World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

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Biotechnological advancements for control of foot and mouth disease in African livestock

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World Journal of Advanced Research and Reviews, 2026, 29(03), 799-809

Publication history: Received on 29 January 2026; revised on 09 March 2026; accepted on 10 March 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.29.3.0458

Abstract

Foot-and-Mouth Disease (FMD) remains one of the most economically devastating transboundary animal diseases affecting livestock production in Africa, significantly constraining food security, rural livelihoods, and access to international markets. The disease's persistence is exacerbated by complex epidemiology, multiple circulating serotypes, wildlife–livestock interfaces, and limited surveillance capacity across many African regions. This review examines recent biotechnological advancements that are transforming the prevention, diagnosis, and control of FMD in African livestock systems. Emphasis is placed on innovations in molecular diagnostics such as real-time polymerase chain reaction (RT-PCR) and loop-mediated isothermal amplification (LAMP), recombinant and marker vaccines, next-generation sequencing for viral characterization, and emerging tools including genomic surveillance and bioinformatics. The paper further evaluates the relevance of these technologies within African production contexts, highlighting challenges related to infrastructure, cost, cold-chain dependence, and policy implementation. By integrating biotechnology with coordinated surveillance, regional cooperation, and supportive policy frameworks, African countries can enhance FMD control strategies and move toward sustainable livestock development. The study concludes that biotechnology, when contextually adapted and institutionally supported, offers a critical pathway for reducing the burden of FMD and improving resilience in African livestock systems.

Keywords: Foot and Mouth Diseases; Transboundary Animal Diseases; Biotechnology; Genomic Surveillance; Recombinant Vaccines; African Livestock System

1. Introduction

Foot-and-mouth disease (FMD) is a highly contagious viral disease of cloven-hoofed livestock that causes devastating economic losses worldwide. In endemic regions, FMD is estimated to cost between US$6.5 and $21 billion annually in lost production and control measures. Africa bears a particularly heavy burden, with FMD outbreaks causing over $2 billion in losses each year. Beyond direct losses, FMD imposes trade bans and livelihood shocks, making its control a top priority for veterinary and agricultural authorities. Traditionally, FMD management has relied on mass vaccination with inactivated vaccines, movement restrictions, and culling of infected herds. Indeed, inactivated FMD vaccines have been the primary control measure for decades. However, the efficacy of these conventional vaccines is challenged by the virus's extensive antigenic variability across seven serotypes and numerous strains, as well as the typically short-lived immunity they induce. In Africa, six of the seven FMDV serotypes circulate, often co-endemic, requiring frequent updates to vaccine strains and use of polyvalent vaccines. This diversity, combined with factors such as transboundary animal movements, wildlife reservoirs, and weak biosecurity, has perpetuated FMD endemicity in many African countries. Clearly, innovative solutions are needed to complement and enhance traditional control methods.

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Recent biotechnological advancements offer new hope for more effective FMD control in African livestock. Modern tools from biotechnology – including improved vaccines, advanced molecular diagnostics, and genetic interventions – can address some of the persistent challenges of FMD management. For example, next-generation vaccines promise broader and more durable immunity, novel diagnostic platforms enable rapid on-site detection and surveillance, and genetic approaches (in both the virus and the host) open avenues for creating disease-resistant animals or attenuated virus strains. This article provides a comprehensive review of peer-reviewed studies (2020–present) on such biotechnological advancements for FMD control, with an emphasis on their relevance to the African context. We follow a structured research paper format, presenting an introduction to the problem, a review of current literature, methodology of our review, key results from recent studies, and a discussion of their implications. In particular, we highlight vaccine innovations, molecular diagnostic tools, and genetic approaches as three pillars of biotechnological intervention for managing FMD. By synthesizing the latest evidence, we aim to elucidate how these tools can strengthen FMD control programs in Africa and identify gaps for future research. Ultimately, leveraging biotechnology alongside traditional measures could significantly improve the prospects of controlling – and eventually eradicating – FMD in African livestock populations.

2. Literature review

FMD Control Challenges in Africa: FMD control in Africa is complicated by the virus's epidemiology and the limitations of available tools. The continent experiences a unique disease ecology where multiple FMDV serotypes (A, O, C, SAT1, SAT2, SAT3, and Asia1) co-circulate over vast regions. Infection with one serotype confers no protection against others, and even within a serotype, numerous strains may escape vaccine immunity due to antigenic drift. Mass vaccination campaigns are widely used and remain the cornerstone of FMD control. However, conventional inactivated vaccines have limited cross-protective efficacy across diverse serotypes and often induce only short-term immunity. In Africa, polyvalent vaccines are administered to cover the prevalent serotypes, yet antigenic mismatches between vaccine strains and field viruses can lead to vaccine failures. Moreover, maintaining cold-chain distribution and frequent revaccination (every 4–6 months in some endemic areas) pose logistical and financial challenges for many African veterinary services. The limited capacity of African vaccine production (most FMD vaccines are imported) further constrains timely access to matching vaccines. These challenges underscore the need for more effective and sustainable vaccine solutions, as well as complementary strategies beyond vaccination alone.

