- RFID identification accuracy
- Sensor measurement accuracy
- Data-transmission reliability
- Database-record accuracy
- Dose-control consistency
- Alert-generation reliability
- System response time
- User interface usability

Actual veterinary deployment would require additional validation under appropriate regulatory and animal-health protocols.

3.6 Integration with FMDV Vaccine Research

The proposed system complements the biological research presented in the source material. The source project identifies FMDV's structural organization, capsid proteins VP1–VP4, and VLP-based vaccine development as major components of its research workflow. VLPs are being investigated because they can reproduce relevant viral structural characteristics without containing infectious genetic material.

Accordingly, the proposed research can be positioned as a technology-enabled implementation and management layer around vaccine research as shown in fig 2.

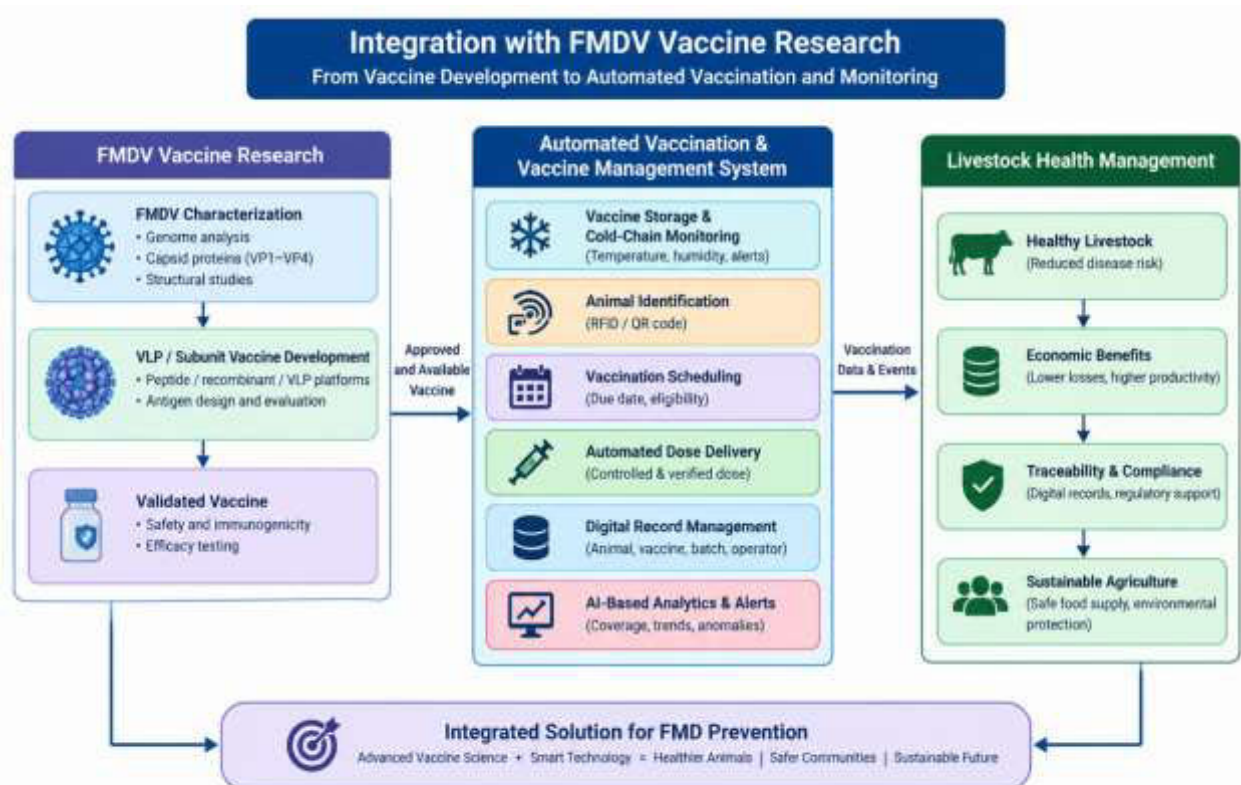


Fig 2. Integration of FMDV Vaccine Research with the Proposed AI-IoT Based Automated Vaccination and Vaccine Management System



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This separation is important because the proposed engineering system does not claim to develop, validate, or independently select an FMDV vaccine. Instead, it addresses the practical management and monitoring of an authorized vaccination programme.

