Analysis of the spatial and temporal risk of Peste des Petits Ruminants Virus (PPRV) outbreaks in endemic settings: A scoping review

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Abstract

Surveillance shows that Peste des Petits Ruminants (PPR) is endemic in both Africa and Asia due to its continuous circulation. Several epidemiological factors work together to support PPR's geographical spread. To investigate the risk of PPR transmission, analytical techniques based on spatial, spatiotemporal, and transmission dynamics have been employed. The risk factors linked to the spatiotemporal distribution and transmission dynamics of PPR at the regional level are poorly understood. This study assessed the risks of Peste des Petits Ruminant Virus (PPRV) epidemics during a comprehensive evaluation of peer-reviewed literature, highlighting the differences between geographical and spatial-temporal techniques used in endemic zones. Utilizing the PubMed and Google Scholar databases, a scoping literature analysis of PPR research papers that evaluated PPR risks in endemic areas using spatial and spatiotemporal techniques was conducted. Eight papers with a global perspective were chosen from 42, 20 of which focused on Asia and 14 on Africa. Of these, 35.7% employed spatial autocorrelation, while 61.9% used clustering analysis. The majority of the studies (71.2%) described temporal trends, whereas 13 publications (30%) used modelling methodologies. Geographic accessibility (n = 19), trade and commerce (n = 17), environment and ecology (n = 12), socioeconomic variables (n = 9), and demography and livestock–wildlife interactions (n = 20) are the five risk factors that were assessed. All the risk factors were related; however, only two papers discussed

the transmission dynamics of PPR. Our understanding of PPR outbreaks in endemic environments has improved because of the review, which also encourages evidence-based decision-making to lessen the virus's effects on small ruminant populations. It has been demonstrated that the association of additional risk variables with livestock trade, the primary force behind livestock migration, significantly increases the probability of PPR outbreaks in endemic areas. Since many studies are conducted in Asia rather than Africa, Africa should be included in future predictive model development to evaluate possible eradication strategies at the national and regional levels.

Keywords: Peste des Petits Ruminant (PPR) epidemics, risk factors, spatial methods, spatiotemporal methods

Context .1

A virus known as Peste des Petits Ruminants (PPR) affects small ruminants, primarily sheep and goats, but it can also infect other domestic animals (1). The PPR virus (PPRV) is a single-stranded, non-segmented RNA virus of the genus *Morbillivirus* in the family *Paramyxoviridae* (2). PPRV's genome spans 15,948 nucleotides (nt) and is structured into six open reading frames (ORFs). The six structural proteins that are encoded by these ORFs are the polymerase (P) or large protein (L), fusion protein (F), phosphoprotein (P), matrix protein (M), hemagglutinin protein (H), and nucleoprotein (N). Additionally, the non-structural proteins C and V are encoded by the ORF transcription unit (3). Four lineages have been described based on two structural proteins, N or F, by phylogenetic studies using partial gene sequences (3). These lineages of PPRV are distributed in several geographical areas, including Africa, Asia and, Europe (4). All four PPRV lineages are present in Africa, where lineage I viruses have been confined to West African countries since 1940. Lineage II is predominantly present in West Africa, although it has recently been reported in the Democratic Republic of the Congo (DRC) and Tanzania (5). Although Lineage III is prevalent throughout northeastern, eastern, and central Africa, as well as the Comoros Islands, it has not been seen in the north or west of the continent (5). To date, PPR has been identified in the northern, western, central, and eastern regions of Africa and is gradually moving southwards. Hundreds of millions of domestic small ruminants and wildlife are at risk of infection as PPRV continues to spread across previously uninfected regions (6). However, the PPRV infection that has been found in previously uninfected areas and the admixture of lineages in countries that have been infected jointly emphasize the geographically and temporally dynamic character of PPR (7). With annual global economic losses estimated at approximately $1.45 to 2.1 billion USD, half of these losses impact Africa,

and a quarter affect Asia. Like other livestock respiratory diseases, losses are caused by mortality, which reaches up to 20% in naive populations, and morbidity, which reaches up to 100% (8,9). A global program to eradicate PPR by 2030 has been formally launched by the Food and Agriculture Organization (FAO) and the World Organization for Animal Health (WOAH), formerly known as the OIE, due to the high impact of PPR on sheep and goat farmers (10). Global PPR eradication campaigns adopt spatial and spatiotemporal risk analysis models for disease prevention, focusing on PPR risk factors and disease transmission dynamics in livestock contacts (11). Network analysis, prediction, and simulation models can be used to identify PPR clusters and their drivers, providing crucial information for disease investigation (12). The enormous availability of such information could support the development of locally adapted control and surveillance strategies (13). Combining such risk factor information with genetic and mobility network data may make it possible to identify disease hotspots, which are crucial for virus entry and dissemination to various regions (13). Identification of PPR hotspots will involve the use of spatial and spatiotemporal tools to analyze PPR epidemic data. Such analysis will also explore the patterns and risk factors of the disease (14). Nevertheless, a variety of spatiotemporal tools are accessible for evaluating a range of spatiotemporal hypotheses to meet distinct goals. When testing a hypothesis, the outcomes of such a study can be directly compared if the analytical methods used are well understood (15). For instance, studies examining how local elements like topography, socioeconomics, demography, and environment can impact disease reporting, identification, and circulation change over time and space (16). An important step in choosing a model's parameters is to consider the disease pathway that is thought to connect epidemiological factors with epidemics (15). In this aspect, disease transmission dynamics are contextualized to a specific location where the contact network is factored into disease diffusion

to various areas. The need for this review remains critical because of the overall knowledge gap on the effectiveness of these tools in the analysis of PPR control in endemic situations (16). To our knowledge, no studies have reviewed the spatial and spatiotemporal methodologies used in PPR research. A narrative review by Mdetele et al (2021) (17) summarizes the occurrence and distribution of PPR in Tanzania. In addition to estimating the prevalence of PPR in sheep and goats, systematic review publications assess probable contributing factors to the disease's heterogeneity in prevalence and distribution (4). The only scoping review conducted by (18) was on PPR diagnostic platforms. Prior reviews did not discuss models, variables, spatial, and spatiotemporal methodological frameworks for PPR risks, leading to a significant lack of information on risk-based spatial and spatiotemporal analysis Kinimi *et al* (2020) (19). By filling this gap, PPR can be controlled and eventually eradicated. This study evaluates spatial and spatial-temporal methodological approaches in Peste des Petit Ruminant (PPR) epidemics, aiming to identify priority research areas, suggest interventions, and standardize modeling inputs for improved comparability.

Data acquisition .2

Protocol .2.1

In compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) standards, a scoping literature review was carried out (Sup. Table 1), in which a checklist for scoping reviews was adopted (20). The approach suggested by Arksey & O'Malley was followed in this study, which included formulating the research question, finding pertinent sources, choosing references, charting the data, compiling, summarizing, and reporting the findings (20) (Figure 1).

Research Questions Identification .2.2

The research questions listed below were the main focus of the scoping review:

(a) What techniques have been applied to investigate PPRV's spatiotemporal and spatial distribution in endemic environments?

(b) Based on the examination of those occurrences, what is known regarding PPR risk from the literature (e.g., finding clusters, hotspots, or seasonal or temporal tendencies)?

(c) Which risk variables have been examined and linked to PPR prevalence in endemic areas in Asia and Africa?

(d) How do the risk factors under investigation affect the dynamics of PPRV transmission?