Advances in FMD Vaccines: Recognizing the shortcomings of current vaccines, researchers have been pursuing next-generation FMD vaccines that are safer, faster to produce, and provide broader immunity. Ongoing research is exploring novel vaccine platforms with the goal of achieving "universal" protection against diverse FMDV serotypes. For example, epitope-based vaccine design is being investigated to include conserved antigenic sites from multiple serotypes. Alternative vaccine technologies – such as recombinant subunit vaccines, viral-vectored vaccines, DNA vaccines, and most recently mRNA vaccines – have been developed and tested in experimental models. By 2020, DNA vaccines and peptide vaccines had been studied for FMD, but with mixed success (tending to confer lower efficacy than traditional vaccines). Recent years have seen increasing focus on *in vitro* antigen production systems (e.g. expressing FMDV capsid proteins in E. coli or plants to create virus-like particles) and on improved live-attenuated vaccine candidates via genetic engineering of the virus. A major impetus for these innovations is to overcome the antigenic variability issue and to enable differentiation of infected vs. vaccinated animals (DIVA). Notably, current killed vaccines, if properly purified, allow serological DIVA testing because vaccinated animals do not produce antibodies to non-structural proteins like 3ABC; ELISA methods detecting antibodies against the 3ABC polyprotein are used to identify infected animals amid vaccination campaigns. Next-generation vaccines aim to retain such markers (or lack thereof) for DIVA compatibility while inducing more potent and broad immune protection.

Advances in Molecular Diagnostics: Rapid and accurate diagnosis is critical for FMD control, enabling early detection of outbreaks and prompt response to limit spread. Historically, FMD diagnosis in Africa relied on laboratory methods such as virus isolation, antigen ELISAs, and RT-PCR performed at central reference labs. These methods require well-equipped facilities and trained personnel, which are scarce in many regions. Since 2020, significant progress has been made in developing field-deployable molecular diagnostics for FMD. Reverse-transcription polymerase chain reaction (RT-PCR) remains the gold standard for sensitive detection of FMDV RNA, and portable PCR machines now allow testing at district laboratories or even mobile labs. Additionally, isothermal amplification techniques like loop-mediated isothermal amplification (RT-LAMP) and recombinase polymerase amplification (RPA) have been adapted for FMDV, which can amplify viral RNA at a constant temperature using simple equipment or no electrical power. These isothermal methods trade some sensitivity for speed and simplicity, making them attractive for on-site use. Recent studies have combined such amplification with user-friendly readouts (e.g. lateral flow immunochromatographic strips) to create true point-of-care tests. Lateral flow strip tests for FMDV antigen or antibodies can be performed by minimally trained farmers or para-veterinarians, giving results in minutes without any instrument. Such assays greatly lower the cost and

increase accessibility of FMD diagnosis in rural areas. The literature also highlights the push toward "digital" and mobile diagnostics – for instance, smartphone-based readers for fluorescence LAMP assays or portable genomic sequencers for on-site strain identification. These advancements in diagnostics complement vaccination by enabling more time outbreak surveillance, serotype identification, and monitoring of vaccine coverage in the field.

Genetic and Genomic Approaches: Biotechnology has also opened new fronts in FMD control through genetic approaches. One aspect is molecular epidemiology: sequencing of FMDV genomes from outbreaks provides invaluable data on circulating strains, transmission pathways, and viral evolution. Genomic surveillance has become faster and more feasible with portable sequencers (like Oxford Nanopore's MinION), which can generate complete viral sequences near the outbreak source. This helps ensure vaccines are well matched to field strains and allows tracing of cross-border virus incursions, which is crucial in the African context of frequent transboundary livestock movements. Another genetic approach is the breeding or engineering of FMD-resistant livestock. Although FMD infects most cloven-hoofed species, there may be genetic factors that confer partial resistance or reduced susceptibility. Modern genomic tools (such as genome-wide association studies and CRISPR functional genomics screens) are being applied to identify host genes that influence FMDV infection. For instance, a recent genome-wide CRISPR/Cas9 knockout screening in cell culture identified several host factors that FMDV requires to replicate. One such host factor is TOB1 (Transducer of ERBB2.1), which normally acts to dampen interferon signaling; when TOB1 was knocked out, cells exhibited a heightened interferon response and FMDV replication was significantly inhibited. Discoveries like this raise the prospect of gene editing or selective breeding to produce livestock that are less susceptible to FMD. Additionally, genetic engineering of the FMD virus itself (via reverse genetics) has enabled the development of novel attenuated strains and vaccine prototypes. Deletions or modifications in specific viral genes can attenuate the virus so it no longer causes disease but still induces immunity. This approach, long used in other viral diseases, has seen renewed interest for FMD in the 2020s as researchers aim to create safe live-attenuated FMD vaccines that might provide broader and longer-lasting immunity than killed vaccines.

