Kedang *et al. BMC Veterinary Research* (2025) 21:180
https://doi.org/10.1186/s12917-025-04621-2

BMC Veterinary Research

RESEARCH

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Spatial-temporal distribution and risk factors of foot and mouth disease outbreaks in Java Island, Indonesia from 2022 to 2023

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Abstract

Background Indonesia faced new outbreaks of foot and mouth disease in 2022 after being officially free from the disease for several decades. The outbreaks were first reported in East Java in April 2022 and subsequently spread to many regions in Indonesia. This study investigated the epidemiology and risk factors of foot and mouth disease outbreaks in Java, Indonesia, from 2022 to 2023. Descriptive, spatial, spatiotemporal, and risk factor analyses were conducted to investigate the patterns and risk factors associated with the outbreaks in Java.

Results Results showed that the outbreaks were distributed across the island. East Java was the most affected region. The outbreaks peaked in June 2022, followed by a downward trend until 2023. Positive spatial autocorrelations were found in both years, indicating that the outbreaks clustered in several areas. The spatiotemporal analysis found a total of 16 clusters in both years, with 11 clusters in 2022 and 5 clusters in 2023. The temporal distribution of clusters indicated a peak period from May to July, with 12 out of 16 clusters occurring during this time. Risk factor analysis found that environmental and agricultural-related factors, including annual precipitation, the presence of livestock markets, the presence of slaughterhouses, the presence of animal health centres, cattle population, and goat population, are significant risk factors for the occurrence of outbreaks in Java. Probability risk mapping found higher risk areas primarily distributed in the eastern and central parts of Java.

Conclusions The outbreaks predominantly clustered in eastern and central parts of Java. The outbreaks peaked in June 2022, followed by a downward trend until the end of 2023. Environmental and agricultural-related factors significantly increased the risk of outbreak occurrence.

Keywords Foot-and-Mouth Disease, Java Island, Risk Factors, Spatiotemporal Analysis

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Background

Foot and mouth disease (FMD) is a viral disease caused by Foot and Mouth Disease Virus (FMDV). FMD affects cloven-hoofed animals such as cattle, buffalo, sheep, goats, pigs, and deer. Infected animals show pathognomonic clinical symptoms, including fever and the appearance of blisters on the nose, mouth, tongue, and all over the hooves. The blisters and lesions lead to lameness and reluctance to eat [1, 2]. FMD is considered one of the most important animal diseases, and it is listed as a notifiable disease by the World Organisation for Animal Health (WOAH).

Historically, FMD was first reported in Indonesia in Malang, East Java, in 1887 and then distributed in many regions of Indonesia. Laboratory results showed that the outbreaks in Indonesia were caused by FMDV serotype O only [3–6]. The government initiated the vaccination program in 1974 in several prioritised areas, followed by additional control strategies such as movement control and stamping-out programs. The last recorded case occurred in December 1983 in Kebumen, Central Java. Subsequently, the vaccination program continued until the end of 1985. Indonesia then declared FMD-free in 1986, followed by official FMD-free status issued by WOAH (formerly OIE) in 1990 [3, 6, 7].

Indonesia had remained free from FMD until a new outbreak was reported in April 2022. Laboratory results confirmed that FMD outbreaks in Indonesia were caused by FMDV serotype O subtype O/ME-SA/Ind-2001e [8, 9]. The first outbreak was reported in Gresik, East Java, and then rapidly spread to many regions and affected thousands of livestock in Indonesia. Java is the most affected region in Indonesia, with over half of the total reported cases in Indonesia [10]. Furthermore, the threat of the FMD outbreak extends beyond Java, posing a risk to millions of livestock throughout Indonesia.

The Indonesian government responded to the outbreaks with the declaration of animal health emergency status, followed by the restriction of livestock movement in several regions. Animal health workers were encouraged to report all suspected cases in their respective areas and submit representative samples to the veterinary laboratory for confirmation tests. The confirmed cases have been recorded by the Indonesia Integrated Animal Health Information System (iSIKHNAS). The Indonesian government also initiated a mass vaccination program targeting key regions with large livestock populations. The government fully funded the vaccination program, covering the area affected by the outbreak. Despite these efforts, new cases continued to be reported.

Previous studies in different countries have shown that the spread of FMD is influenced by several risk factors, including agricultural and environmental aspects such as livestock population, climate conditions, and livestock markets [11, 12]. Studies in West Java found that FMD outbreaks were associated with environmental factors, including altitude and vegetation, and livestock factors, including cattle population, milk production, and leather production [13]. Understanding the distribution patterns and the risk factors is crucial in managing and controlling the spread of FMD. However, scientific research on the risk factors and distribution patterns of FMD outbreaks in Indonesia is limited, resulting in a lack of information on the spread of FMD, particularly in Java, where the majority of outbreaks occurred. Therefore, this study specifically aimed to analyse the epidemiology, identify spatiotemporal pattern and assess the risk factors to FMD outbreaks in Java Island, Indonesia, during the period from 2022 to 2023.

Results

Prevalence and epidemic curve

The outbreak of FMD in Java affected various species, including large and small ruminants. In summary, cattle accounted for most cases and outbreak farms reported in 2022 and 2023, while small ruminants, including goats and sheep, were the least affected. During this period, 41,129 farms were identified as outbreak sites, impacting 308,148 animals, including 296,915 cattle (96.4%), 5,437 buffalo (1.8%), 2,697 goats (0.8%), and 3,099 sheep (1.0%). The number of outbreak farms dropped significantly from 37,266 in 2022 to 3,863 in 2023, while total cases fell from 294,368 to 13,780. The incidence rate declined from 5.58 to 0.25% in cattle, 7.01 to 0.17% in buffalo, 0.03 to 0.002% in goats, and 0.06 to 0.02% in sheep.

The first reported FMD outbreak in Java, according to iSIKHNAS, was recorded on 10 April 2022, located in the Wringianom subdistrict, Gresik district, East Java province. The report continued on 21 April 2022, which affected several cattle farms in Sukodono subdistrict, Sidarjo district, East Java province. By the end of April, the outbreaks were recorded in several subdistricts across three districts in East Java, including Gresik, Sidoarjo, and Lamongan districts.

The outbreak of FMD in Java in April 2022 recorded 39 outbreak farms and 410 cases during the first month of the outbreak. The epidemic quickly escalated, reaching its peak in June 2022 with 19,049 outbreak farms and 157,931 cases. In response, the declaration of epidemic status was announced in early May 2022, following the first phase of mass vaccination at the end of June and during July 2022. A second phase of mass vaccination was conducted from January to February 2023, followed by localized vaccination efforts targeted at specific areas in the subsequent periods. These measures led to a significant decline in cases, culminating in the declaration of endemic status in June 2023, marking a shift from epidemic control to routine disease management.

The temporal analysis of FMD outbreaks shows a sharp increase in early 2022, followed by a significant decline from August to December 2022, as shown in Figs. 1 and 2. A slight spike in recorded cases and outbreak farms occurred in early 2023 from January to February. Several provinces, including Yogyakarta, West Java, Banten, and Central Java, experienced increased cases and outbreak farms again in the middle of 2023 from May to July, as shown in the logarithmic scale of the monthly temporal graph in Fig. 2. The data indicates a recurring pattern of outbreak peaks approximately every 5 to 6 months. The epidemic curve also shows spatial variation in outbreaks, with East Java having the highest incidence, followed by Central Java, West Java, and Yogyakarta, while Jakarta and Banten reported lower levels of outbreaks.

Spatial analysis

Spatial distribution mapping showed the FMD outbreak distributed across Java. The geographical distribution of cumulative incidence of FMD in Java is shown on the choropleth map in Fig. 3. A total of 1,547 subdistricts and 677 subdistricts reported the outbreak in 2022 and 2023, respectively. A total of 638 subdistricts out of 2,146 in Java reported a persistent FMD outbreak that occurred in two consecutive years.

The geographical distribution of subdistricts with Standardised Morbidity Ratio (SMR) more than one is shown on the choropleth map in Fig. 4. Significant positive Moran indices were observed in 2022 and 2023 (Table 1), indicating spatial autocorrelation in both years. This suggests that subdistricts with similar values of SMRs, whether high or low, were clustered in neighbouring areas, revealing a spatial pattern in the outbreak distribution.

The results of local spatial autocorrelation using Local Indicators of Spatial Association (LISA) are presented in Fig. 5. The High-High clusters were predominantly distributed in the eastern and central parts of Java in 2022 and 2023, with a smaller number observed in the western part of Java. In 2022, Low-Low clusters were primarily concentrated in the western part of Java, with a few clusters located in the central and eastern regions. However, the Low-Low clusters significantly decreased in 2023, indicating a notable shift in the spatial distribution pattern of FMD outbreaks compared to the previous year.

