Research Article

Beyond Vaccination: Integrated Biosecurity and Movement Control are Critical for FMD Management in a High-Risk Livestock Transit Area of Indonesia

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Abstract | This study investigated the Foot -and-Mouth Disease (FMD) in a high-risk livestock transit area, where rapid animal movement facilitates virus spread. Focusing on Kendal Regency, a key interprovincial corridor in Central Java, the study assessed transmission risk to smallholder farmers, evaluated vaccination effectiveness, and examined farmers' biosecurity awareness. A cross-sectional survey was conducted in several sub-districts of Kendal Regency, collecting serum from cattle with clinical FMD signs. A total of 242 samples were analyzed using ELISA to detect FMD antibodies, and 100 cattle were tested by rRT-PCR for active infection. Multiple linear regression analysis was conducted to assess the impact of vaccination on the reduction of FMD cases. Spatial analysis revealed that the 2022 FMD outbreak was concentrated in areas with high livestock movement, which likely facilitated disease transmission. The total number of cases declined markedly in 2023 ($p=0.14$). The first vaccination round in 2022 ($B = 1.75$, $p < 0.001$) and the first round in 2023 ($B = 0.17$, $p = 0.021$) had a significant positive effect on reducing FMD cases. The ELISA results showed 98.7% seropositivity for FMD virus serotype O, indicating strong post-vaccination immunity, and all rRT-PCR tests were negative, suggesting the absence of active viral circulation during surveillance. However, biosecurity remained weak: only 11% of farms displayed restricted-access signs, and 9% had isolation pens, revealing poor implementation. These findings indicate that vaccination drove the decline in FMD cases in livestock transit areas despite limited biosecurity; however, strengthening biosecurity in these areas remains essential for sustained prevention.

Keywords | Foot and mouth disease, Vaccination, Farmer awareness, Transit area, Biosecurity, Surveillance

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INTRODUCTION

Foot-and-mouth disease (FMD) in Indonesia was first documented in East Java Province in 1987 and was associated with the importation of dairy cattle from the Netherlands. Following a 36-year period of FMD-free status, the disease was reintroduced in East Java on May 2022. The FMD is a highly contagious transboundary animal disease caused by a virus genus Aphtovirus of the Picornaviridae family (Rahman *et al*., 2025), that has profound economic implications on the global livestock industry. In ruminant, transmission occurs predominantly through inhalation of aerosolized droplets, although alternative routes include fomites, birds, and contaminated feed with initial viral replication occurring in the respiratory tract, followed by systemic dissemination throughout

the host (Brown *et al*., 2022; Kerfua *et al*., 2023). The FMD infection in dairy cows resulted in decreased milk production up to 21%, hence adversely impacting farmers' income (Salsabilah *et al*., 2024).

The control of FMD remains a major concern in endemic regions such as Indonesia, particularly in livestock trade and transit areas where animal movement is intensive. Previous work on livestock transportation networks showed that livestock movement is one of the primary causes of disease dissemination (Moreno *et al*., 2023). In Indonesia, Java Island is the most populous region, comprises West, Central, and East Java. East and Central Java serve as major livestock production centers, while West Java hosts the national capital and several food processing industries, resulting in high demand for livestock products, particularly meat.

Human population density on Java island influences FMD transmission risk in livestock transit systems through several mechanisms beyond simply increasing demand for animal products. Dense human populations require continuous and large scale supply of meat and animal products. This leads to frequent livestock transport between farms, maekets, and slaughterhouses. Due to its geographical location, Central Java province frequently functions as a transit corridor for livestock transportation from East Java to West Java province. Substantial animal movement occurs, especially in the northern area of Kendal Regency (Figure 1), which is traversed by major toll roads connecting East and West Java, thereby increasing the risk of disease introduction and spread.

Figure 1: Location of study area.

Given that FMD can be transmitted via airborne particles and indirectly through contaminated vehicles and personnel, investigating its epidemiology in livestock transit regions is crucial. In addition, farmer awareness of biosecurity measures is essential in preventing the further outbreak of FMD.

The objective of this study was to assess FMD transmission risk in a livestock transit area, evaluate vaccination effectiveness, and analyze farmers' biosecurity awareness in Kendal Regency, Central Java, as the livestock transit area, including the assessment of the impact of vaccination on the reduction of FMD cases. The spatial distribution of FMD cases was analyzed in relation to livestock movement intensity to determine whether high-mobility areas were associated with increased incidence. The FMD infection in beef cattle was identified based on clinical signs and confirmed using real-time RT-PCR (rRT-PCR). In addition, the study assessed farmers' awareness and implementation of biosecurity measures to examine their role in outbreak occurrence.