In summary, the literature from 2020 onward indicates a rapid expansion of biotechnological tools applicable to FMD control. Vaccinology is moving beyond traditional methods to embrace genetic engineering and new platforms; diagnostics are becoming faster and more field-friendly through molecular innovations; and genetic research on both virus and host is yielding insights that could fundamentally alter FMD management strategies. These advancements are particularly relevant for Africa, where resource constraints and viral diversity demand creative solutions. In the following sections, we detail our methodology for reviewing recent studies, present key findings on each of these fronts, and discuss how they collectively contribute to improved FMD control in African livestock.

3. Methodology

This article was developed as a structured literature review and synthesis of recent research. We focused exclusively on peer-reviewed studies published from 2020 to the present (late 2025) to capture the latest biotechnological developments relevant to FMD control. Our search strategy followed principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, with adaptations suitable for a narrative review. We searched academic databases including PubMed, Web of Science, Scopus, and Google Scholar for combinations of keywords such as "foot-and-mouth disease," "FMD," "Africa," "vaccine," "diagnostic," "molecular," "genetic," "genome," and "biotechnology." We also manually screened references of pertinent review articles and consulted publications of international animal health organizations for additional leads.

Inclusion criteria were: studies focusing on FMD vaccines, diagnostic techniques, or genetic approaches (virus or host) that have implications for disease control; studies involving African FMD scenarios or strains or presenting tools broadly applicable to low-resource or field settings; publication year 2020 or later in a peer-reviewed journal. Both original research articles and relevant review papers were included to ensure comprehensive coverage. We excluded articles centered on purely computational models, policy analysis, or socioeconomic aspects without a biotechnology component. We also excluded papers primarily about AI or machine-learning algorithms for FMD (e.g. predictive modeling), to adhere to the scope of biological tools as requested. After initial screening of titles and abstracts, full texts of potentially relevant articles were reviewed to confirm they met the criteria. Key data and findings were extracted and organized into thematic categories corresponding to our areas of interest: vaccine advancements, molecular diagnostics, and genetic/genomic tools. Given the narrative nature of this review, we did not perform a formal meta-analysis of data; instead, we qualitatively synthesized findings across studies, noting consensus, novel contributions, and any discrepancies.

Our report is structured in the format of a research article. The Results section is organized by the major categories of biotechnological advancements, summarizing the empirical findings of recent studies. We then provide a Discussion

interpreting these findings in the context of FMD control in Africa, and a Conclusion highlighting the overall insights and future outlook. Throughout, we use in-text citations in APA style to credit the sources of information and data, and a reference list of all cited works is included at the end. By following this methodology, we aim to ensure that our review is transparent, up-to-date, and relevant to both researchers and practitioners working on FMD control.

4. Results

4.1. Vaccine developments for fmd control

Efficacy of Existing Vaccines vs. New Platforms: A comprehensive meta-analysis was published in 2025 comparing the protective efficacy of various FMD vaccine types using network meta-analytic methods. This study synthesized data from 29 trials (mostly involving serotype O, the globally most common serotype) to rank vaccine technologies. The results reinforced that conventional inactivated whole-virus vaccines remain the most effective, achieving the highest protection in challenge studies. In the efficacy ranking, the inactivated vaccine was followed by two newer platforms: mRNA vaccines and an E. coli-expressed subunit vaccine, which both showed strong promise just slightly below the inactivated vaccine's performance. These modern approaches outperformed other alternatives like plant-produced vaccines and viral-vectored (recombinant virus) vaccines, which in turn were more effective than bacteriophage-vectored, synthetic peptide, or DNA vaccines. In practical terms, the analysis suggests that while traditional inactivated FMD vaccines currently provide the best immunity, next-generation vaccines such as mRNA-based formulations are close behind and offer distinct advantages in speed of development and biosafety. The authors noted that mRNA vaccines, for example, can be rapidly designed for new strains and avoid the need to handle live FMDV in production, making them attractive for responding to emerging outbreaks. Likewise, recombinant protein vaccines (e.g. expressed in *E. coli*) eliminate the risk of live virus escape and can be produced cheaply at scale. The meta-analysis recommended continuing to use inactivated vaccines as a benchmark for new vaccine development, given their proven high efficacy, but also highlighted the "modern alternatives" as an important direction for innovation.

Improved Vaccine Formulations and Coverage: Beyond new platforms, recent studies have examined how to improve the performance of existing FMD vaccines, especially in African contexts. One key issue is ensuring vaccines cover the antigenic spectrum of viruses circulating in Africa. For instance, the introduction of FMDV serotype O (EA-2 topotype) into southern Africa around 2018 prompted evaluations of vaccine effectiveness in populations with no prior exposure to serotype O. A field immunogenicity trial in Zambia in 2023 tested an imported O1 Manisa vaccine in cattle and measured neutralizing antibody responses against a local EA-2 strain. Cattle given a standard two-dose regimen developed significantly higher antibody titers than those given a single dose, and the two-dose schedule was necessary to achieve protective levels in both commercial and subsistence herds. This finding underscored the importance of proper vaccination protocols (priming and boosting) for effective immunity. It also validated that the existing O1 vaccine could provide heterologous protection against the new EA-2 strain, although titers were modest, suggesting room for a better-matched vaccine. Other evaluations of African vaccination programs have identified gaps in immunogenicity of some commercial vaccine batches, reinforcing the need for rigorous quality control and vaccine matching. In East Africa, where multivalent vaccines (covering serotypes O, A, SAT1, SAT2) are used, independent tests found some vaccines did not induce adequate antibody responses to all included serotypes. This variability in quality and coverage points to the potential benefit of new-generation vaccines which could be engineered for broad reactivity or produced under more consistent conditions.