Search strategy and selection criteria .2.3

Spatial and spatial-temporal analysis served as the basis for a scoping evaluation of the PPRV threats. Risk factors in endemic areas were discovered with the assistance of a library professional for an electronic bibliographic search, and the search strategy comprised a set of keywords on spatial and spatiotemporal techniques. Two computerized bibliographic databases

were systematically searched to find peer-reviewed original publications published in English-language journals between January 1993 and June 2024. The peer-reviewed publications that were part of this review were found using Google Scholar and the MEDLINE (PubMed) database. Boolean operators were used to select the papers based on phrases like "peste des petits ruminant virus (PPRV) AND risks AND spatial and spatial-temporal analysis AND epidemics AND endemic countries." In order to get results, essential terms were trimmed down during the PubMed search. A total of 766 documents were found through the searches of the two electronic databases (Google Scholar: 648, and PubMed: 118, as shown in Figure 2).

Eligibility criteria .2.4

PPR research using spatial, temporal, or spatiotemporal techniques for data analysis and inference was considered in this scoping review. Studies on various spatiotemporal analytical tools that can be employed for epidemiological research are based on the classification put forward by Kanankege (2020) (21). These can be categorized according to the analysis's goals: (a) description and visualization, (b) pattern identification and geographical or spatiotemporal dependence, (c) spatial smoothing and interpolation, and (d) modeling and regression research. We were especially interested in research that included putative PPR risk factors to forecast illness occurrence or that looked at epidemiological parameters associated with PPR outbreaks at the population level within the modeling and regression category. All publications with original peer-reviewed articles were chosen to meet the inclusion requirements. Based on data from the most recent WOAH list of members and areas designated as PPR-free (Resolution No. 17, 89th General Session, May 2022), PPR endemicity was determined. However, research carried out in nations with recognized free zones or PPR-free certifications, like Russia, was eligible for inclusion (22). Consequently, research that (a) used data from population outbreaks in PPRV-

endemic nations; (b) reported patterns or distributions of PPR epidemics; or (c) used data that was geographically or temporally connected to model PPR risk; (d) was published in an English-language peer-reviewed scientific publication between January 1990 and July 2024; and (e) confirmed cases of PPR in wildlife and livestock (such as cattle, small ruminants, and camels) were taken into account for inclusion.

Exclusion criteria

Excluded were studies that used data from farm epidemic surveys that included risk factors and self-reported PPR occurrences. Furthermore, this synthesis excluded studies that were intended to be risk assessments, epidemic investigations, or narrative literature reviews that reported PPR occurrence and trends (without further data analysis). Studies from nations that are known to be PPR-free, with or without immunization, were not included in the review, as Figure 1 illustrates.

Selection of relevant and reliable studies .2.5

To balance sensitivity and specificity in research, a search method was created utilizing electronic databases, Boolean, and proximity operators. Titles and abstracts were used to filter reports, removing duplicates and irrelevant papers. Reasons for exclusion were noted, and full texts were obtained for inclusion. Articles were examined for selection by two reviewers with expertise in molecular epidemiology and PPR surveillance. Conflicts that arose during the screening process were resolved.

Figure 1: PPR status depending on the acknowledgement of WOAH PPR. The grey areas are either unregistered PPR status, endemic, or reported occasional incidents.

Data extraction from included studies .2.6

Every study's data was extracted by a single reviewer using a pre-made, standardized form in a Microsoft Excel spreadsheet that contained the following:

(a) Study attributes including author, publication year, years examined, nation, geographic reach, and species;

(b) PPR epidemic information and diagnosis, including the surveillance system, data source, and diagnostic criteria;

(c) The type of analytical tool used, the process for grouping and identifying patterns in the data, the method for assessing the data based on time and season, and the list of epidemiological factors that were investigated and their outcomes.

JJM and JNH extracted and validated data from papers, analyzing them for accuracy and quality appraisal. Spatial distribution, cattle commerce, weather, climate change, and species/age/sex were among the topics found through thematic analysis.

Collating, summarizing, and reporting the findings .2.7

The sizes and data formats suggested by Carpenter, (2001) (15) were used to categorize the methods for formally evaluating the existence of clusters. As previously mentioned by Kanankege, (2020) (21), the framework was adapted to categorize analytical tools for spatial or spatial-temporal analysis according to their function. Using five primary categories, epidemiological models examine the variables that affect PPRV introduction, transmission, survival, and the efficacy of control strategies; A) spatial accessibility; (b) the demography of livestock and the interactions between livestock and wildlife; (c) the trade in livestock; (d) socioeconomic considerations; and (e) ecology and environment. The term "other factors" was used to group epidemiological covariates that did not fall into any of the categories (Sup. Table 2

and Figure 4). By merging essential elements and presenting data narratively, the review investigates the relationship between epidemiological determinants and PPR epidemics. R version 4.3.3 (*ggplot2*, *webR*, *tidyr*, and *dplyr*) was used for the analyses (23).

Results .3

General characteristics of the selected studies .3.1

A total of 42 studies for the quantitative synthesis and 57 papers for the qualitative synthesis were included using the electronic search approach. Out of the original pool of approximately 766 publications that were screened, 101 were examined in full text, and 57 of those were removed due to their inability to meet the eligibility requirements (Figure 2).

Figure 2: Flowchart showing the bibliographic search and final inclusion of study records in the review

Time intervals and geographic regions .3.2

In Africa and Asia, the distribution of studies by geographic scale and scope differed (Figure 3). The research included in Figure 3 spans 21 nations across two continents (Africa and Asia). Most studies were carried out at the national level using PPR pandemic data from official sources (95%), with 45% covering the entire country. PPR epidemics were frequently identified based solely on clinical presentation in most studies, with data gathered through passive monitoring systems (37.5%) (Sup. Table 2). Studies varied in the cattle species for which outbreaks were documented and in the spatial units used for analysis (Sup. Table 2). Epidemic reports from sheep and goats were included in certain research (50%, n = 20). Nevertheless, PPR epidemics in other species categories were examined in 2.5–5% of the documented investigations. Several studies examined long-term epidemic data, the longest being a 44-year

PPR outbreak case series from India (24). Eleven studies analyzed epidemic data collected over a ten-year period; however, the duration of each study varied (median = 3 years; range: 1–44). Although a number of papers included diverse analytical tools and objectives, the majority focused on the description and visualization of epidemics.

Figure 3: Geographical distribution of the papers that were part of the scoping review.

Figure 4: Classification of risk variables for Peste des Petits Ruminants outbreaks using conceptual frameworks.

Methods used to identify spatial and temporal variations of PPRV risk factors .3.3

Error! Reference source not found. shows various spatial, temporal and spatiotemporal methods used to visualize patterns, explore spatial clusters, and model risks across space and time. Although the results of some studies suggested the use of these techniques, they did not clearly state how useful they were. Over half of the studies used spatial clustering analysis techniques to test the hypothesis of non-random PPR epidemics. Specifically, 35.7% used spatial tools, while 26.2% applied spatial-temporal methodss. Four studies used various approaches for identifying clusters in parallel, including Moran's I, maximum entropy spatial statistic, Getis-Ord, and the Clark Evans test. SaTScan was used for simultaneous cluster detection (11). In three studies, the direction of PPR epidemic progression was determined using spatiotemporal directionality tests.