This study hypothesizes that (1) high livestock mobility in the transit area of Kendal Regency facilitates the transmission of FMD, resulting in higher incidence in high-movement zones; (2) vaccination is associated with a significant reduction in FMD cases and increased seroprevalence; and (3) there is limited biosecurity awareness and poor compliance among farmers. The findings are expected to inform evidence-based FMD control strategies and policy formulation, contributing to reduced economic losses and improved disease management in Indonesia.

MATERIALS AND METHODS

Object and subject of research

Primary data in this study were obtained through several activities, including field visits to conduct direct observations of farms and livestock health conditions. In addition, interviews were carried out with farmers and relevant stakeholders to obtain information on biosecurity and vaccination practices. Secondary data were derived from reports and records of veterinary health officers in Kendal Regency, including data on disease distribution, vaccination programs, and the progression of FMD cases, as well as laboratory test results for post-vaccination FMD surveillance.

Research location and data collection

Data on FMD cases, outcomes, and vaccination were collected from all livestock areas in Kendal Regency. Laboratory testing was performed at the Wates Veterinary Center, Yogyakarta. Surveillance was conducted using ELISA and real-time PCR tests. Samples were collected from animals susceptible to transmission, particularly at livestock markets and from traders' (collectors') animals. Post-vaccination surveillance aimed to assess the immune response of livestock vaccinated against FMD (using blood serum samples) and to monitor the circulating virus during the vaccination period (using oral swab samples). A total of 242 serum samples and 100 oral swabs were collected from

clinically healthy and suspected cattle, out of 15,369 animals that had received either the first or second vaccination. The samples were sent to Wates Veterinary Center in Yogyakarta for serological and molecular testing to confirm the presence of FMD virus and to know the response post-vaccination.

The survey designed to assess the farmer's awareness of biosecurity uses a semi-structured interview with open-ended questions designed to elicit detailed recall of the initial wave of outbreaks in 2022 after Indonesia experienced the first FMD incursion until 2023. Questions were focused on existing and routine on-farm biosecurity protocols to provide background information regarding pre-outbreak practices and potential risks. The questionnaire was administered to 100 livestock farmers as respondents.

Farmers were selected using a purposive sampling approach in the livestock transit area of Kendal Regency, Central Java. The inclusion criteria were farmers who owned or managed cattle, had animals located in sub-districts reporting FMD cases, and were willing to participate in the study and provide informed consent. Only farmers with cattle showing clinical signs consistent with FMD or with documented exposure history were included in the sampling frame for laboratory testing. The exclusion criteria included farmers who did not keep cattle during the study period, those whose animals were not located within the defined transit-risk zones, and incomplete or unreliable survey responses or sample records.

Analysis method

This research is a case study conducted in Kendal Regency, Central Java Province, Indonesia. A case study is an empirical research method that examines a contemporary phenomenon in depth within its real-life context, particularly when the boundaries between the phenomenon and its context are not clearly defined. Therefore, this study is specifically focused on the Kendal Regency area.

Data analysis

The data in this study were analyzed statistically using IBM SPSS Statistics version 26.0. The analysis was conducted in several stages to ensure the validity of the relationships among variables. A paired sample t-test was employed to determine whether there was a significant difference in the number of FMD cases between 2022 and 2023. Furthermore, linear regression analysis was performed to evaluate the extent to which vaccination contributed to the reduction of FMD cases in Kendal Regency. Regression analysis was also conducted to examine the relationship between serological and virological results, as determined by ELISA and rRT-PCR, and the effectiveness of vaccination in reducing FMD cases in 2022 and 2023.

The data presented in Figures 3, 4 and 5 are distribution maps created using QGIS (version 3.x), allowing visualization of FMD case patterns, vaccination coverage, and high-risk areas across the districts. These distribution maps were then integrated into a dashboard to display multiple data layers, providing an overview of the operational impact of FMD on cattle farmers in Kendal Regency. In Figure 3, red color gradations represent cumulative FMD incidence per 100 animals, while in Figures 4 and 5, blue color gradations indicate vaccine coverage per 500 animals.