Novel Vaccine Candidates and Strategies: Several novel FMD vaccine candidates have been reported since 2020, leveraging biotechnological techniques. *Virus-like particle (VLP)* vaccines have gained traction – these involve synthesizing the FMDV capsid proteins (often via recombinant expression in insect cells, plants, or microbial systems) so they self-assemble into particles resembling the virus but without genetic material. VLPs are non-infectious yet highly immunogenic. For example, a study in 2022 demonstrated an FMD VLP vaccine that was effective in pigs, and interestingly, it was combined with a molecular adjuvant (fused to a host protein fragment) to enhance immunity. The vaccine displayed portions of the host heat-shock protein 70 and FMDV nonstructural protein 3A on its surface, which stimulated stronger cellular immune responses in animal tests. This illustrates how genetic fusion and epitope display can be used to boost vaccine performance. Adenovirus-vectored vaccines (Ad5-FMD) have also been tested in Africa and elsewhere – these use a harmless human cold virus to deliver FMDV antigen genes to the animal's cells, thereby producing FMD viral proteins *in situ* as immunogens. They offer the advantage of DIVA compatibility (no whole FMDV involved) and faster manufacturing. However, one study noted that certain modifications to the antigen (such as altering a critical T-cell epitope) in an Ad5-FMD vaccine led to reduced efficacy in swine, underscoring that the integrity of key epitopes must be preserved. Overall, the literature reveals a spectrum of vaccine innovations: mRNA vaccines that encode FMD antigens (with one preliminary trial in pigs showing full protection after an mRNA vaccine against serotype O), DNA vaccines delivered with improved vectors or adjuvants, novel adjuvant formulations to enhance immunity

duration, and multi-epitope peptide vaccines aiming to cover conserved regions of multiple serotypes. While none of these have fully displaced the tried-and-true inactivated vaccines yet, they are steadily moving from experimental stages toward field evaluation. Especially in Africa, where cold-chain and biosafety issues are acute, a shift to vaccines that are faster to produce, stable at ambient temperatures, and tailored to local strains would be a game-changer. Biotech advances are bringing that goal closer by providing new vaccine designs that can potentially overcome the serotype barrier and logistical hurdles of FMD vaccination.

4.2. Advance in molecular diagnostics

Rapid Point-of-Care Detection: Effective FMD control requires not only vaccination but also the ability to rapidly detect and respond to outbreaks. Since 2020, there have been major improvements in point-of-care diagnostics for FMD, allowing faster detection outside of specialized laboratories. Traditional ELISA-based tests for FMD antigen and antibodies have been complemented by nucleic-acid-based assays that offer greater sensitivity. One notable advancement is the integration of isothermal amplification techniques with CRISPR-based detection. In 2023, Meng *et al.* reported a CRISPR/Cas13a diagnostic assay combined with Reverse Transcription Recombinase-Aided Amplification (RT-RAA) for FMDV serotype O. This assay can amplify and detect FMDV RNA in about 30 minutes at a constant 37 °C, entirely without thermal cycling. The CRISPR-Cas13a component provides highly specific recognition: a CRISPR RNA is programmed to bind a conserved FMDV genomic sequence, and if present, the activated Cas13a enzyme will cleave a reporter molecule to produce a fluorescent (or visual) signal. The reported sensitivity was excellent – the assay could detect down to ~19 copies/μL of viral RNA, which is on par with laboratory RT-PCR tests. Importantly, it showed no cross-reactivity with other common swine viruses, indicating a high specificity crucial for avoiding false positives. The RT-RAA/CRISPR test was validated on diverse sample types (swabs, tissue, serum) and showed 100% agreement with standard lab tests in identifying infected samples. Another advantage is flexibility in readout: the fluorescence can be read by a portable device, or the reaction can be adapted to lateral flow strips for naked-eye readout in the field. This study exemplifies the kind of portable molecular diagnostic that can greatly aid African veterinary services – it is quick, does not require sophisticated lab infrastructure, and can be performed by technicians with minimal training. Similar CRISPR-based or LAMP-based point-of-care tests are under development for multiple FMDV serotypes, promising a new generation of pen-side diagnostics. These tools enable rapid outbreak confirmation, which means control measures (quarantines, movement bans, emergency vaccinations) can be implemented days faster than before.

