Review

What to Expect from Brazil as a Nation Certified as Free from Foot-and-Mouth Disease (FMD) without Vaccination

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Abstract: Achieving Foot-and-Mouth Disease (FMD)-free status without vaccination marks a significant milestone for Brazil, a major agricultural powerhouse with extensive cattle herds and vast borders. This certification represents not only a scientific and logistical achievement but also an opportunity for enhanced market access and strengthened biosecurity. However, transitioning to this status involves challenges, including maintaining stringent monitoring and surveillance, managing porous border regions, and mitigating risks from neighboring regions with varying FMD statuses. This review explores the expectations surrounding Brazil's new status, including anticipated economic benefits, the influence on Brazil's international trade position, and the role of sustainable disease management practices. We also discuss potential risks, such as accidental reintroduction and surveillance gaps, which could impact livestock health and trade dynamics. With a focus on effective biosecurity, regional cooperation, and advanced diagnostic capabilities, Brazil's journey to maintaining FMD-free status highlights both the opportunities and complexities of disease control in a nation deeply reliant on its agricultural sector. This status demands ongoing surveillance to support Brazil's agricultural economy and ensure long-term health security for its livestock industries.

Keywords: biosecurity; surveillance; economic impact; livestock health; border management; trade; disease control

1. Introduction

Brazil's agricultural sector, a powerhouse within the nation's economy, stands at a pivotal juncture with the anticipated certification as free from foot-and-mouth disease (FMD) without vaccination. This status is more than just a marker of disease eradication; it signifies Brazil's commitment to elevating animal health standards, strengthening biosecurity measures, and positioning itself as a premier supplier in the global livestock trade. With agriculture and livestock activities comprising nearly a quarter of Brazil's Gross Domestic Product (GDP), achieving FMD-free status without vaccination offers a strategic advantage that aligns with the country's economic priorities and international trade ambitions [1].

The foot-and-mouth disease virus, which affects cloven-hoofed animals such as cattle, pigs, sheep, and goats, poses serious economic and health risks for livestock-dependent economies. For decades, Brazil has maintained a robust FMD vaccination program to control and mitigate the spread of the disease. The widespread use of vaccination has allowed the country to prevent large-scale outbreaks and safeguard the health of its livestock population. However, transitioning to a vaccination-free status reflects a new phase in Brazil's animal health strategy—a step that requires rigorous disease control and monitoring, but one that promises significant rewards [2].

The strategic rationale behind pursuing FMD-free certification without vaccination is grounded in the economic and trade benefits that such a status confers. International markets, particularly in

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regions like North America, Europe, and parts of Asia, have strict import requirements for livestock and animal products. These markets frequently impose trade restrictions on countries that use FMD vaccination, due to concerns over the virus potentially entering their borders through vaccinated animals. By achieving FMD-free certification without vaccination, Brazil gains access to these high-value markets, enabling the country's livestock producers to command higher prices and enter trading partnerships that were previously out of reach. This expanded market access not only enhances Brazil's export potential but also stimulates growth within the livestock industry, creating a positive ripple effect across the rural economy and strengthening the financial foundation of small-scale producers and large agribusinesses alike [3].

However, achieving and maintaining an FMD-free status without vaccination brings with it a set of complex challenges. Brazil's expansive geography—spanning over 8.5 million square kilometers—includes a range of diverse climates and ecosystems, from tropical rainforests in the Amazon to arid plains in the Northeast. Monitoring and controlling animal health across this vast terrain is inherently challenging, as regions with limited infrastructure or access present logistical hurdles in implementing consistent disease surveillance. Moreover, Brazil shares borders with several countries, some of which continue to manage active FMD cases. These porous borders represent a constant threat, as animals and people moving across these regions increase the risk of FMD transmission into Brazilian territory [4].

Further complicating the challenge is the need for significant investment in biosecurity infrastructure, personnel training, and public awareness campaigns. To maintain an FMD-free status without vaccination, Brazil will need to deploy cutting-edge technology and engage in continuous surveillance, ensuring that any suspected cases are quickly identified, isolated, and addressed. This endeavor requires robust collaboration between the public and private sectors, as well as the cooperation of local communities and livestock owners, who play an essential role in adhering to biosecurity protocols. Government agencies, agricultural associations, and veterinary professionals must work in unison to reinforce biosecurity practices that limit the potential for disease reintroduction [5].

The potential rewards of this certification are as compelling as the challenges. As Brazil positions itself as a leading global supplier of FMD-free livestock products, it will likely see an increase in export revenue, job creation in rural areas, and overall sector growth that benefits communities nationwide. Additionally, the status reinforces Brazil's credibility and influence in the international agricultural community, potentially setting a precedent for other large agricultural nations with similar geographic and economic profiles [6]. In this document, we will explore the expectations, challenges, risks, and monitoring requirements associated with Brazil's certification as FMD-free without vaccination. We will also examine the economic gains anticipated from this status, particularly in terms of export growth, market access, and rural development. Ultimately, Brazil's journey to FMD-free certification reflects not only a significant milestone in animal health but also a transformative step toward a more resilient and globally competitive agricultural sector.

2. Expectations for Brazil as an FMD-Free Country Without Vaccination

In summary, achieving FMD-free status without vaccination is expected to bring a range of positive outcomes for Brazil, both domestically and internationally. Economic gains through increased market access, strengthened biosecurity infrastructure, heightened global competitiveness, rural development incentives, and improved industry standards are just a few of the anticipated benefits. Additionally, the status reinforces Brazil's role as a leader in the global agricultural community, enhancing its diplomatic influence and creating new opportunities for partnerships. However, these expectations hinge on Brazil's ability to maintain rigorous disease surveillance and response systems, highlighting the importance of ongoing investment in biosecurity and a commitment to high standards in animal health [5,6].