Figure 5: Dimensions and data forms used for classification of cluster analysis, modified from

Spatial autocorrelation or spatial clustering .3.4

Of the investigations, 35.7% (n = 15) showed evidence of using PPR spatial autocorrelation approaches for illness cluster identification. However, because different methods were employed to find these clusters (unusual aggregations of epidemics) and hotspots (excess levels of epidemics compared to a threshold level), the data configuration of these findings tended to differ both within and between studies (16). Heterogeneous results were reported by four studies, which noted the discovery of random or clustered patterns that differed depending on the time period or analytical technique. For instance, several studies found that the identification of spatial association was impacted by annual changes (25–27). The subsequent two investigations (11,28) found random spatial patterns and clustering tendencies that changed over time, as well as different clustering techniques applied in the research. Sup. Table 5 summarizes the cluster evaluation techniques and overall results of the assessed studies. Possibly as a result of local disease status, tool modifications, hypothesis testing, and assumptions made, cluster size, as indicated by a significant radius, varies greatly between studies.

Temporal and seasonal trends assessment .3.5

Depending on the underlying data's temporal aggregation, the majority of studies (71.2%, n = 30) detailed the temporal patterns of PPR outbreaks aggregated each day, week, month, or year. The model known as the Generalized Linear Negative Binomial Regression (11), Generalized Linear Mixed Models (GLMMs) (29), Negative Binomial (27), linear (13,24,30,31) or logistic regression models (32) were used to explore or test hypotheses related to temporal trends. Other studies resorted to Bayesian approaches (2,3,33). The NAADSM (North American Animal Disease Spread Model) (12,34), Autoregressive Integrated Moving Average Model (ARIMA) (35), Least Cost Path (LCP) (36), Random Forest (26), Ensemble algorithm (37), Event-Driven Memoryless model of state transitions (38), Regression Tree Models (26), and Mantel

Correlograms (13), were employed to investigate the relationship between genetic distances and various measures of network and geographic distance. Moreover, four studies formally analyzed PPR seasonality through the assessment of seasonal trends distributed geographically and socioeconomically (1,22,24,25).

Modelling approaches .3.6

A variety of geographical and spatial-temporal tools were used to evaluate the relationship between a number of epidemiological parameters and PPR epidemics, as well as to describe the patterns of PPR epidemic distribution and identify disease hotspots using clustering approaches. Thirteen (30.9%) of the studies in this study used covariables to forecast PPR risk, create risk probability maps, or investigate the relationship between population-level epidemiological factors and the outbreaks. Eleven studies modeled or projected PPR counts (19%, n = 8) using epidemiological parameters (11,14,27,33,35–37,39–41)**.** Six studies focused only on predicting PPR epidemics using epidemiological factors as covariates to forecast the PPRV suitability area and estimate the spatial risk based on the number of outbreaks in PPR passive surveillance data (25–27,37,42,43). Transmission dynamics were also evaluated using a metapopulation model (33). Before applying statistical models to evaluate the risks of the PPR epidemic, visualizations and descriptions of numerous PPR epidemics were conducted. These visualizations and descriptions provided an effective environment for understanding the distribution of the PPR epidemic over space and time. Data visualization and descriptions were used by 34 studies (80.9%), and this was the most reliable method used by all the studies to present the distribution of PPR epidemics. Various analytical approaches used for data visualization and description include GLMNB (11), GLMMs (29), and negative binomial to evaluate the possible risk factors

linked to each outbreak's PPR disease case count (1,27). Either linear regression models (13,24,30,31) or logistic regression models were used to explore or test hypotheses related to temporal trends. GeoDa 1.14.0 was used to perform Geographically Weighted Regression (GWR), with climate and geographical variables acting as predictors and log-transformed PPR cumulative incidence serving as the dependent variable (28). Bayesian techniques, such as Bayesian Time-Scaled Phylogenetic Analysis, were used in other investigations (2,3,44) along with the Empirical Bayesian Kriging (EBK) technique for risk map generation and geostatistical prediction. NAADSM (North American Animal Disease Spread Model) (12), Autoregressive Integrated Moving Average Model (ARIMA) (35), Least Cost Path (LCP) (36), The Naïve Bayes (NB) and Random Forest machine learning algorithms (26), Ensemble algorithm(37), Regression Tree Models (26), and Mantel Correlograms (13) were employed to examine the relationship between genetic distances and various measures of geographical and network distance. The seasonal population matrix model was used to assess the ability of different vaccination schedules that can be incorporated into the PPR control program (45). Using ArcGIS v10.4, hot spot and cluster analyses were performed to determine the hot and cold spot regions (1). Maximum Entropy Ecological Niche (MaxEnt) modeling was employed to detect suitable areas for PPR virus distribution (46). GIS-based multi-criterion decision analysis was used to identify areas at risk of PPR occurrence and spread (43). To investigate how the virus spreads during memoryless state transitions in Afghanistan, an event-driven model of PPR derived from the Susceptible-Exposed-Infectious-Recovered (SEIR) model was employed (38).

Epidemiological risk factors associated with PPR epidemics .3.7

Nine studies found that socioeconomic factors significantly influence PPR risk, even though trade and commerce, environmental and ecological conditions, animal demographics, spatial accessibility, and other epidemiological features accounted for a larger share of the variation. Risk factors linked to PPR outbreaks in Asia and Africa are identified in the review, as shown in Figure 6 and Sup. Table 4. Two studies were not examined, and epidemiological parameters were incorporated across studies, indicating a consistent risk pathway linking them to outbreaks. The study lists all examined covariables in detail in Figure 6 and Sup. Table 4.

Figure 6: Distribution of models at regional and subregional levels, containing variables from every category in the conceptual framework

Livestock demographics and livestock–wildlife interactions .3.7.1

According to Sup. Table 2, The primary objective of twenty studies (six in Africa, twelve in Asia, and one worldwide) was to identify hotspots by examining the impact of susceptible livestock populations on PPR risk. Sheep and goat populations were reported as covariates more frequently than other susceptible species, even though many other species were taken into consideration (e.g., camel, cattle, and pigs) (Sup. Table 2). In three out of 17 studies, there was a correlation between small ruminant population size and sheep and goat density, or a higher risk of PPR (19,32,47). In general, 47.4% (7/19) of research done in Asia and Africa linked this category of wildlife-livestock interaction to PPR risk.

Livestock Trade .3.7.2

Livestock trade-related factors were included in 19 studies, nine in Africa and 10 in Asia, as in Sup. Table 2. Eight studies (three in Africa and five in Asia) included the distance or adjacency

to an international boundary in their models, demonstrating the common goal of examining the impact of international connections on PPR risk using proxy variables that represented the likelihood of an international trade network or cross-border movements. Six investigations found that the incidence of PPR decreased with increasing distance to an international border (11,13,27,36,48,49). Additionally, elements of the market dynamics were taken into account, such as the movement of live animals or their products. Identifying markets in China, Ethiopia, Uganda, and Comoros was crucial for determining the outbreaks in those countries (1,11,47,50). Two investigations examined the relationship between PPR epidemics and human demography (25,49).

Accessibility and networks .3.7.3

Using topographical and landscape factors such as water bodies and permanent transport networks, 14 studies (five in Africa, seven in Asia, and two worldwide) investigated PPR risk (Sup. Table 2). Studies in African countries show a link between spatial accessibility and PPR risk, while Asia has a different association. Greater risk is found near major transportation routes or dense road networks (11,43). According to one Ethiopian study, one of the primary indicators of PPR transmission was the quantity of successful encounters per unit of time (at pastures or watering spots, as well as through live-animal commerce) (33). Four studies assessed the influence of natural landscape elements on inland waterbodies and rivers, with only one highlighting the buffering effect of adjacent waterbodies against PPR (25).