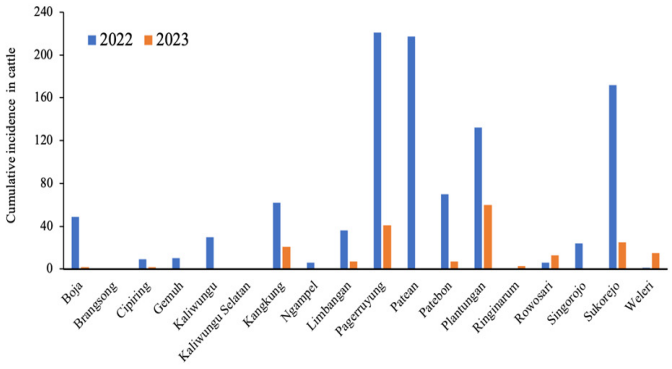

Figure 2: FMD cases at subdistrict level in Kendal Regency of Central Java Province.

RESULTS

Assessment of FMD infection and vaccination

The FMD outbreak in Kendal Regency (Figure 1), which lies along a major interprovincial transportation route, has been relatively high, particularly among large ruminants such as cattle. Figure 2 presents the number of cases by subdistrict in 2022 and 2023. Spatial distribution of Foot and Mouth Disease (FMD) cases in 2022 and 2023 are presented in Figure 3; whereas vaccination coverage in Kendal Regency in 2022 and 2023 for 1st and 2nd rounds are illustrated in Figures 4 and 5.

The outbreak began in May 2022 and lasted until December 2023, during which time several cattle exhibited symptoms consistent with FMD, including fever, lameness, excessive salivation, and oral vesicles. Affected cattle were primarily owned by smallholder farmers and traders who utilized temporary holding yards for short-term livestock transit. Spatial distribution mapping showed the FMD outbreak distributed across the Kendal regency. The total number of cases shown in Figure 2 declined markedly from 1,045 in 2022 to 196 in 2023 (p=0.14). The average number of FMD cases per sub-district in 2022 was 58 cases, whereas in 2023 the average decreased to 11 cases per subdistrict. This indicates an overall reduction of 81% in the average number of cases across all subdistricts. The results of the paired samples t-test comparing FMD outbreaks between 2022 and 2023 indicate a statistically significant difference between the two periods (Table 1). There was a statistically

Table 1: Paired samples T-Test results for FMD outbreaks in 2022 and 2023.

Parameters	Mean	Std. Error Mean	95% CI	t	p-value
Cumulative incidence in 2022 – Cumulative incidence in 2023	47.2	15.8	13.7 – 80.6	2.976	0.008

Table 2: The effect of each vaccination round on the reduction of FMD cases.

Variables	SE	Std. coefficients Beta	t	p-value
Vaccination 2022; Round 1	0.35	1.75	4.52	<0.001
Vaccination 2022; Round 2	0.49	-0.25	-0.74	0.47
Vaccination 2023; Round 1	0.53	0.17	0.88	0.021
Vaccination 2023; Round 2	0.06	-0.79	-2.57	0.39
Model summary	r = 0.944	R^2 = 0.892	SE=24.2	p <0.001

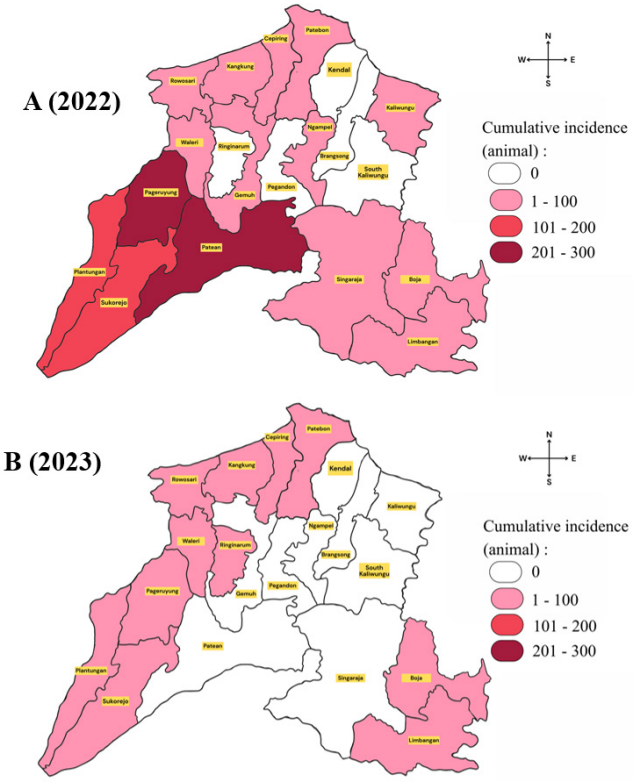

Figure 3: Cumulative incidence of FMD at subdistrict level in Kendal Regency of Central Java Province in (A) 2022 and (B) 2023.