2.1. Economic and Trade Benefits

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One of the most immediate and anticipated benefits of achieving FMD-free status without vaccination is enhanced access to premium global markets. Countries that do not vaccinate against FMD are generally considered safer trading partners, as they present a lower perceived risk of FMD transmission. Many high-value markets, including those in North America, Europe, and parts of Asia, maintain strict import regulations that restrict the entry of animal products from countries still reliant on FMD vaccination. Achieving FMD-free status without vaccination will enable Brazil to overcome these trade barriers, thus allowing it to export livestock products to regions that have been previously inaccessible or limited by regulatory constraints [7].

With expanded access to premium markets, Brazilian livestock producers are expected to experience an increase in export volumes and prices. The demand for high-quality meat products is growing in countries with strict biosecurity standards, and these markets are often willing to pay a premium for products from FMD-free regions. By reaching these high-value markets, Brazil can secure higher profit margins for its meat products, which will ultimately strengthen the country's position as a leading global supplier. Additionally, FMD-free status may facilitate Brazil's entry into niche markets for specific animal products, such as organic or premium cuts, which are particularly attractive to health-conscious and high-income consumers [8].

The economic impact of FMD-free status is also expected to have a ripple effect across Brazil's rural economy. Higher demand and better prices for livestock products will likely increase revenue for farmers and ranchers, stimulating growth and investment in rural areas. This may lead to job creation, improved infrastructure, and enhanced access to services in these regions. For Brazil, where rural communities often rely on livestock farming as a primary source of income, the socio-economic benefits of FMD-free status are substantial and may contribute to reduced poverty and improved quality of life in rural regions [7,8].

2.2. Strengthened Biosecurity and Surveillance Systems

Achieving and maintaining FMD-free status without vaccination requires a sophisticated biosecurity infrastructure to monitor and control potential outbreaks. One expectation associated with this new status is the establishment of enhanced surveillance systems, which will include real-time monitoring, data analysis, and rapid response mechanisms. Brazil will need to adopt cutting-edge technologies, such as geographic information systems (GIS), remote sensing, and artificial intelligence (AI), to ensure comprehensive coverage and timely detection of any signs of FMD [9].

This shift toward more advanced biosecurity practices will not only help Brazil maintain its FMD-free status but will also set a new standard in animal health management. The establishment of these systems represents a long-term investment in Brazil's agricultural infrastructure, which will benefit the country beyond FMD control. Effective biosecurity measures reduce the risk of other transboundary animal diseases, contributing to a more resilient livestock sector overall. Moreover, improved disease surveillance enhances Brazil's readiness to respond to emerging infectious diseases, aligning with the global trend toward proactive disease prevention and control in the context of One Health—a multidisciplinary approach that emphasizes the interconnection between human, animal, and environmental health [10].

2.3. Increased Competitiveness in the Global Market

As Brazil attains FMD-free status without vaccination, its competitiveness in the global livestock market is expected to strengthen significantly. This new status aligns with international standards of animal health, allowing Brazil to meet the stringent requirements set by organizations such as the World Organisation for Animal Health (OIE) and the Food and Agriculture Organization (FAO). Compliance with these standards demonstrates Brazil's commitment to high-quality production, making it a more attractive trading partner to countries that prioritize biosecurity and food safety [11].

Increased competitiveness also translates to greater leverage in trade negotiations. As one of the largest meat producers in the world, Brazil holds a prominent position in global trade, and FMD-free certification without vaccination enhances this position. This status not only boosts Brazil's credibility

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but also grants it stronger bargaining power when negotiating trade agreements with countries that impose strict health standards. Brazil can leverage its FMD-free status as a unique selling point, differentiating itself from competitors who continue to rely on vaccination and thereby increasing its influence in setting international standards and policies related to animal health and trade [12].

2.4. Incentives for Rural Development and Industry Standards

Another key expectation for Brazil's FMD-free certification without vaccination is the positive impact it will have on rural development. The livestock sector is deeply interconnected with Brazil's rural economy, supporting millions of jobs and providing a foundation for rural livelihoods. As demand for Brazilian meat products grows in new markets, the financial benefits will extend to rural communities, creating opportunities for small and medium-sized producers to expand their operations and invest in better facilities, training, and technology [13].

The government and private sector are expected to implement new initiatives to support rural development in light of the increased demand for FMD-free livestock products. These initiatives may include grants, subsidies, and training programs aimed at helping farmers adopt biosecurity measures, improve animal health management, and enhance productivity. In addition, there may be a focus on creating a more integrated supply chain, encouraging collaboration between producers, processors, and exporters to maintain high-quality standards and increase efficiency [11].

Achieving FMD-free status without vaccination also sets a precedent for industry standards in animal health. To preserve this status, livestock producers will need to adhere to strict biosecurity and disease prevention protocols. Over time, these practices are likely to become ingrained In Brazil's livestock industry, raising the bar for animal welfare, environmental sustainability, and production quality. By establishing a culture of high standards, Brazil can further differentiate itself as a source of premium livestock products and build long-term resilience against future disease threats [12,13].

2.5. Implications for Brazil's International Standing and Agricultural Diplomacy

As one of the largest agricultural exporters in the world, Brazil's journey to FMD-free status without vaccination carries significant diplomatic weight. This certification reinforces Brazil's reputation as a responsible and reliable participant in the global agricultural community. By demonstrating its ability to control and prevent FMD without vaccination, Brazil solidifies its role as a leader in animal health management, particularly among emerging economies and countries with similar geographic and agricultural profiles [13,14].