Association between environmental factors and PPR epidemics .3.7.4

The review of 13 studies on PPR outbreak risks, including those in Africa, globally, and Asia, identified 10 environmental and ecological factors as key categories (Sup. Table 2). The most frequently analyzed features were season, temperature, and precipitation (1,22,24–26,30,37,49).

Landscape was also assessed by five studies (25,31,42,49). Seasonality, landscape, weather, and climate-related covariables are strongly linked to PPR epidemics, with lower altitudes being more associated with PPR risk compared to higher altitudes (25,27,49). Temperature, precipitation, humidity, sun radiation, wind speed, and other variables that affect land cover status all have an impact on PPR epidemics (25,26,37). Studies in Asia (4/4) and Africa (3/15) found a correlation between PPR risk and ecological features, but the variables investigated varied, indicating different analytical goals.

3.7.5. Economic and social advancement

Only nine studies (Sup. Table 2) (27) used socioeconomic data to evaluate the risks of PPR spread globally and in the Republic of Kazakhstan, respectively, using socioeconomic and geographic factors such as landscape characteristics. The literacy rate and the availability of veterinary services (such as the number of veterinarians, technicians, and animal health professionals) were the subjects of two studies (25), one conducted in Asia and the other in Africa. Poor animal health and veterinary services assessed in Mandi City, northwest India, have increased the risk of PPR infection (25). The contribution of the urban population to PPR epidemics was reported by two studies, one in Africa and the other in Asia (25,35).

PPR transmission dynamics and respective control measures .3.8

To illuminate important PPR transmission dynamics, evaluation of PPR risks was conducted in almost all studies except two (9,17), which did not explicitly evaluate this covariate. Four studies explicitly evaluated transmission dynamics in relation to control measures (33,35,40,41). The first study, conducted in Ethiopia, used a metapopulation model that mimics PPRV spread to evaluate the degree of PPRV transmission in endemic situations. (33). The second study used a mathematical model to assess the impact of four vaccination strategies implemented at different

times in reducing the PPR burden (41). In India, Susceptible-Exposed-Infectious-Removed (SEIR) model was used to evaluate PPR transmission dynamics (35). Another study conducted in Tanzania provided evidence of the PPR transmission pattern (40). However, the probability of PPR transmission is linked to several covariables evaluated in this review; only 13 studies were influenced by livestock contact. Livestock movement, as the main contact parameter in PPRV transmission, has been evaluated using network analysis to identify PPRV hotspots (13). Those covariables included temporal and spatial aspects, production systems, and the use of PPR control strategies such as vaccination and early reporting systems (9,25). Additionally, all six studies assessing the effectiveness of immunization found that regions participating in PPR vaccination programs had a lower probability of PPR outbreaks (Sup. Table 2). Despite the indisputable significance of PPR transmission dynamics, most studies have used temporal and spatial resolution during epidemiological data collection. The diverse range of these linked covariables encompasses all epidemiological parameters included in this review.

Discussion .4

PPR epidemics have significantly impacted African and Asian economies, necessitating spatial and spatiotemporal approaches for disease management. However, the uneven burden may be attributed to diverse data sources and analytical approaches. An increasing trend is observed in studies using spatial and temporal analysis to estimate PPR risks in endemic countries (21). This review highlights advancements in understanding disease risk tracking, control planning, and the eventual elimination of PPRV through the assessment of PPR transmission dynamics.

Modeling approaches .4.1

This review analyzes the spatiotemporal distribution of PPR using visualization and descriptive tools. It improves understanding of PPR impact in endemic countries and aids in designing

control strategies such as vaccines or surveillance buffer zones. As more data become available, model development and refinement are crucial for understanding local PPR risks. Predictions need to account for livestock mobility patterns.

Spatial autocorrelation .4.2

Spatial autocorrelation, or spatial dependence, is a key component of PPR spatial epidemiology (25). Quantification of spatial autocorrelation in some studies was done using global spatial autocorrelation indices (21), i.e., Moran's I (25)**,** Mantel test (13), and Getis-Ord (27). When evaluating seasonal and temporal changes in disease, it is crucial to analyze spatial-temporal autocorrelation. The identification of outbreaks, clusters, or hotspots might provide clues about the hidden reasons behind the rise in disease incidence and related factors that contribute to endemicity (15). The usefulness of these results is not limited to hotspot detection but extends to targeted PPR control measures, including proactive or reactive vaccination, culling or depopulation, and/or quarantine.

Temporal trends .4.3

Epidemics of PPR, like other diseases, tend to show seasonal variation due to continuous changes in environmental and ecological factors. In our review, we have identified how these environmental and ecological factors underlying the seasonal transmission of PPR are critical for predicting and understanding the long-term environmental trends and their effects on livestock health. PPR spread is influenced by animal contacts, resource sharing, economic activities, and trade. Seasonal variations in precipitation, temperature, and the availability of pasture and water can affect livestock mobility and PPR risk projection. Seasonal activities such as festivals and dowries during harvest also increase the risk of PPR spread. Control strategies include strategic

vaccination and movement restrictions prior to disease outbreaks. These risk factors vary geographically and demographically.

Risk factors associated with PPR epidemics .4.4

This review examines risk factors related to sheep and goat disease, focusing on demographics and livestock interactions. It highlights the importance of livestock movement, geographic and environmental factors, and the increased density of wildlife or livestock in interface areas. The review also highlights the role of socioeconomic activities in promoting interaction between people and animals. Identifying PPR-prone areas is crucial for risk-based surveillance and control measures (43).

Livestock-wildlife Interactions .4.4.1

The impact of livestock–wildlife interactions on the risk of PPR epidemics is linked to the density of susceptible species at livestock-wildlife interface areas. In this review, several studies have shown evidence of PPR outbreaks in protected area due to their proximity to PPR risk zones. Limited evidence of PPR in wildlife species in Africa is surprising given the increasingly visible epidemics in wildlife across Asia (48). Evidence from our models suggests that the spatiotemporal patterns of PPRV outbreaks in wildlife were similar to those in livestock, indicating spillover of PPR virus from livestock to wildlife. Global climate changes have resulted in shifts in species distributions and habitat suitability, consequently reducing resource availability and increasing wildlife–livestock interactions. In our models, evidence of increased risk of PPR infection due to disrupted relationships between species, habitat, and climate-leading to mortalities of wildlife species, e.g., saiga (*Saiga tartarica tartarica*) in Kazakhstan-has been demonstrated (51).

Accessibility and network .4.4.2

Livestock movement is a key risk factor for PPR outbreaks, with most models indicating that geographical infrastructure links are crucial for contact between livestock populations (43). Large water bodies such as lakes, rivers, and oceans pose a PPR risk due to their accessibility, but poor infrastructure and proximity to these water bodies may limit disease spread. Expanding vehicular transportation and limited access to resources may reduce disease contamination. Our review identifies critical sites for PPR transmission in livestock movement, improving local control and surveillance strategies by combining genetic and mobility network data (13).