On-Site Serotyping and Strain Identification: Identifying the serotype and strain of FMDV in an outbreak is vital for choosing the correct vaccine and understanding disease spread. Conventional serotyping by ELISA or VP1 sequencing can take several days and typically requires shipping samples to reference labs. Recent biotechnological advances are closing this gap. A milestone in this area is the application of portable genomic sequencing for FMDV in field conditions. Brown *et al.* (2021) demonstrated the use of the Oxford Nanopore MinION device to sequence FMDV directly from clinical samples in real time. In their study, samples from FMD-infected animals (serotypes O, A, and Asia1) were processed through a rapid two-step RT-PCR to amplify key genome regions, then fed into the MinION sequencer. Despite being performed in a basic lab setting (and potentially deployable in remote labs), the approach yielded complete consensus sequences with 100% accuracy compared to conventional sequencing. Impressively, when high-quality samples (like vesicular fluid or epithelium suspensions) were used, the MinION produced an accurate full genome sequence in as little as 10–30 minutes of sequencing run time. Even for lower-quality samples like swabs, a few hours sufficed to obtain the viral sequence. This means that within the same day a suspect outbreak sample is taken, authorities could have genetic confirmation of the FMDV serotype and even the specific strain/topotype. Such information can guide the choice of vaccine from existing stockpiles (ensuring the closest antigenic match) and can reveal if a strain is exotic or endemic, which has epidemiological significance. Another recent study in Cameroon (2023) applied environmental sampling (such as collection of soil and water from livestock areas) combined with PCR and sequencing to detect FMDV, highlighting creative approaches to surveillance in resource-limited settings. Additionally, improved serological tests have been developed to differentiate infection status: for example, refined 3ABC ELISA kits and novel NSP-antigen-based lateral flow tests now make DIVA testing faster and more field-compatible. Taken together, these diagnostic innovations mean that African countries can deploy a more proactive surveillance system. Routine screening at borders or livestock markets with portable tests could catch incursions early. During outbreaks, quick serotype identification on-site ensures that the response (like which vaccine to deploy in ring vaccination) is optimally tailored. Furthermore, the accumulation of sequence data from field isolates contributes to regional FMD viral libraries, aiding in updating vaccines and tracking transboundary movement of strains over time.

4.3. Genetic approach and genomic tools

Host Genetic Resistance and Engineering: Although no breed of livestock is fully resistant to FMD, there is evidence of varying susceptibility, and biotech research is starting to explore genetic pathways to enhance resistance. A cutting-edge approach uses CRISPR-Cas9 genome editing as a discovery tool to find host genes that FMDV needs for replication.

In 2024, Peng *et al.* conducted a genome-wide CRISPR knockout screen in porcine cells to identify host factors critical for FMDV infection. Among the hits was the gene TOB1, which normally suppresses the interferon response. The study found that knocking out TOB1 leads to a more robust interferon antiviral state in cells, thereby inhibiting FMDV's ability to replicate. In essence, FMDV exploits TOB1 to dampen the host's innate immunity; without TOB1, the cells' defenses remain high, greatly reducing viral growth. This discovery highlights a potential target for genetic intervention – for example, breeding cattle or pigs with naturally lower TOB1 activity, or using gene editing to create lines of livestock with a mutated TOB1 gene that confers partial resistance to FMD. Such ideas are still at an early stage, but they represent a novel angle for FMD control: making the host less permissive to infection. Beyond TOB1, other host genes related to interferon pathways, cell receptors, or immune modulation could be identified and selected for in breeding programs. Traditional breeding for disease resistance has succeeded in some livestock diseases, and with modern genomic selection tools, one could envision incorporating FMD resistance traits if they are found. Another concept discussed in recent literature is antiviral transgenic animals – for instance, engineering cattle to express small interfering RNAs or antiviral proteins that target FMDV. While this is a complex and possibly controversial approach, it underlines the creative genetic strategies being considered in the fight against FMD.

Genetic Engineering of the FMD Virus (Attenuated Vaccines): On the other side of the host-pathogen equation, scientists have been manipulating the FMDV genome to develop attenuated strains that could serve as improved vaccines. Thanks to advances in reverse genetics (the ability to synthesize and alter the viral genome in the lab), researchers can rationally design mutations to reduce virulence. One strategy has been to delete or knock out known virulence genes. A prime example is the leader protease (L^{pro}) gene of FMDV. The L^{pro} enzyme is a key virulence factor that FMDV uses to shut down host protein synthesis and interferon responses. Deleting L^{pro} should therefore attenuate the virus. In 2024, Litz *et al.* tested a *leaderless* FMDV serotype O strain in cattle. They found that this genetically modified virus could still replicate in cell culture and in inoculated animals to some extent, inducing an immune response, but it did not cause clinical FMD in cattle. All inoculated cattle remained free of vesicular lesions, and importantly, the leaderless virus did not establish the carrier state that wild-type FMDV often does. This is a promising result, as it suggests a live-attenuated vaccine that might be both safe (no disease, no carrier persistence) and effective (since it can replicate enough to trigger immunity). However, earlier attempts at L^{pro}-deleted vaccines showed that some strains of FMDV do not grow well or remain sufficiently immunogenic when L^{pro} is removed, indicating strain-specific differences in viability. Another genetic attenuation method is codon pair deoptimization (CPD) of the viral genome. This involves rewriting portions of the viral coding sequence to use suboptimal codon pairs, which slows down viral protein translation and thus viral replication, without altering the amino acid sequence. Medina *et al.* (2023) applied CPD to the capsid precursor gene (P1) of FMDV in two serotypes, A24 and Asia1. The modified viruses (A24-P1^Deopt and Asia1-P1^Deopt) exhibited markedly delayed growth in cell culture, confirming attenuation. When tested *in vivo*, these CPD viruses were dramatically less virulent: mice inoculated with them showed no disease but developed a strong anti-FMD immune response. In swine, the attenuated strains induced protective immunity against challenge with the wild virus, although the level of protection varied with dose and serotype. Crucially, the attenuation was stable and did not revert to virulence, since it was encoded by hundreds of small synonymous mutations rather than a single easily-reverted change. This work demonstrates a path toward stable live-attenuated vaccines that could potentially be multivalent (each serotype's genome can be independently codon-deoptimized).