Spatiotemporal analysis

Spatiotemporal analysis using the space-time permutation (STP) model revealed 11 and 5 significant spatiotemporal clusters of FMD outbreaks in Java in 2022 and 2023, respectively (Fig. 6; Table 2). Results showed that the most likely cluster of FMD outbreak in 2022 covered eight districts in East Java province, namely Gresik District, Sidoarjo District, Pasuruan District, Lamongan District, Jombang District, Mojokerto Municipality, and Surabaya Municipality, between 10 April and 21 May 2022. This result aligned with the first month of

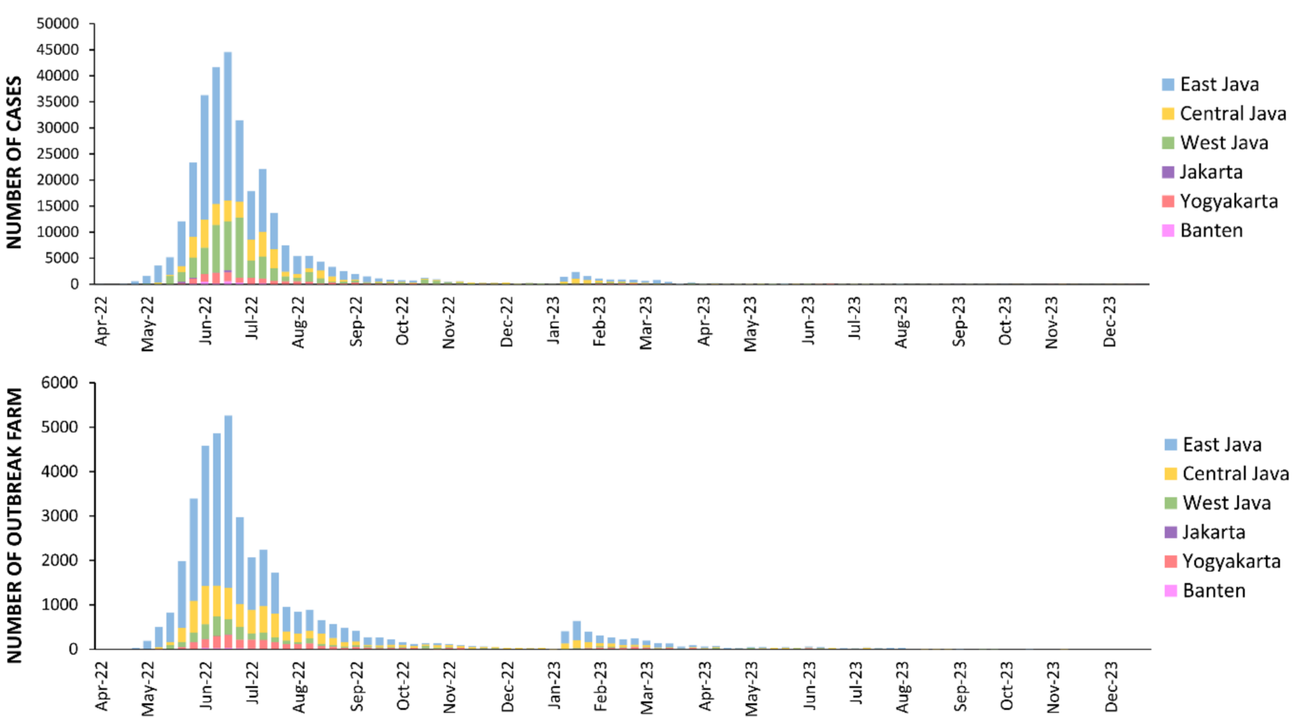


Fig. 1 Weekly temporal graph of FMD cases and outbreak farms in Java from 2022 to 2023

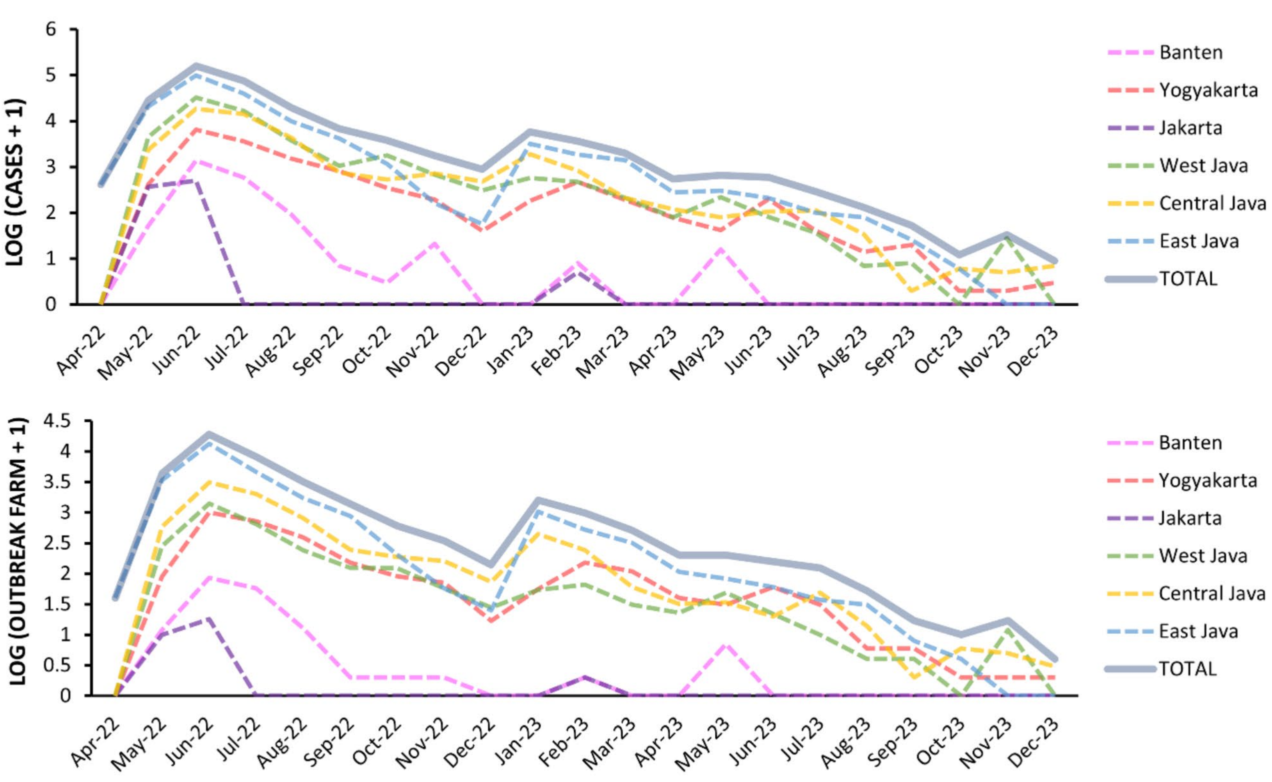


Fig. 2 Monthly temporal graph of FMD cases and outbreak farms in Java from 2022 to 2023 in logarithmic scale

the recorded outbreak in Java that occurred in Gresik, Lamongan, and Sidoarjo in April 2022.

The result of the most likely cluster of FMD outbreak in 2023 covered twelve districts in East Java province and Central Java province between 9 January and 29 January 2023. Two secondary clusters in 2022 and one secondary cluster in 2023 were very small, with a radius of only 0 km. This indicates that these clusters only covered outbreaks in a single village and were too small to be visible on the map due to their minimal geographic spread.

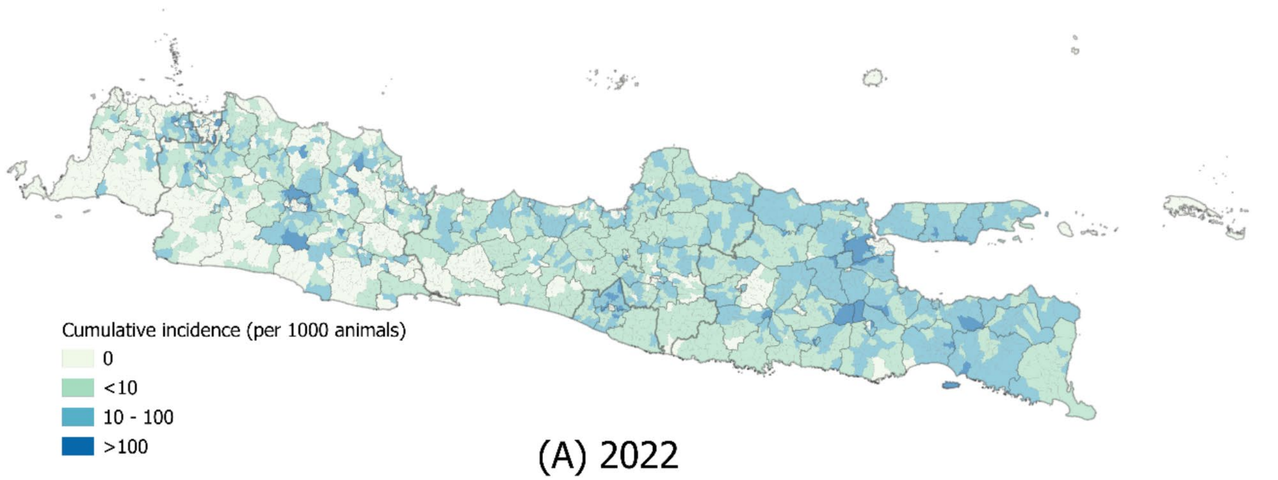
Risk factor analysis

The results of univariable logistic regression for each risk factor are shown in Table 3. Significant factors were subsequently included in a multivariable logistic regression using the backward elimination method. No multicollinearity was found between the variables, as indicated by the variance inflation factor (VIF) values less than 5. Interactions between independent variables were assessed, but none were significant. The final model results are shown in Table 4. The final model results revealed that subdistricts with higher annual precipitation had decreased odds of FMD outbreaks. In contrast, subdistricts with livestock markets were 2.59 times more likely to experience an outbreak, while those with slaughterhouses and animal health centres had 1.46 times and 1.51 times higher odds, respectively. Furthermore, a ten-fold increase in cattle and goat populations raised the odds of an outbreak by 3.41 and 1.43 times, respectively, emphasising the role of environmental and agricultural factors in the spread of FMD in Java.

The model was evaluated with the area under the curve (AUC) of 0.86, the Hosmer-Lemeshow test of 0.18, and the Cragg-Uhler pseudo-R^2 of 0.44. An AUC of 0.86 indicates good discrimination performance, while the Hosmer-Lemeshow test ($p = 0.18$) indicates a good fit between predicted and observed values. Additionally, a Cragg-Uhler pseudo-R^2 of 0.44 indicates a reasonable fit. These metrics indicate that the final model was deemed reliable, meeting the criteria for a good predictive model. The probability of an outbreak in each subdistrict was calculated using the predictive model based on the results of final multivariable logistic regression analysis. The probability results were then illustrated in the risk map shown in Fig. 7. The high probability subdistricts were primarily located in the eastern and central parts and distributed as a small number of subdistricts in the western part of Java.