significant reduction in cases from 2022 to 2023 (p = 0.008). The positive t-value (t = 2.976) indicates that the number of FMD cases in 2022 was substantially higher than in 2023.

Based on the spatial distribution across districts, FMD incidence in 2022 was notably high, particularly in the northern and west region of Kendal regency, where toll roads connecting East and West Java facilitate substantial animal movement and increase the risk of disease transmission (Figure 3A). In 2023, the spatial distribution of cases decreased considerably (Figure 3B), suggesting that control measures, particularly the two rounds of vaccination conducted in 2022 (Figure 4) and the two rounds carried out again in 2023 (Figure 5), were effective in limiting the spread of the disease. The emergency vaccination program in 2022 (Figure 4), consisting of first and second rounds, primarily targeted high-risk areas to rapidly build protection among animals. Figure 5 shows first and second rounds of vaccinations in 2023, reflecting a shift from outbreak response to sustained disease control. The vaccination areas for the second round in 2023 were determined by the local government based on the number of cases and the availability of vaccine stock.

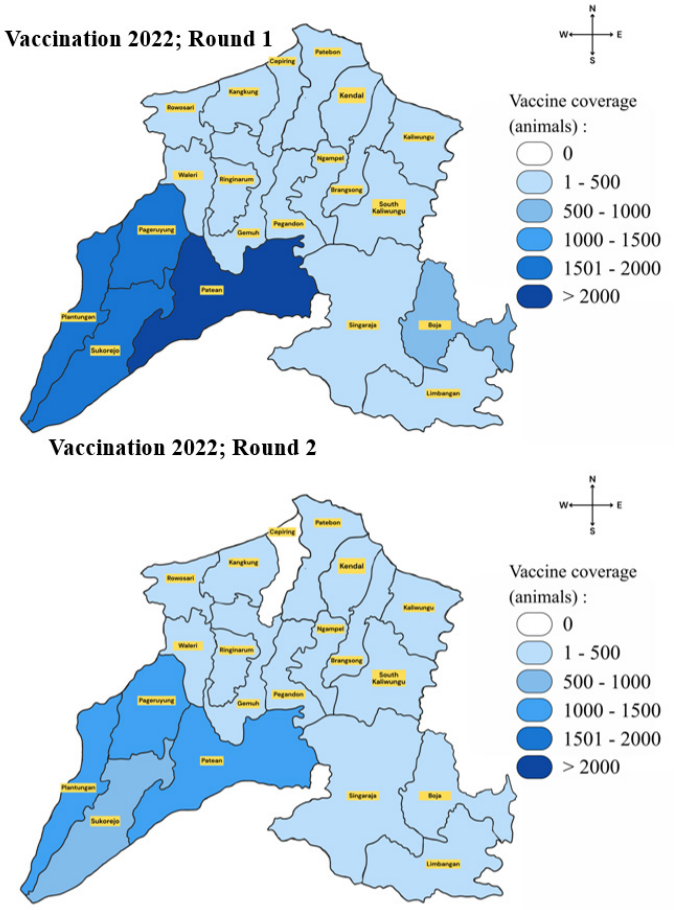

Figure 4: Spatial distribution of FMD vaccine coverage for rounds 1 and 2 by sub-district in Kendal Regency, a livestock transit area, in 2022.