Brazil's FMD-free status without vaccination is expected to enhance its soft power and influence in international agricultural organizations, trade groups, and forums focused on animal health and food security. This status can serve as a model for other nations facing similar challenges, as Brazil's success may inspire other large agricultural countries to pursue disease eradication through improved biosecurity and surveillance instead of relying solely on vaccination. As a result, Brazil may play a more active role in shaping policies, promoting best practices, and advocating for the integration of One Health principles at the global level [11,15].

In addition, Brazil's FMD-free status could open doors for international partnerships and collaborations. Countries and organizations with advanced biosecurity expertise may be more inclined to work with Brazil on initiatives related to disease control, trade facilitation, and sustainable agricultural development. These partnerships can support knowledge exchange, capacity building, and technology transfer, ultimately contributing to Brazil's long-term agricultural resilience and international standing [12,16].

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3. Challenges in Achieving and Maintaining FMD-Free Status Without Vaccination

Achieving FMD-free status without vaccination represents a formidable goal for any country, but Brazil's unique geographic, economic, and agricultural profile adds additional layers of complexity. Transitioning to and sustaining this status requires a high level of biosecurity, a unified approach across vast and diverse regions, and effective management of cross-border risks. Each of these elements presents its own set of challenges, as outlined below. Brazil faces a complex set of challenges in achieving and maintaining FMD-free status without vaccination. Geographic and logistical constraints, cross-border risks, economic pressures on producers, and the need for sustained political and social support are all critical factors that must be addressed. Building a robust biosecurity infrastructure, fostering public trust, and ensuring rapid response capabilities are essential to safeguarding Brazil's livestock industry and realizing the long-term benefits of FMD-free status. Overcoming these challenges will require coordinated efforts from government agencies, the private sector, and international partners to ensure that Brazil remains resilient against FMD and upholds its place as a global leader in agriculture [17,18].

3.1. Geographic and Logistical Constraints

Brazil is one of the largest countries in the world, with a land area that spans multiple biomes and climates. The diversity and vastness of Brazil's landscape create significant logistical challenges for disease monitoring, animal movement control, and overall biosecurity. The country's livestock industry is spread across numerous regions, from the highly developed agribusiness sectors in the south to the more remote and less accessible areas in the Amazon Basin. The size and layout of the country make it difficult to establish a cohesive and comprehensive surveillance network. Monitoring animal health across Brazil's rural and often isolated areas requires substantial resources and infrastructure, including veterinary staff, transportation, and communication systems. Additionally, rural regions may lack the resources to maintain the high standards of biosecurity needed for FMD-free status without vaccination. These challenges highlight the need for innovative solutions, such as mobile veterinary units and remote monitoring technologies, to address the country's unique geographic demands [11-13].

3.2. Cross-Border Disease Risks

One of the most significant challenges Brazil faces in achieving FMD-free status without vaccination is the risk of FMD introduction from neighboring countries. Brazil shares borders with several countries, including Venezuela, Bolivia, and Paraguay, where FMD outbreaks have been reported in recent years. Cross-border movement of animals, people, and goods increases the likelihood of FMD introduction, posing a constant threat to Brazil's FMD-free aspirations.To address these cross-border risks, Brazil will need to collaborate closely with neighboring countries on joint disease surveillance, information sharing, and coordinated response efforts. However, achieving such coordination is challenging, as neighboring countries may have varying levels of resources, infrastructure, and commitment to FMD eradication. Additionally, the political and economic dynamics in neighboring countries can affect the continuity and reliability of cross-border biosecurity efforts. For example, economic or political instability can lead to lax enforcement of biosecurity measures or an increase in informal trade, further increasing the risk of FMD spread [19,20].

3.3. Building and Maintaining Comprehensive Biosecurity Infrastructure

Achieving and maintaining FMD-free status without vaccination demands a sophisticated biosecurity infrastructure capable of rapid disease detection, monitoring, and containment. While Brazil has made significant strides in recent years, transitioning to an FMD-free status without the protective buffer of vaccination requires a further enhancement of existing biosecurity systems. This entails investing in technologies and facilities to facilitate real-time disease tracking, routine testing, and emergency response capabilities. Implementing these systems across Brazil's vast territory poses logistical and financial challenges. A key concern is ensuring consistent and timely data collection

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from all regions, including remote and under-resourced areas. Additionally, maintaining biosecurity infrastructure requires continuous funding and skilled personnel. Training veterinarians, farmers, and livestock handlers in biosecurity protocols is essential, but it can be difficult to achieve consistent knowledge and practices across the entire livestock sector. Without sustained financial and logistical support, there is a risk that biosecurity infrastructure could deteriorate over time, leaving Brazil vulnerable to potential FMD outbreaks [21,22].

3.4. Economic Pressures on Livestock Producers

Transitioning to FMD-free status without vaccination places economic pressures on livestock producers, particularly small and medium-sized farmers who rely on vaccination as an affordable disease management tool. Phasing out vaccination may create initial uncertainties for producers, who may worry about the increased risk of FMD reintroduction and the potential financial losses that could result from an outbreak. Additionally, the cost of complying with enhanced biosecurity protocols—such as implementing on-farm disease prevention measures, constructing secure animal holding areas, and conducting regular health screenings—may strain the resources of smaller producers. To address these concerns, the government and industry associations may need to offer financial support and incentives to help producers adapt to the new standards. However, balancing economic support for producers with the need for stringent biosecurity practices is a delicate task. If economic pressures are not adequately managed, some producers may resist the transition or be forced to leave the industry, which could disrupt Brazil's livestock supply chain and impact rural economies [11,23].