Socioeconomic factors .4.4.3

This review evaluates the impact of socioeconomic factors on the risks of PPR spread, focusing on political, economic, veterinary services, and stakeholders' knowledge. A herd-level, event-driven PPR model was developed to identify effective management strategies for different herd compositions and circumstances. For example, in Afghanistan, the lack of scientific data —due to the political situation —has impacted large-scale disease mitigation strategies. A cost-benefit analysis was conducted to assess the economic significance and impact of PPR. Assessing stakeholders' knowledge is crucial for involving livestock keepers in control and eradication programs. The study reveals that socioeconomic vulnerability, climate change, and risk mitigation strategies —such as livestock mobility and herd diversification —are key drivers of the spread of PPR, influenced by factors such as cultural events, husbandry methods, and economic conditions. Other social practices, such as livestock marriage dowries, can also promote the spread of PPR to other areas through livestock mobility. The social and political status of PPR-endemic countries significantly influences future regional transmission dynamics, necessitating careful consideration of control benefits in cost-benefit analyses to support resource mobilization and political will.

Livestock trade .4.4.4

The review examines market dynamics of sheep and goat production linked to PPR risks, examining the likelihood of livestock trade facilitating PPR spread in specific areas. It also considers infrastructure such as road and railway networks and slaughter facilities. For instance, in Bangladesh, the livestock movement within herds and through central, small, and large local markets of the local small and large markets has been associated with PPR outbreaks (28). Another model evaluating urbanization and habitat characteristics has shown clear evidence of PPR risk to the livestock trade (29). The review highlights regional variations in livestock trade infrastructure, highlighting the need for different control strategies in local contexts. It emphasizes the importance of empowering sub-Saharan countries with adequate livestock trade infrastructure to strengthen PPR surveillance and control to meet the 2030 PPR eradication target.

Ecology and environment .4.4.5

Studies on landscape and climatic features linked to PPRV environmental circulation, stability, and survival have been assessed in this review. Results have shown geographical variation in risk magnitude. For example, areas with good precipitation tend to have better pasture and water supply (42). Shrinkage of Grazing land due to factors such as the expansion of conserved areas, agricultural activities, and climate change has been linked to PPR risk. In this review, we have identified prediction models that can be used to design control strategies according to the environment and ecology of the respective area. For example, in China, identifying seasonal pattern is critical for vaccination schedules because high summer temperatures lower animal immunity (36). The ecological niche model discussed in this study has demonstrated how ecological and environmental characteristics are related to PPR outbreaks. The annual maximum

temperature was inversely correlated with PPR outbreaks because PPRV is more susceptible to high temperatures. Other elements, such as seasonal variations in precipitation (warm vs. dry season), exhibited a substantial positive correlation with PPR outbreaks, whereas wind speed had a negative association (37). Prediction models allow us to identify the right time for deploying control measures; implementation outside this time range becomes ineffective. Hence, the 2030 PPR eradication target has been identified using prediction models (37).

PPR transmission dynamics .4.4.6

The dynamics of PPR transmission depend on the rate of transmission from PPRV-infected animals to susceptible hosts. In disease models, this rate is captured by a single parameter called the probability of transmission. In our review, several studies have applied spatial transmission dynamic modeling approaches to investigate PPR transmission dynamics and control. These models have been useful in generating scenario analyses of the potential course and severity of PPR epidemics by characterizing and forecasting the spatiotemporal transmission patterns of PPR epidemics, or by assessing the effectiveness of interventions and the feasibility of achieving elimination targets (24). In addition to capturing pertinent mechanisms of PPR transmission —such as the possible influence of environmental factors —our review has included important epidemiological characteristics of PPR infection (48). A specific type of spatial dynamic model, known as a metapopulation model, divides the population into a number of interacting groups based on demographic or spatial data (33). For instance, in Ethiopia, PPRV incursions from lowlands into highlands occur as a result of unequal distribution of pasture, water, and animal markets, necessitating immunization that targets interfaces between various population sites. Our understanding of PPR transmission dynamics has the potential to enhance communication speed between response teams during outbreak events. The outbreak will prompt coordinated actions

530 from the point of origin and contributors, immediate epidemiologic characterization on the
531 ground, evaluation to establish spread pathways, and specimen collection for molecular
532 characterization of the virus —all while executing spatial prediction models —using the
533 understanding of PPR transmission dynamics (33).

534 **Strength .4.5**

535 This scoping review provides detailed information on risk-based spatiotemporal techniques for
536 PPR spread in endemic situations. It highlights a promising trend in the use of spatial
537 epidemiology tools to understand PPR's transmission mechanisms. The review identifies areas
538 for future research and highlights methodological limitations in existing studies. It also provides
539 a fair depiction of PPR risk mapping initiatives, using a thorough search method in compliance
540 with PRISMA Scoping criteria.

541

542 **Limitations .4.6**

543 The study acknowledges the challenge of modeling PPR risks in endemic situations due to the
544 lack of real data and the complexity of approaches. Some models are hypothetical, focusing on
545 mathematical tools for generating new ideas. The study acknowledges the potential overlooking
546 of relevant publications and studies published in other languages due to the inclusion of only
547 English-language sources.

548 **Conclusion .4.7**

549 Spatial and Spatiotemporal approaches have played a critical role in advancing our
550 understanding of available disease management options for PPR. However, the uneven burden of
551 PPR may be attributed to the diverse data sources, covariates, and analytical approaches
552 employed. Future development of prediction models to assess potential eradication efforts at

national and regional levels should also take Africa into consideration, as many studies have been conducted in Asia rather than Africa.

Ethics

Not relevant

Authorization for publishing

Inapplicable

Materials and data accessibility

The corresponding author can provide the datasets used and/or analysed in this study upon reasonable request.

Conflict of interest

There are no conflicting interests, according to the authors.

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Author Contributions

Concept and design of the study: JJM, SK, GM, AC

Data collection: JJM, JNH

Data analysis and interpretation: GM, AC, JJM, JNH

The manuscript was drafted by JJM

The manuscript has been critically revised for significant intellectual content by JNH, GM, AC, SK, DM, EM, EO, GO, and GPO.

Analysis of statistics: JJM

SK, GM, and AC provide administrative, technical, and material support.

Study oversight: SK, GM, and AC

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797
798 **Supplementary tables (Sup. Tables)**
799
800
801 Sup. Table 1: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for
802 Scoping Reviews (PRISMA-ScR) Checklist

803 Sup. Table 2: A classification system that includes a comprehensive list of the epidemiological
804 factors that have been reported in the included studies

805 Sup. Table 3: Features and synopsis of the studies that are included

806
807 Index of research papers mentioning at least one covariate associated with the Sup. Table 4:
808 likelihood of PPR outbreaks, broken down by region and subregion.
809
810 An overview of techniques for utilizing PPR epidemic data to study spatial, Sup. Table 5:
811 temporal, or spatiotemporal clustering.
812
813
814 **Supplementary Materials**

815 Sup. Table 6: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for
816 Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	3
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	4
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	4
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	4
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	4

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	5
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	6
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	6
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	NA
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	6
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	7
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	7
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	NA
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	8
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9-16,
DISCUSSION			

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	17-21
Limitations	20	Discuss the limitations of the scoping review process.	21
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	22
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	22

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818 Sup. Table 7: A classification system that includes a comprehensive list of the epidemiological
819 factors that have been reported in the included studies