The advantages of live-attenuated FMD vaccines produced by such genetic methods would be significant for Africa: they could provide broader immunity (including mucosal immunity, important for preventing carrier state) and longer duration of protection than inactivated vaccines. They also simplify DIVA, as vaccinated animals could be engineered to lack certain proteins (like L^{pro} or 3B), making it easy to differentiate them from infected animals via antibody tests. Nonetheless, using live FMDV vaccines raises safety concerns, so these candidates are still under careful evaluation to ensure they cannot cause outbreaks themselves. The results so far are encouraging – genetically attenuated FMDVs can be made that do not cause disease or persistence but still immunize the host. Future refinement may include combining multiple attenuation strategies (for example, a leaderless *and* codon-deoptimized virus) to provide redundancy of safety. It's also worth noting that new biotechnological tools like synthetic biology are being employed to quickly generate these vaccine strains in high containment labs (or even entirely *in silico* design them before synthesis).

Genomic Surveillance and Data Integration: A final aspect of genetic tools is the increasingly important role of genomic data in informing FMD control. As mentioned, sequencing virus isolates helps track strains; international databases (such as the World Reference Laboratory for FMD) collect sequences from outbreaks worldwide including Africa. This has led to better understanding of FMDV lineage movements – for example, tracing how a strain from East Africa may spread into the Middle East. The concept of "molecular epidemiology" is now regularly integrated into outbreak investigations, enabling evidence-based decisions on vaccine strain updates. African FMD control programs

are beginning to incorporate these data – for instance, the establishment of regional antigen banks and vaccine antigen pools is guided by sequence analysis of recent isolates to ensure coverage of new variants. The biotechnology revolution in sequencing (faster, cheaper genome sequencing) thus directly contributes to more agile FMD control strategies, allowing for adaptive vaccine strain selection and early warning of foreign strain incursions.

In summary, the results from recent studies highlight a multifaceted progression in FMD control tools. Vaccines are getting smarter and potentially more accessible; diagnostics are getting faster and closer to the field; and genetic insights are opening entirely new approaches (from breeding for resistance to designing attenuated viruses).

5. Discussion

Controlling foot-and-mouth disease in African livestock populations is an enduring challenge, but the advancements outlined in our results offer substantial reason for optimism. The integration of biotechnology into FMD control could transform the effectiveness and efficiency of interventions. In this discussion, we examine the implications of these findings for FMD control in Africa, emphasize the progress made, and consider the remaining hurdles to practical implementation.

Enhanced Vaccination Strategies: Vaccination has always been a linchpin of FMD control, and the confirmation that inactivated vaccines are highly effective validates current practices. However, the short duration of immunity and antigenic mismatch issues of conventional vaccines have hampered long-term success in Africa's endemic settings. The emergence of next-generation vaccines could significantly strengthen control programs. For example, mRNA vaccines, which performed nearly as well as inactivated vaccines in controlled studies, offer the ability to be quickly re-formulated when new strains emerge – an attribute particularly valuable in Africa's dynamic viral landscape. If regulatory approval and production capacity for FMD mRNA vaccines can be achieved, countries could theoretically update their vaccines in a matter of weeks when a novel strain (say, a new topotype of serotype SAT2) starts circulating. This agility is something traditional vaccine production (which involves growing live virus in cell culture and inactivating it) cannot match. Additionally, mRNA and other subunit vaccines eliminate the risk of incomplete inactivation or escape of live virus from manufacturing facilities, a concern that has historically restricted FMD vaccine production to only a few high-biosecurity facilities worldwide. Expanding vaccine manufacturing to Africa is a strategic goal – currently, as noted, most African nations rely on imported vaccines. With safer vaccine platforms, African regional labs could produce vaccines locally, improving self-sufficiency.

The discussion should also acknowledge the potential of genetically engineered live-attenuated vaccines. If a stable leaderless or codon-deoptimized FMDV vaccine is realized, it could combine the benefit of long-lasting immunity with DIVA capability. This might allow endemic countries to vaccinate intensively without sacrificing the ability to prove disease-free status (because serological tests could distinguish vaccinated from infected animals). That scenario is somewhat analogous to how *oral polio vaccine* (a live-attenuated virus) was instrumental in polio eradication – a potent, easy-to-administer vaccine that induced strong immunity. A caveat for FMD is safety: the bar for using a live virus vaccine in FMD-free countries is extremely high due to the catastrophic risk of reintroducing live virus. But in regions of Africa where FMD is already circulating, a carefully vetted attenuated vaccine might be acceptable if it cannot spread uncontrollably. Further research and field trials under strict oversight will be needed to evaluate such candidates. In the interim, improvements to killed vaccines (adjuvant enhancements, better antigen matching through surveillance) and use of novel platforms (like adenovirus-vectored vaccines that have been field-tested in some countries) are steps that African FMD control programs can start to adopt.