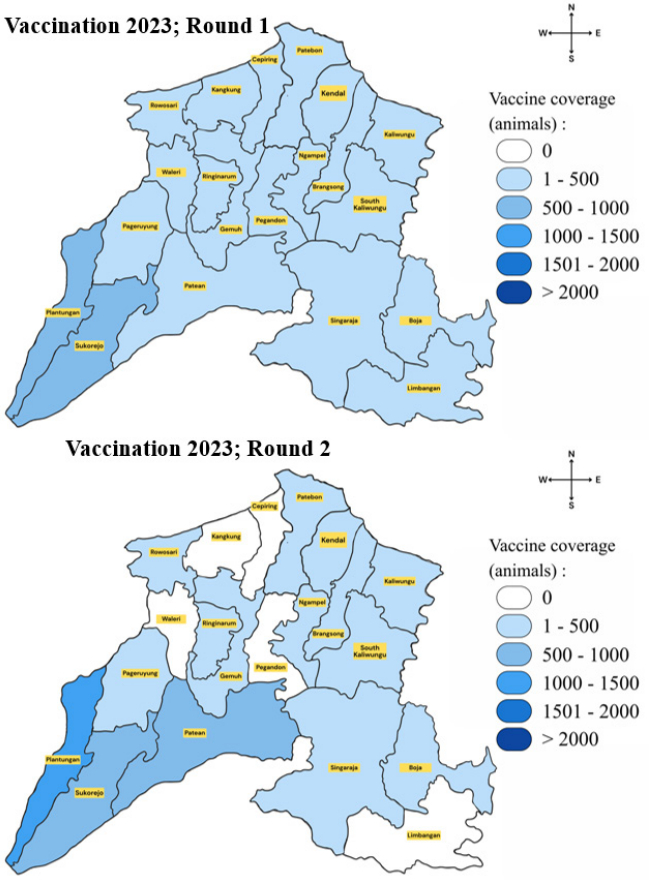

Figure 5: Spatial distribution of FMD vaccine coverage for rounds 1 and 2 by sub-district in Kendal Regency, a livestock transit area, in 2023.

A multiple linear regression analysis was conducted to assess the impact of four vaccination rounds on the reduction of FMD cases, as presented in Table 2. The results showed that the first vaccination round in 2022 (B= 1.75, $p < 0.001$) and the first round in 2023 (B= 0.17, p= 0.021) had a significant positive effect on reducing FMD cases, whereas the second round in 2022 (B= -0.25, p= 0.47) and the second round in 2023 (B= -0.79, p= 0.39) were not significant. The multiple regression model demonstrated excellent fit, with a correlation coefficient of $R = 0.944$, $R^2 = 0.892$, and $p < 0.001$. This indicates that approximately 89.2% of the variability in FMD case reduction can be explained by the combined effect of the four vaccination rounds, highlighting that the predictive model is highly informative even though the second vaccination rounds in 2022 and 2023 were individually non-significant.

Diagnostic assessment

The serological analysis using ELISA revealed that 239 out of 242 sampled cattle (approximately 90%) were seropositive for FMD antibodies, confirming a robust immune response following vaccination (Table 3). Complementing this, real-time PCR testing of 100 oral swab samples returned negative results, (Table 4), indicating the absence of active viral infection at the time of sampling. Together, these findings suggest that the observed reduction in FMD cases was not only due to clinical recovery but also reflected effective immunization and containment of viral circulation within the population. This high seroconversion rate provides biological support for the multiple linear regression findings, which indicated that the first vaccination rounds in 2022 and 2023 had a significant positive impact on reducing FMD cases. Although the second vaccination rounds in 2022 and 2023 were not individually significant in the regression model, the presence of antibodies suggests potential protective effects, particularly as booster immunizations for the already partially immune population.

Table 3: Serological testing using ELISA to confirm the presence of antibodies against FMD serotype O.

Sub districts	Village	Total sample	Seronegative	Seropositive
Patean	Mlatiharjo	68	2	66
Patean	Selo	51	1	50
Plantungan	Karanganyar	32	0	32
Sukorejo	Hardjodowo	29	0	29
Sukorejo	Ngadiwarno	12	0	12
Sukorejo	Selokaton	50	0	50
	Total	242	3	239

Table 4: Results of rRT-PCR testing conducted during the surveillance period.

Sub-district	Village	Total sample	Negative	Positive
Patebon	Mergosari	34	34	0
Sukorejo	Kebumen	66	66	0
Total		100	100	0

Table 5: Farmer awareness and on-farm biosecurity practices related to FMD spread.