Epidemiological class	Scope	Co-variates	Reference
Spatial accessibility	Represents the connectedness of an area or the likelihood of a site being reached or entered from other locations.	Roads and/or railways – Distance to, density, presence, length, or distribution.	(11); (36);(24)(28) (52); (31);. (43)(13) (1)(53)
		Water – Crossing points, border with body of water, length of rivers, distance to waterbodies or area/density of inland water.	(35) (36); (33)(28); (25)(43)(31)
livestock demographics and wildlife interactions	Explores the multispecies nature of PPRV.	Livestock/wild ruminants' population and/or density	(11) (35); (14); (36) (39) (39);(33); (27); (19)(40)(37)(43)(28)(52)(25)(54)(55)(51)(56)(
		Distance to protected areas/national park or forest coverage	(11) (36); (44);. (48)(43)(25)(29)

Livestock trade	Examines market-related dynamics or aspects acting as a proxy for the likelihood of economic exchange of goods and services in a location.	International border – Distance to or adjacency	(11); (14); (36); (33) (27);; (48). (54)(13)(49)
		Human population and/or density	(49) (25)(27)
		Slaughtered volume and/or slaughterhouses presence/distance to	(28).
		Livestock markets – Presence or distance to	(39) (55).
		Livestock exports/imports volume	(35) (52)
		Meat production/demand	(53)(39).
Socio-economic development	Tangible or intangible indicators of social, economic,	Political and economic state	(57)(12)(27)(41)(38);
		Veterinary services	(25) (33).
	political, or cultural processes occurring with the capacity to influence the dynamics of PPRV	knowledge	(43)
		Urban population	(29)(25)
Ecology and environment	Landscape and climatic features studied in connection to PPRV environmental circulation, stability, and survival.	Season	(25) (22) (24)(1)
		Water availability and wetland areas	(27)
		Humidity	(26) (42)
		Temperature and precipitation	(26). (49)(37)
		Diurnal range, isothermality	(26)
		Elevation	(27); (25) (49)
		Agroecology	(26)(24)
		Solar radiation	(25) (26)(37)

		Landcover	(25)(49)(42)(31)(48)
		Wind speed	(26)
PPR transmission dynamics and Control	Any other aspect not represented above related to PPR transmission dynamics and control measures,	PPR transmission dynamics	(35), (33) (57)(45)
		Vaccination	(58) (38)(55) (41)(45)(33)(59)(34)
		Time-Space	(11) (28)(15)(2)(3)
		Production system or grazing area	(9) (12), (25)(59)

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822 Sup. Table 8: Features and synopsis of the studies that are included

	Reference	Country	Period	Spatial coverage	Outbreak diagnostic criteria	Data source	Spatial analysis unit
	Nkamwesiga et al., 2022	Uganda	2007–2020	Countrywide	Laboratory confirmation	Official	District
	Gao et al., 2019	China	2013-2018	Countrywide	Clinical	Official	Village
	Balamurugan et al., 2021	India	1995-2019	Countrywide	Clinical	Official	District
	Rahman et al., 2021	Bangladesh	2014- 2017	Countrywide	Mixed	Official	Subdistri
	Cao et al., 2018	China	2013 - 2016	Countrywide	Clinical	Official	Village
	Agoltsov, et al., 2022	Global	2022	Regional	Mixed	Official	Country
	Ruget et al., 2019	Comoros	2012	Countrywide	Unspecified	Official	Region
	Zhang et al. 2022	India	2010-2018	Countrywide	Clinical	Official	Herd
	Fournié et al.,2018	Ethiopia	2018	Countrywide	Unspecified	Official	Village
	Zeng et al.,2021	Regional	2021	Regional	Unspecified	Official	Country
	Rony et al., 2017	Bagladesh	2005- 2014	Countrywide	Clinical	Official	Sub-distr
	Ma et al., 2017	China	2013- 2017	Countrywide	Clinical	Official	Province
	Abdrakhmanov et al. 2021	Republic of Kazakhstan/ China	2007–2020	Countrywide	Unspecified	Official	districts
	Haroun et al., 2021	Qatar	2009-2016	Countrywide	Laboratory confirmation	Official	Veterinar Laborato (VL) faci
	Dou et al., 2020	Unspecified	2020	Global	Laboratory confirmation	official	Unspecif
	Herzog et al., 2020	Tanzania	2020	Countrywide	Laboratory confirmation	Official	Village
	Benfield et al., 2021	Mongolia	2017	Countrywide	Laboratory confirmation	Official	Subdistri
	Aguilar et al., 2020	East Africa	2015 -2017	Regional	Laboratory confirmation	Official	Flock
	Vashist et al., 2021	India	2014	Local	Laboratory confirmation	Official	Flock

	Batailleid et al., 2021	West Africa	2010 -2013	Regional	Laboratory confirmation	Official	Country
	Gao et al., 2021	China	2021	Regional	Unspecified	Official	Country
	Jemberu et al., 2022	Ethiopia	2017-2018.	Local	Laboratory confirmation	Official	Subdistri
	Folitse et al., 2017	Ghana	2005–2013	Countrywide	Laboratory confirmation	Official	Regions
	Fathelrahman et al., 2021	Africa	2020	Regional	Laboratory confirmation	countrywide	Laborato confirma
	Bouchemla et al., 2020	World	2007- 2017	Global	Laboratory confirmation	Official	Country
	Zhang et al., 2022	Africa	2006-2018	Global	Laboratory confirmation	Official	Country
	Bouchemla et al., 2018	world	1997-2017	Global	Laboratory confirmation	Official	Country
	Niu et al., 2021	world	2008- 2018	Global	Unspecified	Official	Country
	Niu et al., 2021	China	2007-2018	Countrywide	Laboratory confirmation	Official	Country
	Hammami et al.,2016	Senegal	1983 - 1999	Local	Unspecified	Official	Village
	Hammami et al.,2018	Senegal	1983 - 1999	Local	Unspecified	Official	Village
	Michael D. Mitchell et al., 2017	Afghanistan	2017	Global	Unspecified	Official	Herd
	Carpenter 2001	Unspecified	2001	Unspecified	Unspecified	Unspecified	Unspecif
	Muniraju et al., 2014	world	1968–2012	Global	Laboratory confirmation	Official	Unspecif
	Bao et al., 2017	China	2013–2014	Countrywide	Laboratory confirmation	Official	Farms
	Carrera-Faja et al., 2023	Tanzania	2023	Local	Laboratory confirmation	Official	Village
	Yessenbayev et al., 2023	Kazakhstan	2018–2020	Local	Unspecified	Unspecified	Farms
	Assefa et al., 2021	world	2004-2019	Global	Laboratory confirmation	Official	Country
	Metaferia et al., 2022	Ethiopia	2006-2020	Local	Laboratory confirmation	Official	Districts

	ElArbi et al., 2019	Mauritania	2015	Local	Laboratory confirmation	Official	Region
	Pruvot et al., 2020	Mongolia	2016-2017	Countrywide	Laboratory confirmation	Official	Country
	Kivaria et al., 2014	Tanzania	2008-2010	Countrywide	Laboratory confirmation	Official	Country

Sup. Table 9: Index of research papers mentioning at least one covariate associated with the likelihood of PPR outbreaks, broken down by region and subregion.