Discussion

The analysis of reported outbreak data in Java revealed that most FMD outbreaks occurred in 2022, marking the first major resurgence of the disease after being free for several decades. This outbreak affected a naïve livestock population with no prior immunity, contributing to its



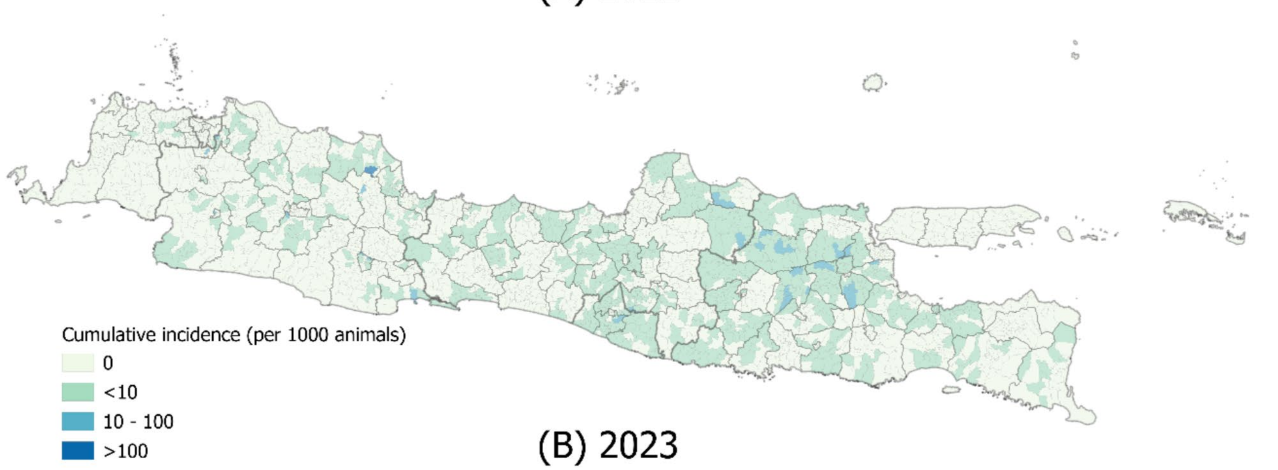


Fig. 3 Cumulative incidence of FMD at subdistrict level in Java in (**A**) 2022 and (**B**) 2023

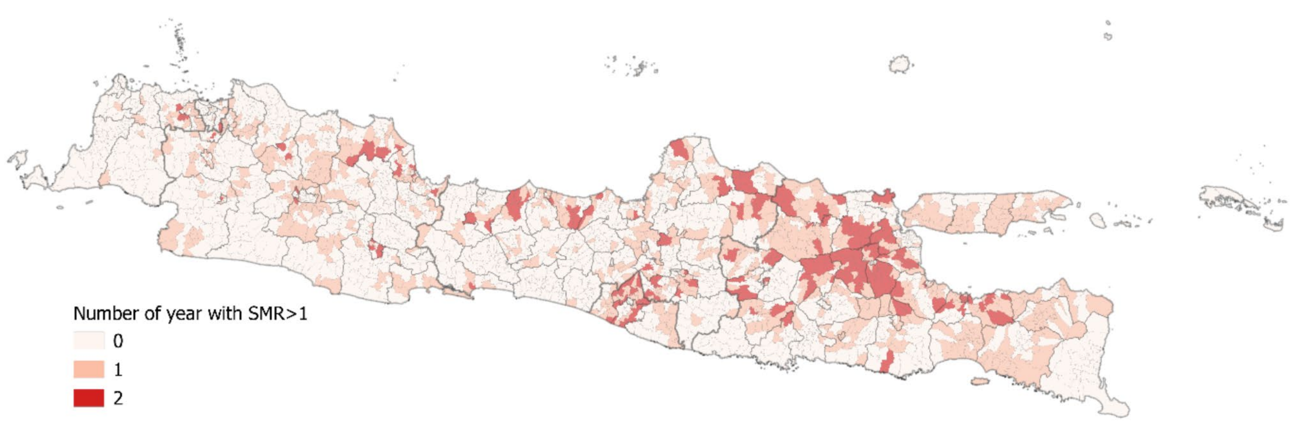


Fig. 4 Standardised morbidity ratio (SMR) at subdistrict-level in Java

Table 1 Global Moran's I index of SMR value

Year	Moran's I index	Moran's I *p*-value
2022	0.254	< 0.001
2023	0.104	< 0.001

rapid spread and highlighting critical gaps in surveillance and control measures. Large livestock, including cattle and buffalo, were the most affected species, while small ruminants, such as goats and sheep, had a much lower incidence rate. This low incidence in small ruminants may be due to the absence of visible clinical symptoms. Small ruminants infected with FMD typically exhibit

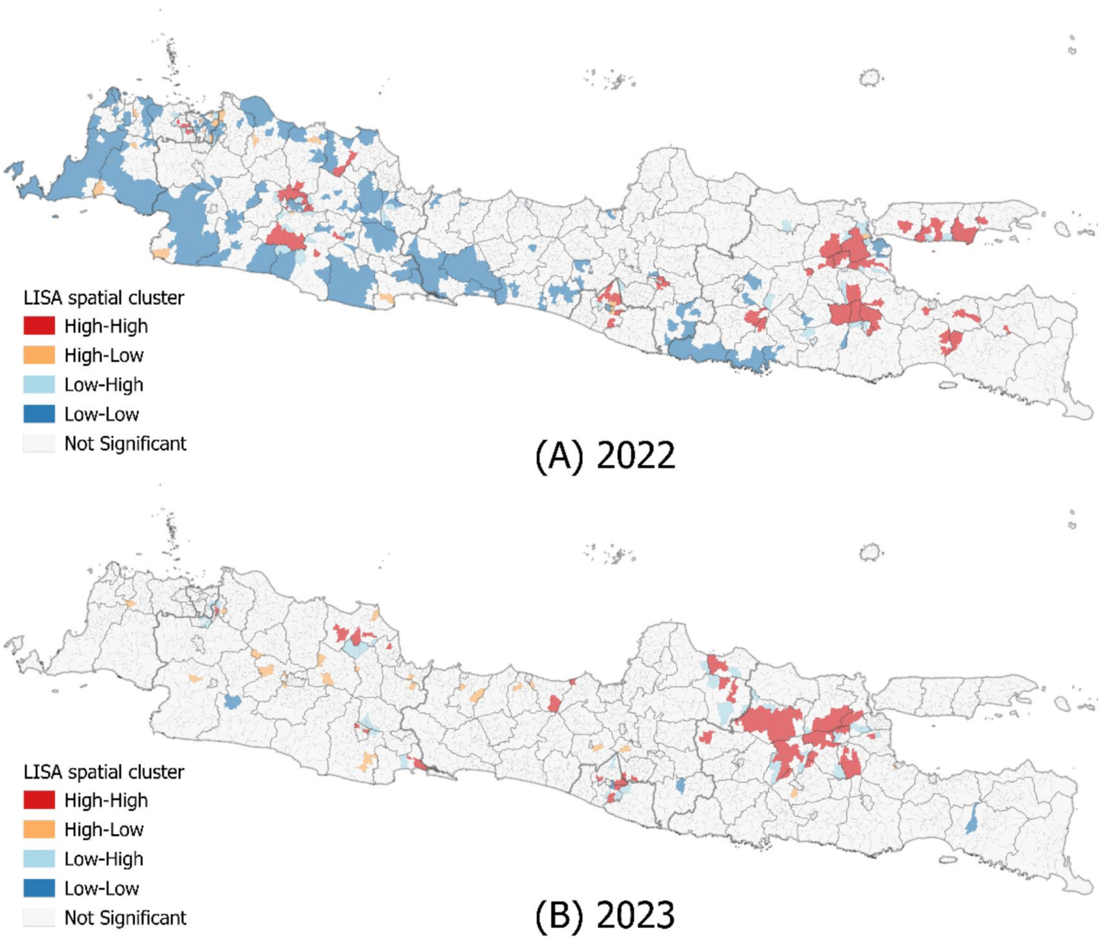


Fig. 5 Local Indicators of Spatial Association (LISA) spatial cluster map of FMD in Java in (**A**) 2022 and (**B**) 2023

mild symptoms or inapparent clinical signs [14, 15]. This could result in underreporting, as infected small ruminants may not display the clear clinical signs that typically prompt a notification.

The FMD outbreak in Java began in April 2022, with the first outbreak reported in Gresik district, East Java, and then spread to Sidoarjo and Lamongan districts in the same month. Although the first outbreak in Indonesia was reported in this area, the source of the outbreak and how the virus entered the country remain unclear. The outbreak rapidly spread and reached its peak in June 2022, reflecting the rapid transmission of the disease within a short period. A sharp increase in outbreaks within a short timeframe might be related to the absence of immunity to FMDV in Indonesian livestock due to the absence of vaccination programs since the country achieved FMD-free status in 1990. Delays in livestock movement restrictions and emergency vaccinations also likely contributed to the rapid spread of FMD in Indonesia, particularly in the Java region. These delays may have been influenced by the time required for decision-making processes, logistical challenges, and the absence of readily available FMD vaccines, as Indonesia had not maintained vaccine production or stockpiles since achieving FMD-free status. The reliance on importing vaccines further prolonged the response time, which could have been mitigated by the existence of vaccine banks, allowing for a more immediate deployment of emergency vaccinations.

Limited knowledge and awareness also contributed to the spread of the disease since the livestock farmers and animal health workers had minimal experience with the disease due to the absence of FMD in Indonesia for several decades. This condition may result in unreported or late reports of suspected cases and lead to delays in disease recognition and responses during the initial period of the outbreak, allowing the disease to spread further before interventions could be implemented.