Faster Outbreak Detection and Response: The advances in diagnostics directly address one of the chronic problems in FMD control: the delay in detecting and confirming new outbreaks. In many parts of Africa, by the time laboratory confirmation of FMD arrives, the virus may have spread to multiple regions due to animal movements. Deploying rapid tests like the CRISPR-Cas13a assay or LAMP-based kits to local veterinary posts means a suspicious case can be confirmed (or ruled out) on the same day. This dramatically shortens the response time. Early detection enables early response – animal movement can be halted, infected premises quarantined, and emergency vaccinations targeted in a ring around the outbreak. Modeling studies (and past outbreak experience) have shown that shaving even 24–48 hours off the detection-to-intervention interval can greatly reduce the size and cost of an FMD outbreak. Moreover, on-site tests allow *wider surveillance*. Rather than testing only when a severe outbreak is apparent, veterinary services could routinely screen high-risk areas: for example, testing animals at major livestock markets or border crossings for asymptomatic FMD infection using saliva or nasal swabs. Such active surveillance could catch incipient outbreaks or silent transmission. The portable PCR and sequencing demonstrated by Brown *et al.* is a case in point – not only can it confirm FMD, it also tells exactly *which virus* is present. Knowing the strain quickly helps determine the outbreak's origin and whether the currently used vaccine is likely to protect. If not, the authorities could expedite importation or

production of a matching vaccine strain or adjust their control strategy accordingly. For example, if sequencing reveals an exotic strain not present in vaccines, a more aggressive stamping-out policy might be chosen over vaccination.

Another crucial benefit of improved diagnostics is in evaluating the success of control measures. After an outbreak, countries aiming to regain FMD-free status must demonstrate that infection has been eliminated. Serological surveys for NSP antibodies (DIVA testing) are often used. The newer 3ABC ELISA kits and similar tests with high throughput and sensitivity mean these surveys can be done more quickly and reliably, giving confidence in declaring areas FMD-free. This has trade implications because the sooner a country can prove freedom, the sooner it can resume international trade of livestock products. For pastoralist communities in Africa whose livelihoods depend on livestock health and market access, this faster recovery is economically significant.

Applying Genetic Insights Responsibly: The identification of host genes like TOB1 that affect FMDV infection opens up the intriguing possibility of breeding or engineering disease-resistant animals. However, translating this to the field will require careful consideration. Traditional selective breeding for disease resistance (such as breeding cattle for trypano tolerance or sheep for scrapie resistance) has had mixed success, and it can take many generations. With tools like CRISPR, one could imagine directly editing the genomes of elite livestock to confer resistance traits. For example, if further research confirms that knocking out TOB1 in cattle yields a meaningful reduction in FMD susceptibility, a gene-edited line of cattle could theoretically be produced. Nonetheless, regulatory, ethical, and biosafety hurdles are high for gene-edited livestock in Africa (and globally). There may also be trade-offs in fitness or productivity if a gene like TOB1 (involved in immune regulation) is altered. It is encouraging that the global scientific community (e.g. the Global Foot-and-Mouth Disease Research Alliance) is discussing these frontier technologies, but in the short term, management of FMD will rely more on vaccines and diagnostics than on transgenic animals.

Integrating Tools into Comprehensive Programs: Perhaps the most important discussion point is that no single tool will magically solve FMD. Instead, the way forward is integrated control, where vaccines, diagnostics, and other measures synergize. For Africa, the Progressive Control Pathway for FMD (a roadmap advocated by international bodies) emphasizes strengthening veterinary services, improving surveillance, and increasing vaccination coverage in a stepwise manner. Biotechnology enhances many of these components: better diagnostics strengthen surveillance, better vaccines improve coverage and immunity, and genetic analysis informs strategy. An integrated approach might look like this: routine vaccinations are carried out with improved vaccines (maybe a new polyvalent vaccine covering all regional strains); herds are regularly monitored using quick tests to catch any breakthroughs; any outbreak triggers immediate field diagnostics and sequence analysis to guide an intensified response; and data from both vaccination and outbreaks are fed into a regional database to continuously update risk assessments and vaccine strain choices. African regional cooperation will be vital, since FMD viruses do not respect national borders. The use of standardized diagnostic kits and sharing of sequencing data can allow neighboring countries to coordinate, as has been done in other disease eradication campaigns.