3.5. Social and Cultural Challenges

The shift away from vaccination in Brazil also involves social and cultural adjustments among livestock producers, veterinarians, and local communities. For decades, vaccination has been the primary method of FMD prevention, and it is a well-established practice in the country's livestock industry. Transitioning to a no-vaccination policy requires a shift in mindset, where all stakeholders recognize the importance of rigorous biosecurity and surveillance as the new standards for disease prevention.Educating producers and other stakeholders about the benefits and necessity of achieving FMD-free status without vaccination is essential. Resistance to change may stem from a lack of understanding of the economic advantages or concerns about the risks involved. Addressing these concerns requires clear and consistent communication from government agencies, veterinary associations, and industry leaders. Public education campaigns, training programs, and workshops can help raise awareness and ensure that producers are well-informed and equipped to comply with the new standards. The government must work to build trust among producers, emphasizing that this transition will ultimately benefit the industry and the country's economy [12,24].

3.6. Ensuring Political and Institutional Support

Achieving and maintaining FMD-free status without vaccination is a long-term commitment that requires strong political and institutional support. This effort demands sustained funding, policy continuity, and consistent enforcement of biosecurity regulations. Changes in political leadership or economic priorities can impact the availability of resources and the level of institutional commitment to FMD eradication efforts. For example, shifts in budget allocations or policy changes could affect funding for surveillance programs, disease control measures, and biosecurity infrastructure. Ensuring political and institutional support requires close collaboration between federal, state, and local governments, as well as engagement with the private sector and international organizations. The government must prioritize FMD-free status as a national objective, integrating it into broader agricultural and economic policies. Additionally, political leaders and institutions must work to build public and industry consensus on the benefits of FMD-free certification, reinforcing the importance of this goal for Brazil's agricultural future [13,22].

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3.7. Risk of Disease Reintroduction and the Need for Rapid Response

Once vaccination is phased out, Brazil will face an increased risk of FMD reintroduction. Without the buffer of vaccination, any introduction of the virus into Brazil's livestock population could lead to a rapid spread, resulting in severe economic and trade impacts. As such, Brazil must be prepared to respond to potential outbreaks with urgency and efficiency. Establishing a rapid-response system that includes quarantine measures, culling of infected animals, and immediate containment protocols is essential to minimize the risk of widespread transmission. The success of such a system depends on timely communication, coordination between agencies, and availability of resources. Delays or gaps in response could have devastating consequences for Brazil's livestock industry and its FMD-free status. Ensuring that all regions have access to emergency response resources, including trained personnel, quarantine facilities, and testing laboratories, is crucial. Additionally, Brazil must be prepared to conduct regular drills and simulations to test the effectiveness of its response protocols and make necessary adjustments based on emerging threats [25,22,13].

4. Risks and Potential Setbacks in Achieving FMD-Free Status Without Vaccination

Transitioning to FMD-free status without vaccination brings significant potential for economic growth, expanded trade, and biosecurity advancements for Brazil. However, this path is not without risks and potential setbacks. The success of this endeavor depends on Brazil's ability to mitigate a range of risks, including disease reintroduction, economic vulnerabilities, public resistance, and challenges in regulatory compliance. Addressing these risks proactively is crucial to safeguarding the long-term benefits of FMD-free status. Achieving FMD-free status without vaccination offers substantial benefits for Brazil, but the journey is fraught with risks and potential setbacks. The country faces challenges related to disease reintroduction, economic vulnerabilities, biosecurity compliance, and emergency response readiness. Addressing these risks requires a comprehensive and proactive approach, including investments in biosecurity infrastructure, support for livestock producers, regulatory enforcement, and emergency preparedness. By anticipating and mitigating these potential setbacks, Brazil can strengthen its ability to sustain FMD-free status and secure the long-term benefits of this achievement for its livestock sector and economy [12,26].

4.1. Risk of Disease Reintroduction and Outbreaks

One of the most critical risks in achieving FMD-free status without vaccination is the potential reintroduction of the FMD virus into Brazil's livestock population. Without the protective buffer provided by vaccination, any entry of the virus could spread rapidly and lead to large-scale outbreaks. This is particularly concerning given Brazil's proximity to neighboring countries where FMD outbreaks have occurred in recent years. Cross-border movement of animals, people, and goods increases the likelihood of FMD reintroduction, especially in border regions with less stringent biosecurity measures. An outbreak of FMD would have devastating consequences for Brazil's livestock industry and economy. The country would face trade restrictions, decreased consumer confidence, and potential economic losses in the billions of dollars due to livestock mortality, decreased productivity, and the costs associated with containment and eradication measures. To minimize the risk of reintroduction, Brazil must maintain strict quarantine protocols at borders, invest in cross-border disease monitoring, and implement rapid response measures in high-risk areas [13,22].

4.2. Economic Vulnerability to Trade Disruptions

Achieving FMD-free status without vaccination is expected to enhance Brazil's access to premium global markets, yet it also exposes the country to new economic risks. An FMD outbreak in a country with FMD-free status can lead to severe trade restrictions, with importing countries suspending meat exports from affected regions. Such trade disruptions would directly impact Brazil's livestock producers, particularly those who rely on export markets for revenue. For a country

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with a substantial agricultural export sector, the risk of trade disruptions due to FMD reintroduction represents a significant economic vulnerability. In the event of an outbreak, Brazil would face additional costs associated with containment measures, compensation to affected farmers, and the restoration of trade relations. This risk underscores the importance of diversifying export markets and establishing contingency plans, including insurance mechanisms, to protect producers and stabilize the market in case of trade suspensions. The government may also consider setting up emergency funds to support producers in the event of an outbreak, which would help mitigate economic losses and provide a safety net for the livestock sector [27,28].