The government then imposed restrictions on livestock transportation in several districts in early May 2022. The first phase of mass vaccination was implemented from late June to July 2022, using a high-potency vaccine. The vaccination program targeted cattle and buffalo as the primary species, followed by goats, sheep, and pigs, and covered all provinces affected by the outbreak. The

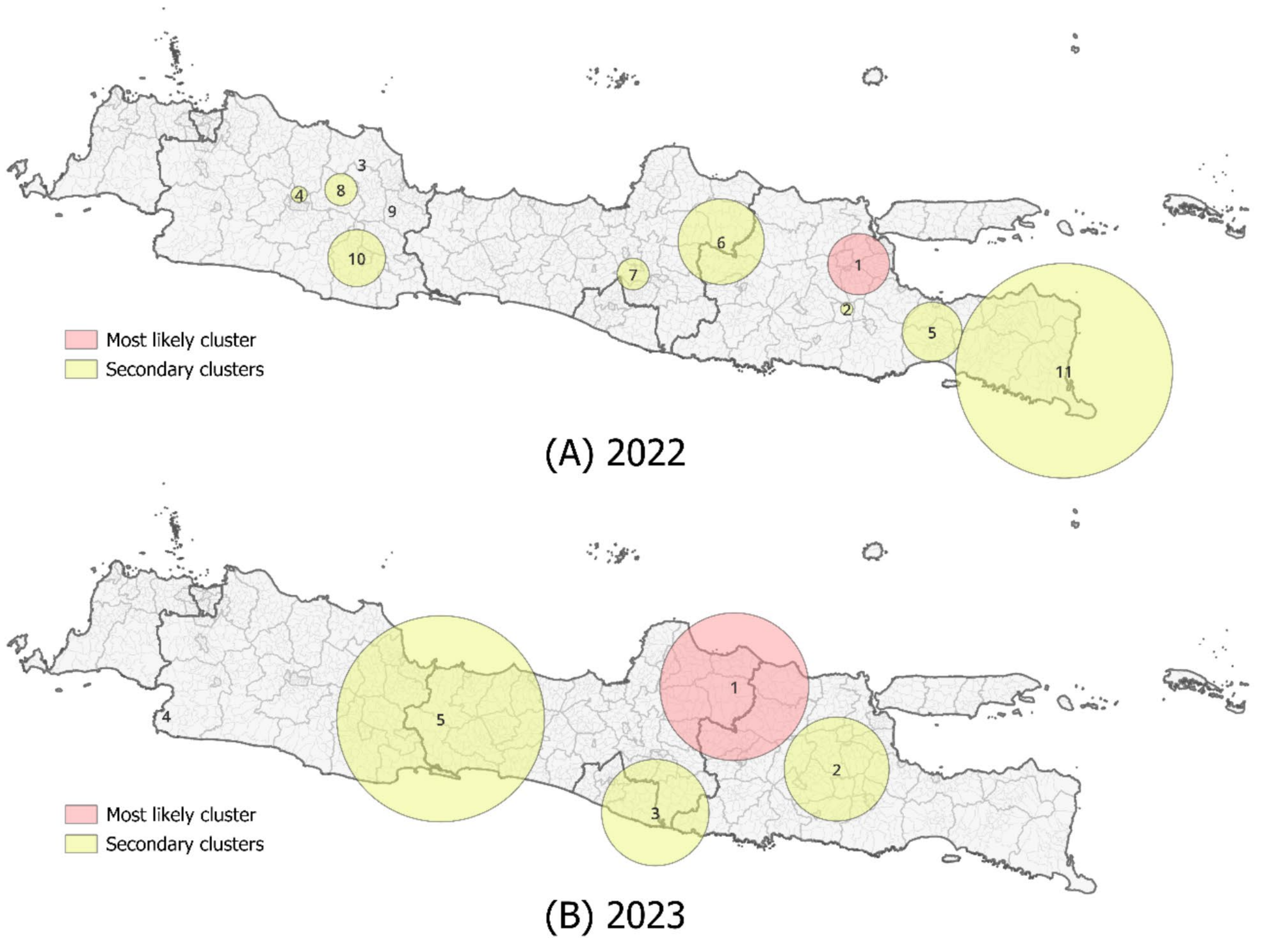


Fig. 6 Spatiotemporal clusters of FMD in Java in (**A**) 2022 and (**B**) 2023 using space-time permutation (STP) model

Table 2 Spatiotemporal clusters by STP model on FMD in Java, 2022–2023

Number	Cluster Type	Cluster Time	Centroid / Radius (km)	O/E	LLR	*p*-value
2022						
1	Most Likely	10 Apr – 21 May	7.434744 S, 112.531698 E / 29.69 km	12.26	8365.32	< 0.001
2	Secondary	17 Jul – 23 Jul	7.825533 S, 112.429013 E / 5.94 km	12.47	3846.89	< 0.001
3	Secondary	7 Aug – 20 Aug	6.563265 S, 108.193005 E / 0 km	28.92	3397.89	< 0.001
4	Secondary	26 Jun – 9 Jul	6.826526 S, 107.644514 E / 7.74 km	3.04	3384.65	< 0.001
5	Secondary	8 May – 4 Jun	8.024440 S, 113.174439 E / 28.71 km	2.98	3138.32	< 0.001
6	Secondary	17 Jul – 1 Oct	7.238937 S, 111.330962 E / 41.49 km	3.06	2268.15	< 0.001
7	Secondary	17 Jul – 23 Jul	7.521351 S, 110.562380 E / 15.36 km	6.00	2017.98	< 0.001
8	Secondary	16 Oct – 22 Oct	6.783565 S, 108.009631 E / 15.55 km	171.68	1868.49	< 0.001
9	Secondary	19 Jun – 25 Jun	6.967316 S, 108.457718 E / 0 km	6.07	1669.92	< 0.001
10	Secondary	15 May – 28 May	7.381525 S, 108.146979 E / 27.69 km	11.67	1434.22	< 0.001
11	Secondary	19 Jun – 16 Jul	8.364573 S, 114.327280 E / 104.15 km	1.52	1323.14	< 0.001
2023						
1	Most Likely	9 Jan – 29 Jan	6.976738 S, 111.446360 E / 71.61 km	2.09	766.30	< 0.001
2	Secondary	20 Feb – 9 Apr	7.695505 S, 112.340389 E / 50.45 km	2.37	491.61	< 0.001
3	Secondary	5 Jun – 23 Jul	8.074753 S, 110.756018 E / 51.61 km	4.66	235.24	< 0.001
4	Secondary	1 May – 7 May	7.228775 S, 106.485121 E / 0 km	106.82	213.59	< 0.001
5	Secondary	10 Apr – 16 Jul	7.256942 S, 108.880951 E / 99.94 km	3.08	134.08	< 0.001

*O/R = Observed to expected ratio, LLR = Log likelihood ratio

Table 3 Results of the univariable logistic regression analysis of the association between FMD occurrence and risk factors at the subdistrict level in Java

Variable	*N* or Mean ± SD		OR (95% CI)	*p*-value
	Outbreak subdistrict	Non-outbreak subdistrict		
Annual precipitation				
< 2000 mm	695	177	Ref.	Ref.
2000–3000 mm	732	301	0.62 (0.50–0.70)	< 0.001
> 3000 mm	158	83	0.48 (0.35–0.66)	< 0.001
Rainy period	18.8 ± 4.09	20.2 ± 4.86	0.93 (0.91–0.95)	< 0.001
Livestock market				
No	1335	545	Ref.	Ref.
Yes	250	16	6.38 (3.81–10.68)	< 0.001
Slaughterhouse				
No	1252	506	Ref.	Ref.
Yes	333	55	2.45 (1.81–3.31)	< 0.001
Animal health centre				
No	1264	518	Ref.	Ref.
Yes	321	43	3.06 (2.19–4.27)	< 0.001
Insemination service businesses	0.42 ± 1.08	0.15 ± 0.72	1.63 (1.37–1.95)	< 0.001
Livestock health service businesses	0.29 ± 0.86	0.07 ± 0.39	2.39 (1.79–3.20)	< 0.001
Cattle population ($\log_{10}$)	2.97 ± 0.83	1.60 ± 1.08	4.07 (3.56–4.65)	< 0.001
Buffalo population ($\log_{10}$)	0.66 ± 0.80	0.79 ± 0.90	0.83 (0.74–0.93)	0.001
Goat population ($\log_{10}$)	3.41 ± 0.63	2.66 ± 1.04	3.22 (2.77–3.73)	< 0.001
Sheep population ($\log_{10}$)	2.67 ± 0.90	2.37 ± 1.26	1.32 (1.21–1.45)	< 0.001
Average farm herd size	5.31 ± 3.55	7.86 ± 7.36	0.89 (0.87–0.91)	< 0.001

*OR = Odds ratio, SD = Standard deviation

vaccines were administered by veterinarians and/or veterinary paramedics, with cold chain management maintained throughout the distribution process. The entire program was fully funded by the government [16–20].

Table 4 Results of the final multivariable logistic regression model of the association between FMD occurrence and risk factors at the subdistrict level in Java

Variable	Coefficients	SE	OR (95% CI)	*p*-value
Intercept	-2.60	0.26	0.07 (0.04–0.12)	< 0.001
Annual precipitation				
< 2000 mm	Ref.	Ref.	Ref.	Ref.
2000–3000 mm	-0.75	0.14	0.47 (0.36–0.62)	< 0.001
> 3000 mm	-0.99	0.19	0.37 (0.26–0.54)	< 0.001
Livestock market				
No	Ref.	Ref.	Ref.	Ref.
Yes	0.95	0.29	2.59 (1.48–4.82)	0.001
Slaughterhouse				
No	Ref.	Ref.	Ref.	Ref.
Yes	0.38	0.19	1.46 (1.01–2.12)	0.045
Animal health centre				
No	Ref.	Ref.	Ref.	Ref.
Yes	0.42	0.20	1.51 (1.03–2.27)	0.038
Cattle population ($\log_{10}$)	1.23	0.07	3.41 (2.93–3.99)	< 0.001
Goat population ($\log_{10}$)	0.36	0.09	1.43 (1.20–1.71)	< 0.001

*OR = Odds ratio, CI = Confidence interval, SE = Standard error

These efforts led to a significant decline in cases from August to December 2022, indicating that emergency response, including vaccination and livestock restrictions, can effectively reduce the spread of the disease during epidemic situations.