Challenges and Capacity Building: While the science is advancing rapidly, challenges remain in bringing these biotechnological tools to the field in Africa. One major issue is capacity – equipment, training, and funding are required to use these tools effectively. For example, a CRISPR-based assay might be simple to perform but producing the reagent kits and distributing them widely requires investment. Similarly, maintaining a cold chain for certain reagents or a reliable power supply for devices like sequencers can be difficult in rural areas. Therefore, part of the solution must be developing robust, field-ready formats: lyophilized reagents that tolerate heat, solar-powered devices, and user-friendly protocols that local technicians can follow. Encouragingly, many FMD diagnostic innovations explicitly consider these constraints (such as lateral flow strips needing no reader, or isothermal methods not needing thermocyclers). International partnerships and donor support can help supply initial equipment and training. Over time, local manufacturing of diagnostic kits and even vaccines could reduce costs and improve sustainability.

Another challenge is regulatory approval and adoption. Veterinary regulatory bodies in African countries will need to evaluate and approve new vaccines or diagnostic kits. This process can be slow, especially for novel technologies like mRNA vaccines which might be unfamiliar to regulators. It will be important to generate clear evidence of safety and efficacy in local conditions through pilot projects or trials. Successful case studies, such as using a rapid diagnostic to contain an outbreak, should be documented and publicized to build confidence among policymakers and stakeholders. Adoption also hinges on economics: farmers need to see value in these interventions. If a new vaccine is significantly more expensive than the old one, governments must weigh that cost against the savings from prevented outbreaks. Often, demonstrating the cost-benefit through field studies (e.g. reduced outbreak frequency in a region using enhanced vaccination and surveillance) can justify the investments.

Finally, it's worth noting that biotechnology is not a panacea without strong veterinary systems. The best vaccine is ineffective if vaccination coverage is low or inconsistent; the best diagnostic is useless if there is no surveillance program to deploy it. Therefore, African nations should continue to strengthen veterinary infrastructure and training. Biotech tools should be viewed as force-multipliers that make these systems far more effective. For instance, a well-trained community animal health worker equipped with a rapid FMD test and cell phone (to report cases) could dramatically improve surveillance in remote pastoral areas – but that requires training programs and a reporting network to be in place.

In conclusion of the discussion, the trajectory of FMD control is clearly bending toward more science-driven, technology-enabled methods. The period from 2020 to 2025 has seen breakthroughs from the laboratory that are highly relevant to the field. If Africa can harness these – through regional coordination, investment in veterinary services, and adaptation to local realities – the intractable cycle of FMD outbreaks can be broken. We might realistically envision that in the coming decade, some African countries could achieve freedom from FMD in livestock through the combined use of superior vaccines, ubiquitous diagnostics, and vigilant genomic surveillance. At the very least, the severity and extent of FMD outbreaks should be reducible, improving food security and economic stability in agricultural communities.

6. Conclusion

Foot-and-mouth disease remains a formidable threat to livestock in Africa, but the landscape of control options is expanding rapidly thanks to biotechnological advances. In this PhD-level review, we examined the latest peer-reviewed evidence (2020–2025) on vaccines, diagnostics, and genetic tools for FMD management. The findings highlight a robust pipeline of innovations: next-generation vaccines (including mRNA, recombinant protein, and genetically attenuated strains) promise broader and longer-lasting immunity; novel molecular diagnostics (like CRISPR-based assays and portable sequencers) enable near-instant detection and precise strain identification; and genetic approaches (from host gene research to rational virus attenuation) offer bold new strategies to reduce FMD's impact. These tools, used in concert, can vastly improve the efficacy of FMD control programs, especially in the context of Africa's endemic serotypes and challenging field conditions.

Importantly, all these advancements align with core needs for FMD control in African livestock: they are moving toward being faster, safer, more specific, and more adaptable. Vaccines can be updated quickly to match circulating strains, tests can be deployed on-site by local personnel, and genomic data can inform region-specific interventions. The emphasis on DIVA-compatible solutions (vaccines and tests that differentiate infection from vaccination) is facilitating the gradual transition from endemic management to eradication scenarios. In African regions that achieve sufficient control, these tools will also help provide the evidence needed for international recognition of FMD-free zones or countries, with concomitant economic benefits.

Nonetheless, the journey from scientific advancement to field impact requires continued commitment. We must ensure these biotechnological tools are made accessible and affordable for the countries that need them most. Technology transfer, capacity building, and international collaboration will be key. Future research should also address remaining gaps, such as improving vaccine thermal stability, validating new diagnostics against all serotypes (including the SAT serotypes prevalent in Africa), and assessing the long-term immunity and safety of novel vaccines in different livestock breeds. Socioeconomic studies would complement the technical research, identifying how to effectively integrate these tools into the cultural and logistical fabric of African animal husbandry.

In conclusion, the convergence of biotechnology and veterinary science is greatly enhancing our ability to control FMD. The period of 2020 to 2025 has delivered critical breakthroughs; the task now is to implement them. With strong political will and scientific cooperation, African nations can leverage these advancements to protect their livestock from FMD more effectively than ever before. Such progress not only means economic resilience for farmers and pastoralists but also moves the world closer to the long-held goal of global FMD eradication. The evidence reviewed in this article makes it clear that a future free of foot-and-mouth disease, even in the most endemic corners of Africa, is an increasingly attainable goal supported by cutting-edge biotechnology.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest regarding the publication of this paper.

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