S/N	**Studies**	**Country**	**Spatial accessibility**	**Livestock demographics and wildlife interactions**	**Livestock trade**	**Socio-economic development**	**Ecology an environme**
1	Nkamwesiga et al., 2022	Uganda	Linked	Linked	Linked	Not linked	Linked
2	Ruget et al., 2019	Comoros	Linked	Linked	Linked	Linked	Linked
3	Fournié et al., 2018	Ethiopia	Linked	Linked	Linked	Not linked	Not linked
4	Hammami et al., 2018	Senegal	Not linked	Not linked	Not linked	Linked	Not linked
5	Herzog et al., 2020	Tanzania	Not linked	Linked	Not linked	Linked	Not linked
6	Aguilar et al., 2020	East Africa	Not linked	Linked	Linked	Not linked	Linked
7	Batailleid et al., 2021	West Africa	Linked	Not linked	Linked	Not linked	Not linked
8	Jemberu et al., 2022	Ethiopia	Not linked	Not linked	Linked	Not linked	Not linked
9	Folitse et al., 2017	Ghana	Not linked	Not linked	Linked	Not linked	Linked
10	Fathelrahman et al., 2021	United Arab Emirates	Not linked	Not linked	Not linked	Not linked	Not linked
11	Zhang et al., 2022	Africa	Linked	Linked	Linked	Not linked	Not linked
12	Hammami et al., 2016	Senegal	Not linked	Not linked	Not linked	Linked	Not linked

13	Carrera-Faja et al., 2023	Tanzania	Not linked	Linked	Not linked	Linked	Linked
14	Metaferia et al., 2022	Ethiopia	Linked	Not linked	Not linked	Not linked	Linked
15	ElArbi et al., 2019	Mauritania	Not linked	Linked	Linked	Linked	Not linked
16	Kivaria et al., 2014	Tanzania	Not linked	Not linked	Linked	Not linked	Linked
17	Abdrakhmanov et al. 2021	Kazakhstan	Not linked	Linked	Linked	Linked	Linked
18	Haroun et al., 2021	Qatar	Not linked	Linked	Not linked	Not linked	Not linked
19	Gao et al., 2019	China	Linked	Linked	Linked	Not linked	Not linked
20	Balamurugan et al., 2021	India	Linked	Linked	Not linked	Not linked	Linked
21	Rahman et al., 2021	Bangladesh	Linked	Linked	Linked	Not linked	Not linked
22	Cao et al., 2018	China	Linked	Linked	Linked	Not linked	Not linked
23	Zhang et al., 2022	India	Linked	Linked	Linked	Linked	Not linked
24	Zeng et al., 2021	Asia	Linked	Linked	Linked	Linked	Linked
25	Rony et al., 2017	Bangladesh	Not linked	Linked	Linked	Not linked	Not linked
26	Ma et al., 2017	China	Not linked	Linked	Linked	Not linked	Not linked
27	Benfield et al., 2021	Mongolia	Not linked	Linked	Not linked	Not linked	Not linked
28	Pruvot et al., 2020	Mongolia	Linked	Linked	Not linked	Not linked	Linked
29	Vashist et al., 2021	India	Not linked	Linked	Linked	Not linked	Not linked
30	Gao et al., 2021	China	Linked	Not linked	Linked	Not linked	Linked
31	Yessenbayev et al., 2023	Kazakhstan	Not linked	Not linked	Not linked	Linked	Not linked
32	Niu et al., 2021	China	Linked	Not linked	Not linked	Not linked	Linked

33	Michael et al., 2017	Afghanistan	Not linked	Not linked	Not linked	Not linked	Not linked
34	Bao et al., 2017	China	Not linked	Not linked	Not linked	Not linked	Not linked
35	Dou et al., 2020	Unspecified	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluat
36	Carpenter et al., 2001	Unspecified	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluat
37	Agoltsov et al., 2022	Unspecified	Linked	Not linked	Not linked	Not linked	Linked
38	Assefa et al., 2020	Unspecified	Linked	Linked	Not linked	Not linked	Linked
39	Bouchemla et al., 2020	Unspecified	Linked	Not linked	Not linked	Linked	Not linked
40	Bouchemla et al., 2018	Unspecified	Linked	Not linked	Not linked	Not linked	Linked
41	Niu et al., 2021	Unspecified	Linked	Not linked	Not linked	Not linked	Linked
42	Muniraju et al., 2014	Unspecified	Not linked	Not linked	Not linked	Not linked	Linked

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827 An overview of techniques for utilizing PPR epidemic data to study spatial, Sup. Table 10:
828 temporal, or spatiotemporal clustering.

Reference	**Time**	**Space**	**Time- space**	**Result**
Nkamwesiga et al., 2022	NA	NA	Mann–Kendall statistics	Clustered
Gao et al., 2019	NA	NA	SaTScan, Multi-Distance Spatial Cluster Analysis	Clustered
Balamurugan et al., 2021	NA	NA	NA	NA
Rahman et al., 2021	NA	Moran's I statistic, empirical Bayesian kriging (EBK) method	SaTScan	Clustered

Cao et al., 2018	NA	Maximum entropy (MaxEnt)	NA	NA
Ruget et al., 2019	NA	Geographic Information System (GIS)-based Multi Criteria Evaluation (MCE)	NA	Not clustered
Zhang et al., 2022	Autoregressive integrated moving average model (ARIMA)	Moran's I statistic	SaTScan v9.6 software	Clustered
Fournié et al., 2018	NA	NA	Monte-Carlo algorithm (ABC-SMC)	NA
Zeng et al., 2021	NA	Maximum entropy (MaxEnt)	K-nearest neighbor cluster analysis	Clustered
Rony et al., 2017	NA	NA	SaTScan	Clustered
Ma et al., 2017	NA	Moran's I statistic.	Na	Clustered
Yessenbayev et al 2023	NA	NA	NAADSM (*e North American Animal Disease Spread Model	Clustered
Abdrakhmanov et al., 2021	Negative binomial (NegBin) model		Getis–Ord Gi* statistics	Clustered
Haroun et al., 2021	NA	NA	NA	NA
Dou et al., 2020	NA	NA	NA	NA
Herzog et al., 2020	NA	NA	NA	NA
Benfield et al., 2021	NA	NA	NA	NA
Aguilar et al., 2020	NA	NA	NA	NA
Vashist et al., 2021	NA	NA	NA	NA
Batailleid et al., 2021	NA	Clark Evans test	Mantel correlograms	Clustered
Gao et al., 2021	NA	Least cost path (LCP) ArcGIS 10.2m	NA	Clustered
Jemberu et al., 2022	NA	NA	NA	NA
Folitse et al., 2017	NA	NA	NA	NA

Fathelrahman et al., 2021	NA	NA	NAADSM (*e North American Animal Disease Spread Model	NA
Bouchemla et al., 2020	NA	NA	NA	NA
Assefa et al., 2021	Ensemble algorithm.	NA	NA	NA
Zhang et al., 2022	NA	NA	NA	NA
Bouchemla et al.,2018	NA	Geo-information system, QuickMAP	Monte Carlo method	Clustered
Niu et al., 2021	NA	Random forest	NA	NA
Niu et al., 2021	NA	Maximum entropy (MaxEnt)	SaTScan	Clustered
Hammami et al., 2016	Seasonal discrete-time population matrix model	NA	NA	NA
Hammami et al., 2018	Seasonal discrete-time population matrix model	NA	NA	NA
Mitchell et al., 2017	Event-driven memoryless model of state transitions.	NA	NA	NA
Carpenter et al., 2001	NA	NA	NA	NA
Muniraju et al., 2014	Uncorrelated exponential distribution (UCED) Model	NA	NA	NA
Bao et al., 2017	Bayesian Markov Chain Monte Carlo (MCMC) method in the BEAST package 1.7.1	NA	NA	Clustered
Carrera-Faja et al., 2023	NA	Maximum entropy (MaxEnt)	NA	NA
Agoltsov et al., 2022	NA	Maximum entropy (MaxEnt)	NA	NA