In early 2023, there was a slight increase in FMD outbreak, possibly due to heightened livestock transportation due to increased meat demand for the New Year festival and also low level of herd immunity after the initial vaccination phase. Duration of immunity can vary depending on the potency of the vaccine used, with high-potency vaccines administered during emergency vaccination generally providing longer-lasting immunity compared to standard-potency vaccines used in routine vaccination programs [21, 22]. Studies suggest that livestock immunity post-vaccination lasts up to six months. Therefore, a booster must be administered for proper immunity protection [21, 23, 24]. These findings explain the increase in cases at early 2023 suspected to be related to decreased herd immunity after the first phase of mass vaccination in the previous six months, around June and July 2022. Although the increase in cases occurred during the period when vaccine immunity would likely have waned, it is important to recognise that the findings alone do not fully explain the rise in outbreaks. Other factors, such as heightened livestock movement and environmental conditions, may have also contributed to the increase of FMD cases during this period. The government initiated a second phase of mass vaccination in January and February 2023, followed by a declaration of the endemic situation of FMD in Indonesia in June 2023 [25]. Despite a decline in total cases and outbreak farms

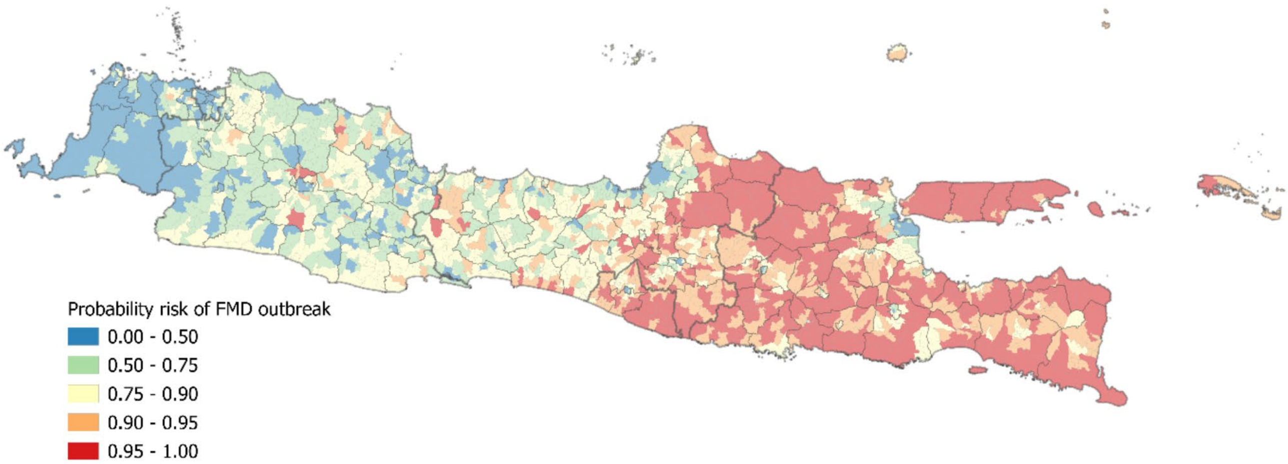


Fig. 7 Predictive map of probability risk for FMD outbreak in Java

in Java throughout 2023, new cases were consistently reported.

The FMD outbreak is mainly concentrated in the eastern and central parts of Java due to the large livestock population in East Java, which has the largest livestock populations in Java and the entire country. The central region of Java, including Central Java Province and Yogyakarta Province, also has significant livestock populations in Indonesia [26, 27]. The high number of FMD outbreaks in the eastern and central regions of Java can be attributed to intense livestock transportation within these areas, particularly in East Java, which serves as a key checkpoint for livestock transportation to and from other Indonesian islands due to its strategic location and large ports facilitating sea-based transport. This heavy movement of livestock likely accelerates the spread of FMD in these regions. The central region of Java serves as a stopover for livestock travelling between the eastern and western parts of the island. This area has the second-highest number of livestock markets and slaughterhouses in Indonesia after East Java [28, 29], indicating significant livestock movement that could contribute to the spread of livestock diseases. Further research is needed to understand the link between animal movement networks and FMD outbreaks in Indonesia, especially in Java.

The SMR analysis revealed that numerous subdistricts in Java experienced higher risk than the regional risk during the FMD outbreak in 2022 and 2023. The SMR is a critical metric, as a value greater than one signifies high-risk areas where the observed cases higher than the expected cases. The subdistricts with higher risks were primarily concentrated in the eastern and central regions of Java. Furthermore, a positive Moran's I index in 2022 and 2023 indicated clustering of the FMD outbreaks across regions rather than randomly dispersed [11, 30]. Local spatial autocorrelation analysis indicated that High-High clusters, indicating high FMD incidence, were mainly found in the eastern and central parts of Java in both years. A noticeable change in the clusters between 2022 and 2023 suggests a shift in the outbreak distribution, possibly due to improved disease management and increased natural immunity. In 2022, the outbreak primarily affected a naïve population, leading to peak and high cumulative incidence, particularly in initial outbreak areas. In 2023, mass vaccination and natural immunity reduced the outbreak, resulting in lower cumulative incidences and more homogenous outbreak distribution, marked by a lower global Moran's Index. Identifying cluster patterns could provide insights into disease transmission dynamics and highlight high-risk areas for effective prevention and control strategies.

This study is the first report to investigate the spatiotemporal clusters of FMD outbreaks in Indonesia, especially in the Java region. The STP model is used for identifying the spatiotemporal clusters because it only requires the number of cases in each coordinate of outbreak location over a specific time period, making it effective in early outbreak detection [31–33]. The study identified 16 spatiotemporal clusters of FMD outbreaks during 2022 and 2023, with 11 clusters in 2022 and 5 clusters in 2023. The most likely cluster was located in East Java Province in 2022 and between East Java and Central Java Province in 2023. The location of the most likely cluster in 2022 aligns with the initial FMD outbreak, which started in the same area covered by the cluster, such as Gresik District, Sidoarjo District, and Lamongan District.

The STP clusters in 2022 and 2023 showed that 12 out of 16 clusters occurred between May and July, indicating that FMD outbreaks most likely occurred during this period. The period from May to July is a period when almost all regions of Indonesia experience the dry season. The dry weather season encourages livestock market activities, as many livestock markets in Java are held in open fields and are heavily dependent on favourable weather conditions [34]. Increased livestock movement may have facilitated the spread of FMD from one region to another, contributing to the heightened transmission during this period.

The movement of farmers and vehicles used in forage collection also contributes to FMD transmission during the dry season. Intensive farming systems are common in Java, where livestock are primarily kept in enclosures and rely on collected forage. In several districts with limited pasture, a semi-intensive farming system allows livestock to graze for limited periods and within short distances before returning to their enclosures [35–37]. Despite this occasional grazing, reliance on collected forage remains significant, particularly during the dry season when natural pasture is scarce. As a result, farmers frequently travel greater distances using vehicles to collect forages. Vehicles, equipment, or farmers' clothing and footwear involved in the collection of forages may contribute to the spread of FMD, even without direct animal movement [38]. Therefore, the movement of farmers and forage transport vehicles continues to be a key factor in the potential spread of FMD.

The peak of incidence from May to July in both 2022 and 2023 also coincides with the Eid al-Adha celebration, which was held from July 9 to July 10 in 2022 and from June 28 to June 29 in 2023. The event involves the sacrifice of livestock, primarily ruminants such as cattle, buffalo, sheep, and goats, which are susceptible to FMD. The demand for livestock during Eid al-Adha is particularly high in Indonesia, often exceeding one million animals annually [39]. The preparation of livestock sales for celebration typically begins months in advance. The high demand for sacrificial animals during this period significantly increases livestock movement, raising the risk of spreading FMD. Early sale and transport of livestock during this period can lead to disease transmission and complicate efforts to control outbreaks. Several studies have reported an association between the high demand for livestock during Eid al-Adha and the occurrence of FMD outbreaks [40–42]. Several studies also mention the surge of FMD outbreaks in Indonesia in 2022 may have been related to the increased demand for livestock a few months before the celebration [43, 44]. Further research is needed to explore the potential link between the celebrations and the emergence of FMD in Indonesia.

The spatiotemporal analysis in this study has limitations. The location coordinates are based on village centroids, which may introduce bias. This is because of the limitations of iSIKHNAS, which only facilitated the village location as the smallest spatial unit. Consequently, all outbreak farms within a village are assumed to share the same centroid, as these points do not represent the actual location of the outbreak farms. The STP model used in this study also focused only on the number of cases and did not include the population size. Future research should consider conducting similar studies in other regions or using more advanced models if finer-scale data become available.

The risk factor analysis at the subdistrict level revealed that annual precipitation, livestock market, slaughterhouse, animal health centre, and livestock population were linked to the occurrence of FMD outbreak. Factors such as annual precipitation had a negative impact on the outbreak. This is due to the livestock markets in Java, which are primarily situated in open fields and do not have sufficient cover to protect animals during the rainy season. Additionally, livestock transportation frequently relies on open trucks or pickup trucks, which limits livestock transportation in rainy conditions. This situation limited livestock trade and movement in subdistricts with higher precipitation and longer rainy seasons, which naturally restricted disease transmission between subdistricts.

This study aligns with several studies that found the association of FMD occurrence with the livestock population and agricultural-related factors, such as livestock markets and slaughterhouses [11, 12, 45]. Livestock markets are identified as significant contributors to FMD transmission, as they facilitate the trade of live animals that are often subsequently moved to new farms across different regions. Livestock markets can increase the risk of disease transmission due to the interactions between infected and healthy herds through close proximity, shared surfaces, or contaminated transport vehicles. Consequently, livestock markets represent a critical point in the livestock movement network, and their role in the spread of FMD is more pronounced. In contrast, slaughterhouses primarily deal with terminal movements of livestock, where animals are removed from the farming population upon slaughter. However, slaughterhouses may still contribute to FMD transmission through factors like improper handling or cross-contamination within the facility [46]. In addition, slaughterhouses play a crucial role in the livestock distribution network, as their presence indicates areas with high livestock movement from various locations. Livestock markets and slaughterhouses bring together animals from different regions, creating a high-risk environment for disease spread if biosecurity practices are not adequately implemented.

The presence of an animal health centre in a subdistrict is related to an increased risk of disease outbreaks. While these centres can lead to faster diagnoses and timely responses, they may become overcrowded and under-resourced during animal health emergency situations, hindering prevention and control efforts. Limited resources and staff shortages can result in suboptimal biosecurity measures, increasing the risk of disease transmission between farms. In such scenarios, shared equipment or vehicles, as well as the movement of animal health workers between farms, can inadvertently contribute to the spreading of FMD, especially if biosecurity protocols, such as disinfecting equipment or changing clothing, are not strictly followed. Moreover, the lower risk in subdistricts without an animal health centre may result from under-reporting due to inefficient surveillance.