No	Biosecurity practices	Yes (%)	No (%)
1	Implementation of disinfection	55	45
2	Use of personal protective equipment (PPE)	45	55
3	Handwashing facilities in the barn	62	38
4	Warning signs to restrict barn access (traffic control)	11	89
5	Barn fencing	33	67
6	Isolation pen	9	91
7	Restriction of access to other livestock	42	58

Overall, the convergence of clinical data (declining FMD cases), spatial distribution patterns, immunological evidence (high seropositivity), and virological confirmation (negative PCR results) reinforces the conclusion that vaccination was a key factor in controlling the outbreak.

Moreover, these serological and virological results are consistent with the predictive power of the regression model (R^2= 0.892) and the positive correlation observed between cases in 2022 and 2023 (r= 0.944; p <0.001) as shown in Table 2, further validating the effectiveness of the vaccination strategy in mitigating FMD incidence in Kendal Regency, a high-risk livestock transit area in Java island.

Management and farmer biosecurity practices

The observed reduction in FMD cases occurred despite suboptimal on-farm biosecurity practices. Survey data indicated that only 55% of farmers regularly carried out disinfection, 45% used personal protective equipment, and merely 9% had isolation pens for sick animals (Table 5). Furthermore, 89% of respondents did not implement access control measures such as signage or fencing to limit barn entry. Given that Kendal Regency serves as a major transit area for livestock moving between East and West Java, these gaps in biosecurity pose a continued risk for FMD introduction and spread. Therefore, while vaccination has been highly effective in controlling outbreaks, these findings highlight the urgent need to strengthen on-farm and regional biosecurity measures, including routine disinfection, isolation of sick animals, use of personal protective equipment, and controlled access to farms, to sustain long-term disease prevention.

Overall, the convergence of clinical data (declining FMD cases), spatial distribution patterns, statistical analyses (paired t-test and regression), immunological/virological evidence (high seropositivity and negative PCR results), and farmer practice surveys underscores the critical role of vaccination in controlling FMD outbreaks in Kendal Regency. However, the unique role of the regency as a livestock transit hub emphasizes that vaccination should be complemented by improved biosecurity to minimize the risk of future outbreaks and maintain population-level immunity.

DISCUSSIONS

The outbreak shows how important livestock transit areas are in spreading foot and mouth disease. These places bring together a lot of animals and have a lot of movement, which makes it easy for the virus to spread quickly (Rushton *et al*., 2018). Livestock transit points often gather animals from various places, which increases the chance of disease spreading since they share space, equipment, and workers. In Indonesia, the role of these areas in spreading disease is more obvious because the country still uses outdated methods for selling and transporting animals, and biosecurity rules are not followed equally in all regions.

The high incidence of FMD outbreaks in Kendal Regency, a key livestock transit hub along toll roads connecting East and West Java, is likely driven by intensive animal movement. Despite two vaccination rounds in 2022, several sub-districts, particularly in the northern and western regions, continued to report high FMD cases in 2023, suggesting that frequent livestock transport, as well as the introduction of new animals from outside the region passing through or entering the area, may have contributed to virus transmission even among vaccinated populations. Kendal regency at Central Java province acts as a key stopover for livestock traveling between the eastern and western parts of the island (Kedang *et al*., 2025). Central Java province hosting the second-highest number of livestock markets and slaughterhouses in Indonesia after East Java province (BPS, 2024), highlighting the potential for disease dissemination. Further studies are needed to clarify the relationship between animal movement networks and FMD outbreaks in Java island.

Even though Kendal regency has a high rate of animals getting vaccinated, some cases of FMD still happen now and then. This shows that just having vaccines isn't enough to stop the disease completely. The 98.7% of animals who tested positive for antibodies shows that the vaccines worked well and that the vaccination efforts were done properly. However, high antibody levels following vaccination indicate a strong immune response; however, this protection is relative and remains highly dependent on the strict implementation of biosecurity measures or preventive protocols (Iversen *et al*., 2022). Previous animal challenge studies demonstrated that hosts can remain asymptomatic while still carrying and shedding high levels of viral RNA from the upper respiratory tract, suggesting their potential role as silent reservoirs of infection (Mastutik *et al*., 2022). Indirect contact via contaminated vehicles, equipment, clothing, and farm personnel has been demonstrated to contribute to the spread of infectious agents between livestock herds, especially when biosecurity practices are inadequate (Rossi *et al*., 2017; Kim *et al*., 2017; Beltran-Alcrudo *et al*., 2019). This shows that stopping the spread of FMD needs a plan that uses vaccination along with good biosecurity measures and controlling how animals and people move around. FMD control does not rely solely on vaccination, it also requires improved surveillance, enhanced vaccination coverage, strengthened biosecurity measures and restrictions on animal movements to effectively reduce disease incidence and transmission (Namatovu *et al*., 2025). Moreover, FAO stated that FMD controlling mechanism should be a combination of vaccination, biosecurity and animal movements restrictions in Global FMD Control Strategy (PCP-FMD) Framework (FAO, 2025). In these areas, farmers' awareness and their willingness to follow biosecurity measures like isolation were key factors.