4.3. Biosecurity and Surveillance Gaps

While biosecurity and surveillance systems are essential for maintaining FMD-free status, gaps in these systems pose a considerable risk to Brazil's livestock industry. Comprehensive biosecurity requires regular disease monitoring, data collection, and strict enforcement of disease prevention measures. However, Brazil's vast territory and diverse livestock production systems present challenges in achieving uniform biosecurity standards. Remote or underserved areas, where veterinary services and surveillance infrastructure may be limited, are particularly vulnerable to lapses in biosecurity. Additionally, maintaining rigorous surveillance and biosecurity measures requires substantial funding and resources. Inconsistent or inadequate funding can lead to weakened disease monitoring and response capacity, increasing the risk of undetected FMD transmission. For Brazil to effectively mitigate biosecurity risks, it must invest consistently in disease surveillance, particularly in high-risk areas near borders or in regions with dense livestock populations. Enhancing biosecurity infrastructure in remote areas, training personnel, and leveraging technology for remote monitoring are essential strategies to address these vulnerabilities [29,30].

4.4. Potential Resistance from Livestock Producers

Transitioning to FMD-free status without vaccination also carries the risk of resistance from livestock producers, particularly small and medium-sized farmers who may view vaccination as an affordable and reliable form of disease prevention. Removing the option of vaccination may create uncertainty among producers who are concerned about the increased risk of FMD and the economic impact of a potential outbreak. Additionally, compliance with strict biosecurity protocols can be costly and time-consuming, placing an additional burden on producers who are already operating on limited margins. Public resistance to the no-vaccination policy may also be influenced by cultural factors, as vaccination has been the primary FMD prevention method for decades. Some producers may question the necessity of the transition or be unwilling to adopt new practices due to perceived risks. Overcoming this resistance requires effective communication, education, and support from government agencies, industry associations, and veterinary professionals. Providing financial incentives, technical assistance, and training programs can help producers adapt to the new standards and foster a sense of collective responsibility for maintaining Brazil's FMD-free status [31,32].

4.5. Weaknesses in Emergency Preparedness and Rapid Response

Achieving and maintaining FMD-free status without vaccination increases the need for a robust emergency preparedness and rapid response system. Any delay in detecting or responding to an FMD outbreak could have severe consequences, as the virus can spread rapidly through livestock populations. An effective response system requires trained personnel, quarantine facilities, diagnostic laboratories, and efficient communication channels. However, weaknesses in these areas, particularly in remote or rural regions, pose a risk to Brazil's ability to contain potential outbreaks. A critical aspect of emergency preparedness is conducting regular simulation exercises to test and refine response protocols. Without these drills, response teams may face challenges in coordinating containment efforts, leading to delays and increased transmission risk. Furthermore, resource constraints, bureaucratic hurdles, or lack of coordination among government agencies and industry

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stakeholders can impede the effectiveness of Brazil's rapid response system. Strengthening emergency preparedness involves continuous training, investment in infrastructure, and ensuring that response protocols are clear, adaptable, and well-communicated across all levels [33,34].

4.6. Regulatory Compliance and Enforcement Challenges

Strict regulatory compliance is necessary to maintain FMD-free status, as any lapse in enforcement of biosecurity measures could increase the risk of FMD transmission. Ensuring compliance across Brazil's extensive livestock sector, which includes a range of production systems and regions, is a complex task. Smallholders and informal livestock operators, in particular, may lack the resources or awareness needed to fully comply with biosecurity regulations. Additionally, enforcing regulations in remote or underserved areas can be difficult due to limited personnel and logistical challenges. Failure to enforce biosecurity standards uniformly can create weak points in Brazil's disease prevention framework, potentially allowing FMD to spread within the country. To mitigate this risk, the government must allocate resources for consistent inspection, compliance monitoring, and enforcement. Providing support and resources to smallholders, conducting outreach programs, and establishing penalties for non-compliance are key strategies to address regulatory challenges and strengthen Brazil's overall biosecurity compliance [12,13,22].

4.7. International Pressure and Reputational Risks

As Brazil works to achieve and maintain FMD-free status without vaccination, it will face scrutiny from international markets, trading partners, and organizations like the World Organization for Animal Health (OIE). Any lapses in biosecurity or outbreaks of FMD could damage Brazil's reputation and lead to increased scrutiny or restrictions from trading partners. Such reputational risks have implications beyond FMD, as they can impact Brazil's broader agricultural exports and its standing in the global agricultural community. Brazil may also face pressure from international stakeholders to maintain high standards and provide regular documentation of its FMD-free status. Failing to meet these expectations could result in trade restrictions or reputational damage that affects Brazil's position as a reliable supplier of agricultural products. To mitigate these risks, Brazil must demonstrate transparency, accountability, and consistency in its disease prevention and monitoring efforts. Proactively engaging with international organizations, providing regular updates on its FMD-free status, and participating in international initiatives related to animal health can help Brazil maintain its reputation and address any concerns from the global community [12,13,22].

5. Monitoring and Surveillance Requirements for Maintaining FMD-Free Status Without Vaccination

Achieving and maintaining an FMD-free status without vaccination requires Brazil to implement a robust and comprehensive monitoring and surveillance system. Such a system is essential for early detection of FMD cases, rapid containment of potential outbreaks, and continuous assessment of disease risks across the country. Surveillance must be meticulous and consistent, particularly as Brazil transitions away from vaccination, which had previously served as a safeguard against FMD. To meet international standards and protect the health of its livestock population, Brazil must establish a multifaceted surveillance framework encompassing field monitoring, diagnostic testing, data management, and collaboration with both domestic and international partners. By investing in a comprehensive surveillance network, strengthening diagnostic capacity, and fostering collaboration at both national and international levels, Brazil can ensure that its livestock sector remains resilient against FMD risks. Vigilant monitoring and proactive risk management are essential to protecting Brazil's livestock industry and reinforcing the country's reputation as a reliable and safe source of agricultural products [35,36].