The livestock population, especially cattle, is a major risk factor for FMD outbreaks. Cattle are highly susceptible to the virus and often display apparent clinical symptoms, facilitating faster identification and reporting of the disease. As a result, areas with larger cattle populations tend to see higher rates of FMD outbreaks. In contrast, small ruminants such as goats can also carry the virus and act as carriers, potentially spreading the disease to other livestock, even though they often show milder or subclinical symptoms, making the disease harder to detect [14, 15]. Without proper monitoring and biosecurity measures, goats can become a silent carrier, contributing to the spread of FMD within and between the farms.

In the final multivariable model, the decrease in coefficients for livestock-related facilities from univariable models is likely due to the inclusion of cattle and goat populations. This suggests that these facilities may overlap with livestock populations in regions with large livestock populations. Although no direct interactions were found, the inclusion of cattle and goat populations in the final model indicates potential confounding, as livestock populations are closely linked to the presence of these livestock-related facilities. With an AUC of 0.86, a Hosmer-Lemeshow test p-value of 0.18, and a Cragg & Uhler pseudo-R^2 of 0.44, the final model was deemed reliable, based on criteria for model evaluation [47–49].

A map of FMD probability risk showed that high-risk subdistricts are primarily located in the eastern and central regions of Java. This prediction aligned with the results from cluster analyses. These areas, along with several subdistricts in the western part of the island, have a higher risk of experiencing another FMD outbreak. Preventing and controlling recurrent outbreaks should be focused on these regions.

This study analyses data from FMD outbreaks in Java, Indonesia, from 2022 to 2023, examining their epidemiological characteristics in relation to existing data on FMD risk factors. However, there are limitations to consider. The FMD data in the study were obtained from a national reporting system that relies on notifications from farmers before the authorised veterinarian or investigator comes to observe the suspected cases. This may lead to underdetection of cases since the farmers may need proper knowledge of FMD or initiatives to inform the authorities about suspected cases. Additionally, the accuracy of case definition during outbreaks may be affected by the ability of veterinarian or investigator to determine clinical findings in the field before collecting representative samples for laboratory confirmation. However, the misdiagnosis based only on the clinical findings is very high since the animals may not develop clinical signs during the investigation [50].

Despite its limitations, the overall findings of this study remain relevant for understanding the FMD outbreak situation in Java, Indonesia. While local authorities actively notify farmers about outbreaks, and animal health workers conduct regular monitoring, resource constraints may have contributed to underreporting, particularly in areas without dedicated animal health centres. Nevertheless, the data used in this study have been validated by credible sources, enhancing their reliability. Although some cases may have been missed, the results still provide valuable insights into the outbreak dynamics and can inform future control and prevention strategies.

This study provides valuable insights for improving FMD prevention and control programs in Indonesia, especially in Java. The findings offer a detailed understanding of the spatial and temporal patterns of FMD outbreaks, helping authorities allocate resources more efficiently. By identifying regions and periods at higher risk for FMD outbreaks, officials can better target vaccination campaigns, surveillance, and biosecurity measures, accelerating FMD eradication efforts. Prioritising these high-risk areas will enable more strategic interventions, reduce the spread of the disease, and optimise the effectiveness of preventive and control measures nationwide.

Conclusion

Foot and mouth disease outbreaks were distributed across Java and predominantly clustered in eastern and central parts of Java. The outbreaks peaked in June 2022, followed by a downward trend until the end of 2023. Environmental and agricultural-related factors are significantly associated with the risk of FMD occurrence. The areas with a higher probability risk of FMD outbreak were primarily located in the eastern and central regions of Java. Insight into patterns and risk factors can help to improve the preventive and control program of FMD in Java.

Methods

Study area

The study area is the Java region, including six provinces that encompass 119 districts/municipalities and 2,146 subdistricts. The area of this study is shown in Fig. 8. This area covers Java Island and other adjacent islands under the administrative regions of respective provinces

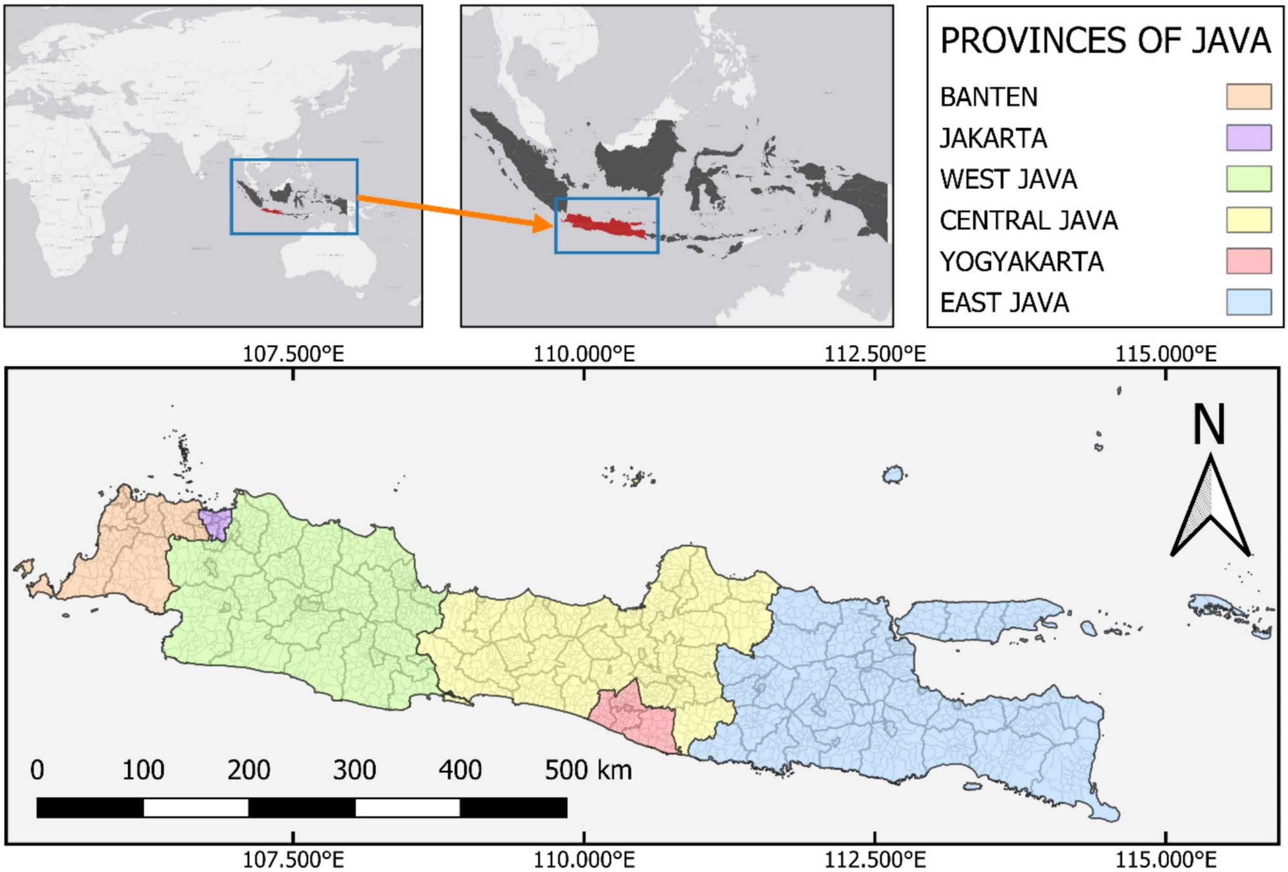


Fig. 8 Map of Provinces in Java

in Java. Provinces in Java can be divided into three parts: the eastern part includes the East Java Province, the central part includes Central Java and Yogyakarta Provinces, and the western part includes the West Java, Jakarta, and Banten Provinces.

Data source

The data on the FMD outbreaks were obtained from iSIKHNAS database. This study used reported FMD data in Java in 2022 and 2023. The data obtained from iSIKHNAS include the identification number, reported outbreak date, the number of sick animals, and the location of the outbreak farm. The locations of outbreak farms were represented by the centroid of each village. Any new outbreak report from a farm within the village used the same centroid location, given the limitations in precise farm coordinates. Documentation and verification of FMD cases were rigorously documented by veterinary officers based on observation of clinical signs, followed by laboratory confirmation tests for representative samples conducted by the Animal Disease Investigation Centre or veterinary laboratories across Java. A case is defined as an individual animal exhibiting clinical signs of FMD, while an outbreak farm is defined as a farm with at least one FMD case recorded in iSIKHNAS during the study period.

Data on the risk factors were obtained from official government publications in Indonesia. Base spatial maps were obtained from the Indonesia Geospatial Information Agency. Environmental data used in this study, including rainy periods and annual precipitation, were obtained from the Indonesia Agency of Meteorology, Climatology, and Geophysics, which provides standardized and reliable meteorological data at the subdistrict level across the country. The presence of an animal health centre in each subdistrict was obtained from the Ministry of Agriculture Indonesia [51]. The presence of livestock markets and slaughterhouses was obtained from the Indonesia Bureau of Statistics [28, 29]. The number of livestock farms, livestock population, insemination service businesses, and livestock health service businesses were obtained from the National Agricultural Census 2023 published by the statistical office (BPS-Statistics Indonesia) in each respective district and municipality [52].

Descriptive analysis

The number of cases and number of outbreak farms were calculated for each subdistrict on a monthly and weekly basis. The cases and outbreak farms were categorised by species and year and plotted as a graph on a weekly and monthly basis to show the temporal trend of FMD outbreaks. Given the significant variation in cases and outbreak farms over different periods, both the linear and logarithmic scale temporal graphs were employed to better illustrate the disease trends.

Spatial analysis

Spatial analysis was performed to analyse the spatial distribution of the FMD across Java. A standardised morbidity ratio (SMR) was calculated for each subdistrict in each year. SMR is calculated based on the number of observed cases divided by the number of expected cases. Expected cases are calculated based on the yearly national or regional incidence rate multiplied by the number of livestock populations in the subdistricts. SMR value of more than one indicates that the risk for the subdistrict is higher than the expected national or regional risk [11, 53]. The SMR can be calculated by

$$SMR = \frac{\sum_i O_i}{\sum_i E_i} = \frac{\sum_i O_i}{\sum_i (P_i \times I)}$$

where O_i is the number of observed cases in subdistrict, E_i is the number of expected cases in subdistrict, P_i is the number of livestock populations in subdistrict, and I is the incidence rate in Java as a regional reference. The number of years that subdistricts had SMR more than one was depicted in a choropleth map. A higher number of years with SMR more than one indicates that these subdistricts are more likely to act as hotspot areas of FMD outbreaks [11].