Limited experience with FMD among farmers and animal health workers, due to its absence in Indonesia for decades, likely contributed to underreporting and delayed recognition of cases, allowing the disease to spread before control measures were implemented. Moreover, socioeconomic issues and a lack of technical help make it harder for farmers to follow FMD control measures. Several farmer characteristics such as household income, participation in farming groups and decision-making roles are closely linked on how farmers respond to FMD outbreaks, affecting their knowledge, attitudes and practices which suggest that socioeconomic issues can hinder effective implementation of control measures (Triatmojo *et al*., 2025). Furthermore, investigation of smallholder farmer biosecurity and implications for FMD in Cambodia suggests that biosecurity practices and animal isolations can determine a successful yet sustainable FMD control in this particular area (Young *et al*., 2017). Another study in West Java provinces Indonesia recommended to replace the dairy cows that have been affected with FMD (Salsabilah *et al*., 2024).

In this study, cases identified in livestock transit areas underscore the critical importance of rapid outbreak detection and timely vaccination. Prompt diagnosis and immediate intervention in these high-mobility zones can substantially reduce disease transmission, highlighting the pivotal role of targeted control measures in key transit corridors for mitigating the spread of FMD. At the Wates Veterinary Center, laboratory testing enabled precise identification of circulating FMD virus strains, facilitating the deployment of strain-specific vaccines. Moreover, effective control in these settings depends on close coordination among local livestock authorities, field veterinarians, and farmers. Such collaboration strengthens disease surveillance, improves case reporting, and accelerates outbreak response, ultimately enhancing the overall effectiveness of FMD control and the management of other livestock diseases (George *et al*., 2021; Sentamu *et al*., 2024).

Although long-term control of FMD requires continuous monitoring and active participation from farmers, regular antibody surveillance and tracking of animal movements are essential for early detection of hidden infections. Strategies such as farmer education, participatory training, and community involvement in monitoring have been shown to improve knowledge and adoption of recommended biosecurity practices, thereby enhancing disease prevention on farms (Dione *et al*., 2020). In high-mobility areas like Kendal regency, coordinated efforts among traders, farmers, and animal health workers are critical. Strengthening institutional coordination, enforcing movement control policies, and enhancing farmer education remain fundamental to sustainable FMD management in Indonesia. Future programs should prioritize not only emergency vaccination but also the establishment of resilient surveillance and communication networks to prevent viral reintroduction in high-risk transit zones.

The observed reduction in FMD cases occurred despite suboptimal on-farm biosecurity practices. These results indicate that the substantial decline in FMD incidence, along with the high seropositivity rates observed in the cattle population, was primarily driven by vaccination efforts rather than enhancements in routine farm biosecurity. Therefore, vaccination appears to have played a pivotal role in controlling FMD outbreaks in Kendal Regency, even in the context of limited adherence to preventive farm-level measures. However, vaccination is insufficient to control disease spread in livestock transit areas, where frequent animal movement elevates the risk of transmission. Effective containment in such contexts requires the integration of vaccination with robust biosecurity measures, regulated animal movement, and rapid on-the-ground response. Close collaboration among local livestock authorities, veterinarians, farmers, and other stakeholders was pivotal in halting the outbreak and enhancing disease surveillance. Sustained monitoring, active farmer engagement, and cross-sectoral coordination remain essential for preventing reintroduction and achieving long-term FMD control, especially in high-mobility transit zones. These findings highlight the importance of combining vaccination programs with resilient surveillance and communication networks to ensure sustainable disease management in regions critical for livestock movement, particularly in high-mobility transit areas.