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5.1. Establishing a National Surveillance Network

An effective FMD surveillance system in Brazil begins with the establishment of a coordinated national network that enables real-time disease tracking and rapid response capabilities. Given Brazil's extensive size and diverse agricultural landscape, this network must be comprehensive, covering all regions, including remote and underserved areas. Veterinary services, local health agencies, and agricultural extension offices should work together to create a web of interconnected monitoring points that can quickly report any suspicious cases of FMD. Key elements of this surveillance network include: A). Regular inspections of livestock: routine health checks and monitoring in high-density livestock areas are crucial for early disease detection. Veterinary teams should be trained to recognize the clinical signs of FMD and to report cases promptly. B). Mobile veterinary units for remote areas: given Brazil's vast and often inaccessible regions, mobile units can provide veterinary care and surveillance in areas that lack permanent veterinary infrastructure. C). Outreach programs for smallholders: engaging smallholders, who may have limited access to veterinary services, ensures that disease surveillance reaches all segments of the livestock population. Outreach initiatives can educate smallholders on FMD symptoms, biosecurity practices, and reporting mechanisms [37,38].

5.2. Diagnostic Testing Protocols

Accurate and timely diagnosis is essential for confirming FMD cases and distinguishing them from other diseases with similar symptoms. Brazil's surveillance system must incorporate advanced diagnostic testing protocols that are capable of detecting FMD virus with high sensitivity and specificity. This requires establishing a network of diagnostic laboratories equipped with the necessary technology, skilled personnel, and standardized procedures for FMD testing. The main diagnostic approaches include: A). Polymerase Chain Reaction (PCR): PCR testing is one of the most reliable methods for detecting FMD virus, as it can identify viral RNA in various samples, including blood, saliva, and tissue. PCR's high sensitivity makes it suitable for early detection, especially in asymptomatic animals or during the initial stages of an outbreak. B). Serological Testing: to detect antibodies against FMD, serological testing is essential for identifying animals that have been previously exposed to the virus. While Brazil transitions to a no-vaccination status, serological testing remains crucial for understanding disease exposure patterns and monitoring immunity levels in the livestock population. C). On-Site Rapid Tests: rapid diagnostic tests, while less accurate than laboratory-based methods, can be used in field conditions to provide preliminary results within minutes. Such tests are particularly valuable for initial screening in remote areas where laboratory access may be limited [39,40].

By combining these diagnostic approaches, Brazil can create a layered testing system that allows for immediate field screening, followed by confirmation through laboratory diagnostics. This tiered strategy ensures that FMD cases are identified quickly and accurately, minimizing the risk of undetected spread [12,22].

5.3. Data Integration and Disease Tracking Systems

Efficient data integration and disease tracking are critical for Brazil's FMD monitoring system. Disease data must be collected, analyzed, and disseminated rapidly across all levels, from local veterinary offices to national authorities. To achieve this, Brazil should implement an integrated digital platform that consolidates data from different regions and sources, including diagnostic results, field reports, and livestock movement records [41].

A well-designed data management system enables: A). Real-time tracking of disease trends: an integrated platform allows authorities to monitor the geographic spread of FMD and assess potential hotspots, enabling timely intervention in high-risk areas. B). Data-driven decision-making: centralized data collection enables government agencies to analyze trends, identify vulnerable regions, and allocate resources effectively. Predictive analytics can also be used to assess the probability of outbreaks based on historical patterns and environmental factors. C). Public

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transparency: providing transparent access to disease data fosters trust among producers, consumers, and international partners. Regularly published reports on FMD status reassure stakeholders that Brazil is actively managing its disease risks [42].

Investment in digital infrastructure, including mobile applications for remote data entry, GPS-based tracking of livestock movements, and machine learning algorithms for outbreak prediction, can significantly enhance Brazil's ability to monitor and respond to FMD risks in real-time [12].

5.4. Border Surveillance and Cross-Border Cooperation

Given Brazil's shared borders with countries where FMD outbreaks have occurred, border surveillance is a high priority in the overall monitoring framework. Effective border surveillance involves rigorous control measures at entry points, quarantine facilities, and collaboration with neighboring countries to track livestock movements and share disease data. Key measures for border surveillance include: A). Quarantine and inspection at entry points: livestock entering Brazil must undergo thorough inspections and, if necessary, quarantine to ensure they are FMD-free. Border inspection stations need to be equipped with diagnostic tools to identify FMD cases before animals enter the country. B). Movement restrictions and checkpoints: in regions with high cross-border traffic, Brazil can establish checkpoints to control animal movements and enforce biosecurity standards. C). Cross-border agreements and joint surveillance efforts: Brazil should collaborate with neighboring countries to establish joint surveillance programs, share data, and harmonize biosecurity measures. By working together, Brazil and its neighbors can create a buffer against FMD transmission, reducing the risk of cross-border outbreaks [43,44].