The spatial autocorrelation of SMRs was quantified using the global Moran's I index. The global Moran's I index can be calculated by

$$I = \frac{N \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \left(SMR_i - \overline{SMR}\right)\left(SMR_j - \overline{SMR}\right)}{\left(\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}\right) \sum_{i=1}^{N} \left(SMR_i - \overline{SMR}\right)^2}$$

where N is the number of subdistricts. SMR_i and SMR_j are the SMRs for the subdistrict i and subdistrict j, respectively. $\overline{SMR}$ is the average SMRs. w_{ij} is the spatial weight matrix that shows the level of spatial relationship between subdistricts. A positive Moran's I index implies a clustering of SMRs in the same neighbourhood areas, while a negative Moran's I index indicates the dispersion of SMRs [11, 54, 55].

Spatial autocorrelation at the local scale was assessed using Local Indicators of Spatial Autocorrelation (LISA), specifically through the Local Moran's I test for SMR in 2022 and 2023 [56]. LISA identifies the presence of spatial clusters by measuring the correlation of values with those of their neighbours. Local Moran's I index was calculated using a 4 K-nearest neighbour (KNN) spatial weight matrix. The resulting clusters were classified into High-High, Low-Low, High-Low, and Low-High, based on the Local Moran's I statistic and its corresponding p-value. The spatial analysis was performed using Python (version 3.12, Python Software Foundation) with the PySAL and ESDA libraries, and the results were visualised in QGIS (version 3.32, QGIS Development Team) to enhance graphical representation.

Spatiotemporal analysis

Spatiotemporal analysis in this study used space-time permutation (STP) scan statistics provided by SaTScan software (version 10.1, Martin Kulldorff). The STP model employs geographical coordinates to identify clusters of outbreaks [57]. The model involves a space-time window to determine the presence of clusters based on the likelihood ratio of the number of cases and expected cases within the window [31]. Input variables for the model include the number of FMD cases in each farm, the geographic coordinates of each farm, and the recorded date of the outbreak. Due to the limitations of the precise coordinates of the outbreak farm, this study assumed that all outbreak farms within the same village shared the same coordinates, using the centroid of the village as the reference point. The spatial window was set at 50% of the population at risk, and the temporal window was set at 50% of the study period. Time aggregation was set at seven days following the average disease incubation period [31]. The significance of identified clusters is assessed using a Monte Carlo simulation (number of replications = 999). The criteria of reporting clusters were set as no geographical overlap with a significance level below 0.05 [31, 33].

Risk factor analysis and mapping

Risk factor analysis was conducted using a logistic regression model. Each subdistrict was treated as an individual unit. The dependent variable was the presence of FMD outbreaks within each subdistrict from 2022 to 2023, categorised as binary. A value of one was assigned if an outbreak occurred in the subdistrict in either year; otherwise, it was recorded as zero. Independent variables in this analysis include environmental and agricultural-related factors. Environmental factors included rainy periods and annual precipitation. The rainy period was defined as the total length of rainy season in a 10-day period unit, and annual precipitation is defined as the total annual precipitation in millimetre unit (mm). Agricultural-related factors include the presence of livestock markets, the presence of slaughterhouses, the presence of animal health centres, the number of insemination service businesses, the number of livestock health service businesses, the livestock population, and farm size. The presence of livestock markets, slaughterhouses, and animal health centres within subdistricts were categorised as binary, while the insemination service business and livestock health service business were count variables, reflecting the total count in each subdistrict. Livestock population data including population of cattle, buffalo, goats, and sheep. Livestock population data in each species were transformed into logarithmic scale using $\log_{10}(\text{population}+1)$ to accommodate subdistricts with zero livestock population. Average farm sizes were obtained from the number of livestock populations divided by total livestock farm households in respective subdistricts.

The risk factor analysis was initially performed using univariable logistic regression analysis. Significant risk factors (p-value < 0.1) in univariable analysis were then subsequently included in multivariable logistic regression analysis with backward elimination [11]. Multicollinearity tests were performed to ensure that there were no highly correlated independent variables. Interactions between independent variables were also examined by adding interaction terms to the model, followed by backward elimination to assess the significance of the interactions. The final model was evaluated using various tests, including goodness-of-fit and pseudo-R-squared, to evaluate the performance of the model [47]. The probability of FMD outbreaks in each subdistrict was calculated based on the final model obtained from multivariable logistic regression. The probability risk of FMD in each subdistrict was calculated as follows:

$$probability\ risk = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n)}}$$

Where β_0 is the intercept. β_n is the coefficient of independent variable *n*, and X_n is the value of independent variable *n*. The analysis was implemented in SPSS (version 29.0, IBM SPSS Statistics) and R (version 4.4, R Core Team), complemented by probability risk mapping with QGIS software (version 3.32, QGIS Development Team).

Abbreviations

AUC	Area Under Curve
FMD	Foot and Mouth Disease
FMDV	Foot and Mouth Disease Virus
iSIKHNAS	Indonesia Integrated Animal Health Information System
KNN	K-nearest neighbour
LISA	Local Indicators of Spatial Association
OIE	Office International des Epizooties
SMR	Standardised Morbidity Ratio
STP	Space-Time Permutation
VIF	Variance Inflation Factor
WOAH	World Organisation of Animal Health

Acknowledgements
The authors thank the Directorate of Animal Health, Directorate General of Livestock and Animal Health Services, Ministry of Agriculture, Republic of Indonesia, for providing the FMD data from iSIKHNAS. We appreciate the contributions of each party with their respective roles in reporting the animal disease data at iSIKHNAS.

Author contributions
Virgilius Martin Kelake Kedang, Thanicha Chanchaidechachai, and Chaidate Inchaisri were responsible for design and conceptualization of the study. Indri Permatasari collected and sorted the data. Data analyses were performed by VMKK with suggestions from CI. VMKK drafted the manuscript with edits from CI. All the authors have read and approved the final manuscript.

Funding
This research was funded by the 90th Anniversary of Chulalongkorn University Scholarship under Ratchadapisek Somphot Fund 2024. The Faculty of Veterinary Science Chulalongkorn University provided the open access funding. The first author was supported by the Chulalongkorn University Graduate Scholarship for ASEAN and Non-ASEAN Countries.

Data availability
The FMD data in this study is available upon request from the Directorate of Animal Health, Directorate General of Livestock and Animal Health Services, Ministry of Agriculture, Republic of Indonesia.

Declarations

Ethics approval and consent to participate
No ethics approval was required in this study. Authority to use the data was obtained from the Directorate of Animal Health, Ministry of Agriculture, Republic of Indonesia.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 14 December 2024 / Accepted: 24 February 2025
Published online: 18 March 2025

References

1. Domingo E, Baranowski E, Escarmís C, Sobrino F. Foot-and-mouth disease virus. Comp Immunol Microbiol Infect Dis. 2002;25(5–6):297–308.
2. Jamal SM, Belsham GJ. Foot-and-mouth disease: past, present and future. Vet Res. 2013;44:1–14.
3. Adjid R. Penyakit mulut dan kuku: Penyakit hewan eksotik yang harus diwaspadai masuknya ke Indonesia. Wartazoa. 2020;30(2):61–70.
4. Ronohardjo P, Adjid A, Wirjono A, Abubakar M. Potensi berbagai vaksin mulut kuku yang dipakai dalam pemberantasan wabah penyakit. Penyakit Hewan. 1984;16:189–96.
5. Ronohardjo P, Nari J, Abubakar M, Sarosa A, Darminto, Adjid A, et al. Studi serologik penyakit mulut dan kuku selama penanggulangan wabah penyakit yang meletup bulan Juli 1983 di Jawa. Penyakit Hewan. 1986;18(32):94–117.
6. Soehadji, Malole M, Setyaningsih H, editors. The experience of Indonesia in the control and eradication of foot-and-mouth disease. Diagnosis and Epidemiology of Foot-and-Mouth Disease in Southeast Asia; 1993 September 6–9; Lampang, Thailand: ACIAR Proceedings.
7. Young PL, Ibrahim I, Soeharsono, Ronohardjo P, Hunt NT. Foot-and-mouth disease in cattle buffalo and sheep in Java. Aust Vet J. 1985;62(11):389.
8. Susila EB, Daulay RSD, Hidayati DN, Prasetyowati SRB, Wriningati, Andesfha E, et al. Detection and identification of foot-and-mouth disease O/ME-SA/Ind-2001 virus lineage, Indonesia, 2022. J Appl Anim Res. 2023;51(1):487–94.
9. Zainuddin N, Susila EB, Wibawa H, Daulay RSD, Wijayanti PE, Fitriani D, et al. Genome sequence of a foot-and-mouth disease virus detected in Indonesia in 2022. Microbiol Resource Announcements. 2023;12(2):e01081–22.