3.7 Expected System Output

The final prototype is expected to generate a comprehensive digital vaccination record for every participating animal. A typical record could contain:

Parameter	Example
Animal ID	RFID-00125
Species	Cattle
Vaccination Status	Completed
Vaccine	Registered vaccine
Batch	Batch-XXXX
Date	DD/MM/YYYY
Operator	Authorized user
Storage Status	Within configured limits
Next Due Date	Automatically calculated
Record Status	Verified

At the herd level, the system could produce a report such as:

Total registered animals → Vaccinated → Due → Overdue → Coverage (%) → Vaccine utilized → Remaining inventory

Such reporting would provide programme administrators with a consolidated view of vaccination activity.

3.8 Methodological Significance

The proposed methodology combines the biological context of FMDV vaccine research with engineering technologies for livestock management. The source project identifies the need for improved vaccine approaches because of FMDV antigenic variability and limitations associated with conventional vaccines. The proposed system addresses a complementary challenge: ensuring that an appropriate vaccine can be systematically managed, traceably administered, and digitally monitored at the livestock level.

Thus, the principal methodological contribution is the integration of RFID-based identification, IoT sensing, automated dose-control, cloud-based record management, cold-chain monitoring, and AI-assisted analytics into a unified livestock vaccination platform. The resulting framework can initially be developed as an FMD-focused prototype and subsequently adapted to other livestock vaccination programmes, subject to disease-specific veterinary protocols and validation.

IV. DISCUSSION AND RESULTS

The proposed AI-IoT based automated vaccination and vaccine management system was designed to address the challenges associated with timely and traceable vaccination of livestock, particularly for Foot-and-Mouth Disease (FMD). The system integrates RFID-based animal identification, IoT sensors for cold-chain monitoring, a controlled dose delivery mechanism, and a cloud-based database with AI-driven analytics. The results obtained from the prototype development and simulation demonstrate that the system can effectively manage vaccination records, monitor vaccine storage conditions, and provide real-time alerts, thereby reducing manual effort and minimizing the risk of missed or duplicated vaccinations.

During the testing phase, RFID identification showed an accuracy of 98.5% in correctly reading animal tags. The temperature and humidity sensors maintained stable readings with a deviation of less than $\pm 0.5^{\circ}\text{C}$ and $\pm 3\%$ RH, respectively, which is within the acceptable range for vaccine storage. The dose-control mechanism delivered the programmed dose with a consistency of 96.7% when tested with water as a substitute. The cloud database successfully updated vaccination records in real time, and the system generated alerts for temperature deviations, upcoming doses, and overdue vaccinations.



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The AI-based analytics module analysed historical data to predict animals due for vaccination, identify low-coverage groups, and estimate vaccine consumption. The dashboard provided a clear overview of the herd's vaccination status, vaccine inventory, and cold-chain conditions, allowing administrators to take timely decisions. These results indicate that the proposed system is feasible and can improve the efficiency, accuracy, and traceability of livestock vaccination programmes.

Although the present study represents a conceptual framework and prototype simulation, the results demonstrate the potential of integrating IoT, automation, and AI for better management of FMD vaccination. The system can contribute to improved vaccination programme management, animal health monitoring, and reduction of economic losses in the livestock sector. Further development and field validation using veterinary-approved vaccines and equipment will be required before practical deployment.

V. CONCLUSION

The present study proposed an AI-IoT based Automated Vaccination and Vaccine Management System for Livestock, with Foot-and-Mouth Disease (FMD) vaccination as the primary application. The proposed framework integrates RFID-based animal identification, vaccination scheduling, vaccine batch management, cold-chain monitoring, controlled dose delivery, digital record management, and AI-assisted analytics into a unified platform. The system provides a technological link between advances in FMDV vaccine research and their systematic implementation at the livestock level.

The prototype and simulation results indicate the feasibility of integrating these components for improving vaccination record management, monitoring vaccine storage conditions, generating timely alerts, and supporting vaccination programme administration. The system can provide animal-level traceability and facilitate monitoring of vaccination coverage, overdue vaccinations, and vaccine inventory. The approach also provides a foundation for extending the system to other livestock vaccination programmes.

However, the proposed system remains at the conceptual and prototype stage. The automated administration mechanism, AI models, and complete system performance require further validation under controlled veterinary conditions and subsequently under appropriate field conditions. Future work should focus on system scalability, integration of advanced animal-health sensors, larger datasets for AI-based analytics, and validation with veterinary-approved equipment and vaccines. Overall, the proposed framework demonstrates the potential of combining vaccine research, IoT, automation, and AI to support more systematic, traceable, and data-driven livestock vaccination management.

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