5.5. Training and Capacity Building

Maintaining a skilled workforce is essential for effective FMD monitoring and surveillance. Brazil must ensure that veterinarians, livestock handlers, and other relevant personnel are trained in disease recognition, biosecurity protocols, and data reporting. Continuous training programs not only improve the capacity of local veterinary services but also help standardize FMD monitoring practices across the country. Capacity-building initiatives may include: A). Workshops and certification programs: regular workshops for veterinarians, farmers, and border inspection staff provide ongoing education on FMD recognition, diagnostic procedures, and biosecurity measures. B). Simulations and drills: conducting mock FMD outbreak simulations allows authorities to test and refine their response protocols. These drills can highlight areas for improvement in the surveillance and response system, ensuring that teams are prepared for real-world scenarios. C). Collaboration with academic institutions: partnering with universities and research institutes can help Brazil stay updated on advancements in FMD surveillance technologies and practices. Academic collaborations can also provide a pipeline of trained veterinarians and epidemiologists to support Brazil's monitoring efforts [45,46].

5.6. Community Engagement and Farmer Education

The success of FMD surveillance in Brazil relies on the active participation of the farming community. Livestock producers play a vital role in disease detection, as they are often the first to notice signs of illness. Engaging and educating farmers on the importance of FMD surveillance encourages timely reporting and adherence to biosecurity measures. Community engagement efforts can include: A). Educational campaigns: informing farmers about the risks of FMD, the benefits of FMD-free status, and their role in disease prevention fosters a sense of shared responsibility. Government agencies can distribute informational materials, hold community meetings, and use social media to reach a wide audience. B). Reporting hotlines and mobile apps: establishing a user-friendly reporting system allows farmers to report suspected FMD cases quickly. Mobile applications or hotlines can make the reporting process accessible, even in remote areas. C). Incentive programs: offering incentives, such as compensation for reported cases or recognition for biosecurity

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compliance, can encourage farmers to participate actively in surveillance efforts. Such programs reinforce the importance of timely disease reporting for the entire livestock sector [12,22,41].

5.7. Regular Audits and International Collaboration

Regular audits of Brazil's FMD surveillance system ensure compliance with international standards and demonstrate Brazil's commitment to maintaining FMD-free status. Independent audits, whether conducted by national agencies or international bodies like the World Organization for Animal Health (OIE), can identify weaknesses in the surveillance system and provide recommendations for improvement. Additionally, international collaboration with countries that have already achieved FMD-free status without vaccination offers valuable insights and best practices. International partnerships can include: A). Technical assistance from OIE and FAO: collaborating with organizations such as the OIE and the Food and Agriculture Organization (FAO) allows Brazil to access technical expertise, capacity-building resources, and financial support for surveillance improvements. B). Knowledge exchange programs: learning from countries with established FMD-free status, such as the United States and Australia, helps Brazil adopt proven strategies for disease prevention and monitoring. C). Participation in regional disease control networks: Brazil can join regional networks focused on animal health to share information, coordinate disease control efforts, and receive support during emergency situations [12,19,22,24].

6. Long-Term Outlook and Sustainability

The long-term outlook for Brazil as an FMD-free country without vaccination is both promising and demanding, requiring sustained commitment, strategic planning, and continuous investment in animal health and biosecurity measures. Achieving FMD-free status without vaccination signifies a significant milestone for Brazil's livestock industry, underscoring its potential to bolster economic growth, open new international markets, and enhance Brazil's role as a global agricultural leader. However, sustaining this status will involve addressing complex, evolving challenges, especially given Brazil's size, diverse ecosystems, and extensive borders with countries still combating FMD [13,18].

6.1. The Path to Sustaining FMD-Free Status

Maintaining FMD-free status without vaccination requires a proactive approach that anticipates and mitigates future risks. This will involve Brazil investing in animal health infrastructure, upgrading disease surveillance technologies, and consistently aligning with international standards. A primary focus should be on strengthening and modernizing its monitoring and response capabilities to ensure early detection of FMD and other emerging infectious diseases. Key priorities for sustaining FMD-free status include: A). Continued Surveillance and Innovation in Disease Monitoring: ongoing investment in advanced diagnostic tools, data integration systems, and real-time disease monitoring will be essential. Emerging technologies, such as machine learning for predictive disease modeling and the use of drones or satellite imaging for monitoring livestock movements, could add innovative layers of protection. B). Adaptability to Climate Change and Disease Evolution: climate change is expected to alter the epidemiological landscape of many infectious diseases, including FMD. As new environmental conditions emerge, Brazil will need to monitor changes in disease patterns closely and adapt its surveillance and biosecurity practices accordingly. Investing in research on how climate influences FMD transmission, as well as creating adaptable response plans, will be critical. C). Strengthening Veterinary Capacity and Infrastructure: to sustain FMD-free status, Brazil must continue to build a skilled and well-distributed veterinary workforce. Expanding training programs for veterinarians and livestock handlers, especially in remote areas, ensures rapid response to potential outbreaks and ongoing support for biosecurity measures across the livestock sector [11,18,22,42].

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6.2. Promoting International Collaboration and Knowledge Exchange

Brazil's position as an FMD-free country presents an opportunity for it to take a leadership role in regional and global disease control initiatives. By actively participating in international organizations such as the World Organization for Animal Health (OIE) and engaging in partnerships with neighboring countries, Brazil can help advance coordinated efforts to eradicate FMD regionally. Benefits of international collaboration include: A). Access to Resources and Expertise: through partnerships with organizations like OIE and the FAO, Brazil can access funding, technical assistance, and global knowledge resources. Collaboration with countries that have successfully maintained FMD-free status without vaccination can also provide insights into best practices and new technologies. B). Cross-Border Disease Control Initiatives: since Brazil shares borders with FMD-affected countries, cross-border cooperation is crucial for mitigating re-introduction risks. Joint surveillance programs, information sharing, and harmonization of biosecurity standards can reduce the likelihood of FMD transmission across borders. C). Leadership in Global Agricultural Standards: as Brazil solidifies its FMD-free status, it has the potential to influence and set standards for animal health in the region. By promoting best practices, Brazil can contribute to a healthier and more resilient livestock industry throughout South America [13,22,29,30].