10. Lase J, Mendrofa V, Putra W, Ardiarini N, Rafian T, Archadri Y, et al. The situation of foot and mouth disease (FMD) virus in Indonesia: data infections and transmission routes. AIP Conf Proc. 2024;AIP Publishing:070021.
11. Chanchaidechachai T, Saatkamp H, de Jong M, Inchaisri C, Hogeveen H, Premashthira S, et al. Epidemiology of foot-and-mouth disease outbreaks in Thailand from 2011 to 2018. Transbound Emerg Dis. 2022;69(6):3823–36.
12. Gao H, Ma J. Spatial distribution and risk areas of foot and mouth disease in Mainland China. Prev Vet Med. 2021;189:105311.
13. Dede M, Sunardi S, Widiawaty MA, Ismail A, Lam KC, Afriana NN, et al. Spatial distribution and environmental factors analysis of foot-and-mouth disease (FMD) in West Java, Indonesia. Cogent Food Agric. 2025;11(1):2440549.
14. Arzt J, Baxt B, Grubman M, Jackson T, Juleff N, Rhyan J, et al. The pathogenesis of foot-and-mouth disease II: viral pathways in swine, small ruminants, and wildlife; myotropism, chronic syndromes, and molecular virus–host interactions. Transbound Emerg Dis. 2011;58(4):305–26.
15. Rout M, Subramaniam S, Mohapatra J, Pattnaik B. Clinico-molecular diagnosis and phylogenetic investigation of foot-and-mouth disease in small ruminant population of India. Small Ruminant Res. 2016;144:1–5.
16. Antari L, Kusumastuti T, Juwari A, Widiati R. Policy response on handling of foot and mouth disease outbreaks in Indonesia. IOP Conf Series: Earth Environ Sci. 2024;1341(1):012089.
17. Kementan. Keputusan Menteri Pertanian Republik Indonesia Nomor 403/KPTS/PK.300/M/05/2022 tentang Penetapan Daerah Wabah Penyakit mulut dan Kuku (Foot and Mouth Disease) pada Beberapa Kabupaten di provinsi Jawa Timur. Jakarta: Kementerian Pertanian Republik Indonesia; 2022.
18. Kementan. Keputusan Menteri Pertanian Republik Indonesia Nomor 510/KPTS/PK.300/M/6/2022 tentang Vaksinasi dalam Rangka Penanggulangan Penyakit Mulut dan Kuku (Foot and Mouth Disease). Jakarta: Kementerian Pertanian Republik Indonesia; 2022.
19. Kementan. Keputusan Menteri Pertanian Republik Indonesia Nomor 517/KPTS/PK.300/M/7/2022 tentang Perubahan atas Kepmentan Nomor 510 tentang Vaksinasi dalam Rangka Penanggulangan Penyakit Mulut dan Kuku (Foot and Mouth Disease). Jakarta: Kementerian Pertanian Republik Indonesia; 2022.
20. Prihatin KW, Amaliya A, Musaffak TR, Rosyada ZNA. Effect of foot and mouth diseases vaccination on basic semen quality parameter in Bali cattle. Jurnal Medik Veteriner. 2023;6(3):37–41.
21. Belsham GJ. Towards improvements in foot-and-mouth disease vaccine performance. Acta Vet Scand. 2020;62(1):20.
22. Peta FR, Sirdar M, van Bavel P, Mutowembwa P, Visser N, Olowoyo J, et al. Evaluation of potency and duration of immunity elicited by a multivalent FMD vaccine for use in South Africa. Front Veterinary Sci. 2021;8:750223.
23. Knight-Jones TJ, Bulut A, Gubbins S, Stärk K, Pfeiffer DU, Sumption KJ, et al. Randomised field trial to evaluate serological response after foot-and-mouth disease vaccination in Turkey. Vaccine. 2015;33(6):805–11.
24. Singh RK, Sharma GK, Mahajan S, Dhama K, Basagoudanavar SH, Hosamani M, et al. Foot-and-mouth disease virus: immunobiology, advances in vaccines and vaccination strategies addressing vaccine failures—an Indian perspective. Vaccines. 2019;7(3):90.
25. Kementan. Keputusan Menteri Pertanian Republik Indonesia Nomor 285/KPTS/PK.320/M/06/2023 tentang Peta Jalan Pemberantasan Penyakit Mulut dan Kuku (Foot and Mouth Disease) dari Wilayah Negara Kesatuan Republik Indonesia. Jakarta: Kementerian Pertanian Republik Indonesia; 2023.
26. BPS. Hasil Pencacahan Lengkap sensus Pertanian 2023 - Tahap II: Usaha Pertanian Perorangan Peternakan (Complete enumeration results of the 2023 census of Agriculture - Edition 2: livestock individual agricultural Holdings). Jakarta: BPS Statistics Indonesia; 2024. 571 p.
27. Kementan. Statistik Peternakan dan Kesehatan Hewan 2022. Jakarta: Kementerian Pertanian Republik Indonesia; 2022. p. 276.
28. BPS. Direktori Perusahaan Pertanian Rumah Potong Hewan (RPH) dan Tempat Pemotongan Hewan (TPH) 2023. Jakarta: Badan Pusat Statistik; 2023. 550 p.
29. BPS. Direktori Pasar dan Pusat Perdagangan Buku II: Pulau Jawa, Bali, Nusa Tenggara, dan Kepulauan Maluku. Jakarta: Badan Pusat Statistik; 2020. 833 p.
30. Chen J, Wang J, Wang M, Liang R, Lu Y, Zhang Q, et al. Retrospect and risk analysis of foot-and-mouth disease in China based on integrated surveillance and Spatial analysis tools. Front Veterinary Sci. 2020;6:511.
31. Arjkumpa O, Sansamur C, Sutthipankul P, Inchaisri C, Na Lampang K, Charoenpanyanet A, et al. Spatiotemporal analyses of foot and mouth disease outbreaks in cattle farms in Chiang Mai and Lamphun, Thailand. BMC Vet Res. 2020;16:170.
32. Arjkumpa O, Suwannaboon M, Boonrod M, Punyawan I, Liangchaisiri S, Laobannue P, et al. The first lumpy skin disease outbreak in Thailand (2021): epidemiological features and spatio-temporal analysis. Front Veterinary Sci. 2022;8:799065.
33. Kulldorff M. SaTScanTM user guide v10.1. SaTScan; 2022.
34. Anggraini L, Ngadiyono N, Bintara S, Baliarti E. Sustainability studies of smallholder livestock based on Climatological conditions, land resources and farmer profile. IOP Conf Series: Earth Environ Sci. 2021;667(1):012091.
35. Azizah S, Kawedar YB. The effects of farming beef cattle on Baluran National park conservation (case study in Karang Tekok, Banyuputih district, Situbondo Regency). Ecol Environ Conserv. 2020;26:1–8.
36. Hilmiati N, Ilham N, Nulik J, Rohaeni ES, deRosari B, Basuki T, et al. Smallholder cattle development in Indonesia: learning from the past for an outcome-oriented development model. Int J Des Nat Ecodyn. 2024;19(1):169–84.
37. Nastiti NA, Riyanto J, Dewanti R, Cahyadi M, Wati AK, Pawestri W, et al. Reproduction and production performance of swamp Buffalo (Bubalus bubalis) at the small-scale holder farmer in Sragen Regency, central Java, Indonesia. Jurnal Sain Peternakan Indonesia. 2023;18(3):140–7.
38. Auty H, Mellor D, Gunn G, Boden LA. The risk of foot and mouth disease transmission posed by public access to the countryside during an outbreak. Front Veterinary Sci. 2019;6:381.
39. Ibrahim A, Budisatria IGS, Widayanti R, Artama WT. The impact of religious festival on roadside livestock traders in urban and peri-urban areas of Yogyakarta, Indonesia. Veterinary World. 2019;12(9):1408.
40. Abd El-Rahim I, Asghar A, Mohamed A, Fat'hi S. The impact of importation of live ruminants on the epizootiology of foot and mouth disease in Saudi Arabia. Rev Sci Tech. 2016;35:769–78.
41. Al-Rawahi WA, Elshafie EI, Baqir S, Al-Ansari A, Wadsworth J, Hicks HM, et al. Detection of foot-and-mouth disease viruses from the A/AFRICA/GI genotype in the Sultanate of Oman. Prev Vet Med. 2024;223:106113.
42. Bouguedour R, Ripani A. Review of the foot and mouth disease situation in North Africa and the risk of introducing the disease into Europe. Rev Sci Tech. 2016;35(3):757–68.
43. Daud M, Abrar M, Ferasyi T, Harapan H. Temporal Geospatial mapping of foot and mouth disease outbreak in Aceh, Indonesia. Adv Anim Veterinary Sci. 2024;12(6):1148–56.
44. Toyyibi AM. Religious life, economy when the plague of foot and mouth disease ahead of Eid Al-Adha sharia maqashid perspective. International Conference on Islamic Studies (ICIS) IAIN Ponorogo. 2022:99–107.
45. Ali I, Rehman A, Mushtaq MH, Ijaz M, Khaliq MS, Khan MSU, et al. Outbreak investigation and identification of risk factors associated with the occurrence of foot and mouth disease in Punjab, Pakistan. Prev Vet Med. 2022;202:105613.
46. Paton D, Sinclair M, Rodriguez R. Qualitative assessment of the commodity risk for spread of foot-and-mouth disease associated with international trade in deboned beef. Transbound Emerg Dis. 2010;57(3):115–34.
47. Dohoo I, Martin W, Stryhn H. Veterinary epidemiologic research. 2nd ed. Charlottetown: VER Inc.; 2009. p. 865.
48. Hemmert GA, Schons LM, Wieseke J, Schimmelpfennig H. Log-likelihood-based pseudo-R 2 in logistic regression: deriving sample-sensitive benchmarks. Sociol Methods Res. 2018;47(3):507–31.
49. Smith TJ, McKenna CM. A comparison of logistic regression pseudo R2 indices. Multiple Linear Regres Viewpoints. 2013;39(2):17–26.
50. Cabezas AH, Sanderson MW, Volkova VV. A meta-population model of potential foot-and-mouth disease transmission, clinical manifestation, and detection within Us beef feedlots. Front Veterinary Sci. 2020;7:527558.
51. Kementan. Pedoman Pelayanan Pusat Kesehatan Hewan (PUSKESWAN). Jakarta: Kementerian Pertanian; 2020. p. 187.
52. BPS. Sensus Pertanian 2023 - Badan Pusat Statistik: Badan Pusat Statistik; 2023 [cited 2024 August 09]. Available from: https://sensus.bps.go.id/main/index/st2023
53. Waller LA, Gotway CA. Applied Spatial statistics for public health data. New Jersey: Wiley; 2004. p. 494.
54. Bivand R, Pebesma E, Gómez-Rubio V. Applied Spatial data analysis with R. New York: Springer; 2013. p. 405.
55. Gómez-Rubio V, Ferrándiz-Ferragud J, López-Quílez A. Detecting clusters of disease with R. J Geogr Syst. 2005;7:189–206.
56. Costa ACTRB, Bhowmick S, Lowe JF, Lage AP, de Oliveira LF, Dorneles EMS. A Spatiotemporal analysis of bovine brucellosis cases in Minas Gerais State, Brazil, from 2011 to 2018. Prev Vet Med. 2024;224:106101.

57. Kulldorff M, Heffernan R, Hartman J, Assunçao R, Mostashari F. A space–time permutation scan statistic for disease outbreak detection. PLoS Med. 2005;2(3):e59.

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