The outbreak of Foot and Mouth Disease (FMD) has not only disrupted beef cattle production but has also generated serious socio-economic impacts on smallholder farming households in Indonesia (Triatmojo *et al*., 2025; Prafitri *et al*., 2024; Helmi *et al*., 2025). Beyond production losses and livestock mortality, FMD has reduced farmers' incomes, weakened household purchasing power, and increased the economic vulnerability of small-scale beef cattle farmers, particularly during periods of movement restriction and market closure (Prafitri *et al*., 2024; Helmi *et al*., 2025). Empirical evidence shows that FMD significantly alters farmers' social behavior, including their knowledge, attitudes, and practices toward animal health and biosecurity, while also increasing household expenditures for animal treatment, which places additional financial pressure on already limited farm resources (Triatmojo *et al*., 2025; Prafitri, 2024). Moreover, farmer characteristics such as income level, participation in farmer groups, cattle ownership, and household decision-making dynamics influence vulnerability to FMD infection, indicating that

socio-economic conditions are closely linked to disease risk and recovery capacity (Triatmojo *et al*., 2025). In this context, the Micro, Small and Medium Enterprise Credit (MSME Credit) program becomes increasingly relevant as a financial coping mechanism, enabling farmers to maintain production activities, cover feed and animal health costs, and gradually rebuild herd productivity after outbreaks (Suhartini *et al*., 2021). However, income shocks induced by FMD can intensify repayment constraints among credit-dependent farmers, underscoring the need for adaptive policy support. Such measures may include flexible repayment arrangements, temporary credit relaxation, and the integration of MSME credit schemes with FMD control programs, veterinary services, and farmer capacity-building initiatives. In this context, the microcredit program administered by the Coordinating Ministry for Economic Affairs should function not only as a financing instrument but also as a socio-economic safety net for beef cattle farmers confronting animal disease shocks (Triatmojo *et al*., 2025; Suhartini *et al*., 2021). Moreover, it is important to emphasize that socioeconomic variables, such as income, education level, and access to resources, were not collected in this study. Future research should therefore incorporate structured socioeconomic indicators to enable more robust multivariate analyses and to better elucidate the relative contributions of economic capacity, knowledge, and service accessibility in shaping disease control practices.

This study has several limitations that should be considered when interpreting the findings. First, the cross-sectional design, conducted across several sub-districts in Kendal Regency as a livestock transit area during FMD outbreak in 2022 and 2023, captures conditions at a single point in time and therefore limits the ability to establish causal relationships between risk factors and FMD occurrence. Second, the sampling approach may not fully represent all livestock actors within Kendal Regency, particularly given the dynamic nature of animal movement in transit areas, which may affect the generalizability of the results. Third, the analysis was primarily descriptive and comparative, and the lack of more advanced statistical modeling limits a deeper assessment of associations between variables. Additionally, this study did not include direct socioeconomic indicators, such as income, education level, or access to veterinary services, thereby constraining the ability to evaluate underlying determinants of farmer practices. Furthermore, the reliance on self-reported data from farmer surveys introduces the potential for recall bias and reporting inaccuracies, especially regarding past disease events and management practices.

CONCLUSIONS

Vaccination was the primary factor driving the substantial reduction of FMD cases, supported by high seropositivity and negative PCR results. Despite limited farm-level biosecurity, strategic vaccination effectively controlled the outbreak. Strengthening biosecurity, particularly in this livestock transit area, is essential to sustain long-term FMD prevention.

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NOVELTY STATEMENT

This study reports original research that has not been published elsewhere. It is the first detailed case study of a Foot and Mouth Disease (FMD) outbreak in a cattle transit area in Central Java, Indonesia, highlighting the role of livestock movement in disease transmission. The findings provide new insights for improving surveillance, biosecurity, and movement control strategies in FMD-prone regions.

AUTHOR\S CONTRIBUTION

DWH: Designed the study, wrote the original draft, data analysis, editing, resources, review, supervision. ETS: Designed the study, data analysis, resources, review, editing, supervision. IDF: Sample analysis, data extraction, developed maps and graphics, review. All authors reviewed and approved the final version of the manuscript.

Ethical approval

All experimental procedures in this study were reviewed and approved by the Animal Ethics Committee and conducted in accordance with the guidelines.

Generative AI and AI assisted technology statement

The authors declare that no generative AI or AI-assisted technologies were used to generate, analyze, or interpret the research data. Generative AI tools were used only to assist in checking grammar, language clarity, and readability of the manuscript during the revision process. All scientific content, interpretations, and conclusions remain the full responsibility of the authors.

Conflict of interest

The authors have declared no conflict of interest.

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