6.3. Economic and Social Benefits of a Sustainable FMD-Free Status

Sustaining FMD-free status offers Brazil both immediate and long-term economic advantages. Over the coming years, maintaining this status could be transformative for Brazil's agricultural economy, benefiting not only large-scale producers but also smallholder farmers who rely on livestock for their livelihoods. Economic and social benefits include: A). Increased Access to High-Value Markets: as an FMD-free country, Brazil can command higher prices for its meat products in premium markets, including countries that restrict imports from FMD-affected regions. This access not only increases revenue for exporters but also contributes to Brazil's overall economic stability. B). Job Creation and Rural Development: as demand for Brazilian livestock products grows, so too will the need for a robust agricultural workforce. Sustainable FMD-free status can stimulate job creation in rural areas, from veterinary services to meat processing, contributing to rural development and poverty reduction. C). Improved Public Health and Food Security: an effective FMD surveillance and control system also reduces the risk of zoonotic disease transmission, promoting public health. By investing in animal health and biosecurity, Brazil can ensure a safer food supply chain, enhancing food security and resilience [31,32,44].

6.4. Building a Culture of Biosecurity and Sustainability

For Brazil to maintain FMD-free status over the long term, the culture of biosecurity must become deeply embedded across all levels of the livestock industry. This cultural shift requires a commitment from all stakeholders, including government agencies, producers, veterinarians, and consumers. Education and awareness campaigns play a crucial role in instilling a biosecurity-first mindset that prioritizes proactive disease prevention and rapid response. Actions to promote a biosecurity culture include: A). Continuous Education and Awareness Programs: providing regular training and resources to farmers, veterinarians, and community leaders helps keep biosecurity practices top-of-mind. Government agencies can use digital platforms, community meetings, and media campaigns to reinforce the importance of biosecurity. B). Incentive Programs for Compliance: rewarding producers who adhere to biosecurity standards can encourage widespread adoption. Financial incentives, certifications, and public recognition can motivate producers to take biosecurity measures seriously. C). Consumer Engagement: engaging consumers in biosecurity awareness fosters a sense of shared responsibility. As consumers become more informed about the benefits of FMD-free status, they may advocate for products that adhere to high animal health standards, further incentivizing producers to maintain rigorous biosecurity practices [36,45,46].

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6.5. Preparing for Future Risks and Building Resilience

Sustaining FMD-free status without vaccination is a dynamic challenge that will require Brazil to be resilient in the face of emerging threats. The country must be prepared to respond to potential crises, whether due to a resurgence of FMD, the emergence of new infectious diseases, or changing economic conditions. Flexibility and adaptability will be key to navigating these challenges while protecting the integrity of Brazil's FMD-free status. Future-focused resilience measures include: A). Establishing Emergency Response Plans: Brazil should develop and periodically update contingency plans for potential FMD outbreaks. Regular simulations and emergency drills help authorities, veterinary teams, and producers respond effectively to unexpected disease events. B). Investing in Disease Research and Surveillance Technologies: supporting research on FMD and related diseases, as well as investing in next-generation surveillance technologies, strengthens Brazil's capacity to stay ahead of potential threats. Innovative research on vaccine alternatives, diagnostics, and epidemiology can inform future strategies. C). Monitoring and Adapting to Global Trends: global trade, climate change, and other factors can shift the landscape of disease risk. By staying attuned to these trends, Brazil can adjust its FMD-free strategy to address emerging risks and maintain a competitive edge in the global market [13,22,33,44].

6.6. A Vision for Brazil's Agricultural Future

Brazil's FMD-free status without vaccination is not merely a disease control measure; it represents a broader vision for a thriving, resilient agricultural industry that meets the highest global standards. By securing and sustaining this status, Brazil positions itself as a leader in animal health, a trusted food supplier, and a key player in advancing agricultural sustainability. The road ahead requires continuous investment, strong partnerships, and a commitment to innovation. With the right combination of vigilance, adaptability, and resilience, Brazil's FMD-free status can be a foundation for long-term prosperity, providing lasting benefits to its livestock industry, rural communities, and overall economy. In this pursuit, Brazil has the opportunity not only to safeguard its agricultural assets but also to enhance food security, public health, and environmental sustainability, shaping a brighter future for generations to come [11,12,20,22,46].

7. Conclusions

Achieving and maintaining FMD-free status without vaccination is a historic accomplishment for Brazil, carrying profound implications for its agricultural sector and positioning within the global market. This certification highlights Brazil's commitment to rigorous biosecurity, enhanced disease surveillance, and sustainable livestock management practices. The transition to an FMD-free status is expected to increase international trade opportunities, reduce reliance on vaccination programs, and boost confidence among global trading partners, potentially leading to a higher economic return for Brazilian agribusiness.

However, this status also presents considerable challenges, particularly in managing the porous borders with neighboring countries where FMD may still be prevalent. Preventing outbreaks and controlling potential disease spread require robust and continuous monitoring systems, rapid diagnostic capabilities, and coordinated cross-border efforts. Furthermore, maintaining this certification will demand ongoing investment in veterinary infrastructure, personnel training, and biosecurity improvements to ensure that Brazil remains resilient against reintroduction risks.

In the long term, Brazil's success in preserving FMD-free status without vaccination could serve as a model for other nations facing similar challenges. If managed effectively, this status will solidify Brazil's position as a leader in animal health management while securing the sustainability and profitability of its livestock industries. The journey ahead will require steadfast commitment, but the rewards—both economic and health-related—hold substantial promise for Brazil's agricultural future.

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