Metaferia et al., 2022	Negative binomial (NegBin) model	ArcGIS 10.2m	Moran's Index, Nearest Neighbor Ratio	Clustered
ElArbi et al., 2019	Monte Carlo Markov Chain procedure	NA	NA	NA
Pruvot et al., 2020	NA	NA	NA	NA
Kivaria et al., 2014	NA	NA	NA	NA

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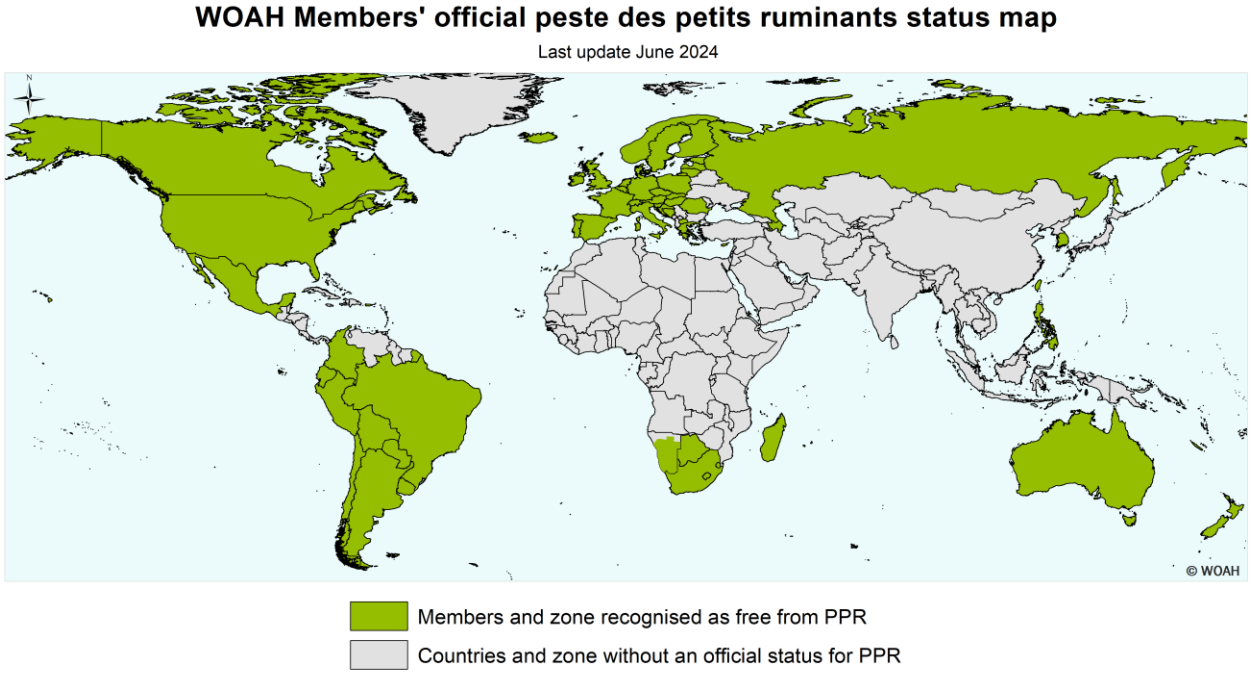

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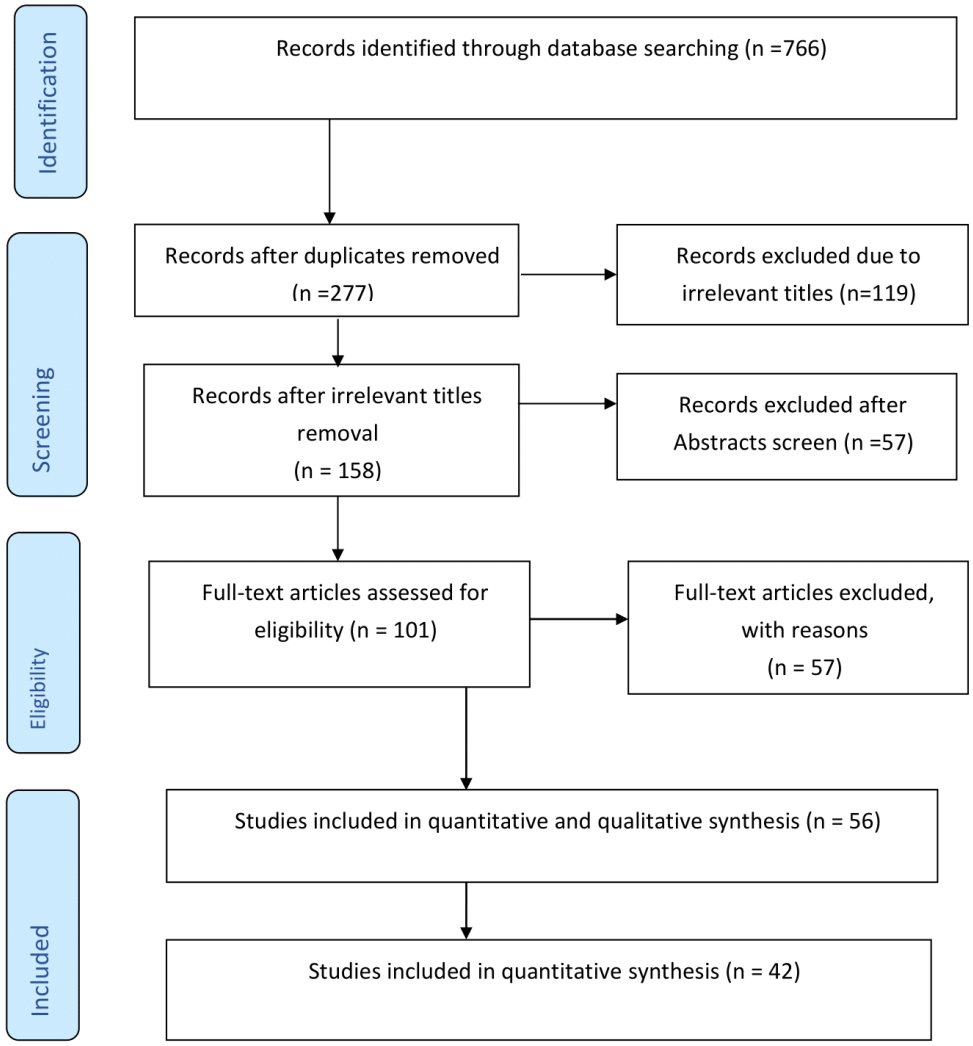
PPR situation based on WOAH PPR status recognition. Regions in grey are endemic, report sporadic episodes, or have an unregistered PPR status.


Identification
Records identified through database searching (n =766)
Screening
Records after duplicates removed (n =277)
Records excluded due to irrelevant titles (n=119)
Records after irrelevant titles removal (n = 158)
Records excluded after Abstracts screen (n =57)
Eligibility
Full-text articles assessed for eligibility (n = 101)
Full-text articles excluded, with reasons (n = 57)
Included
Studies included in quantitative and qualitative synthesis (n = 56)
Studies included in quantitative synthesis (n = 42)

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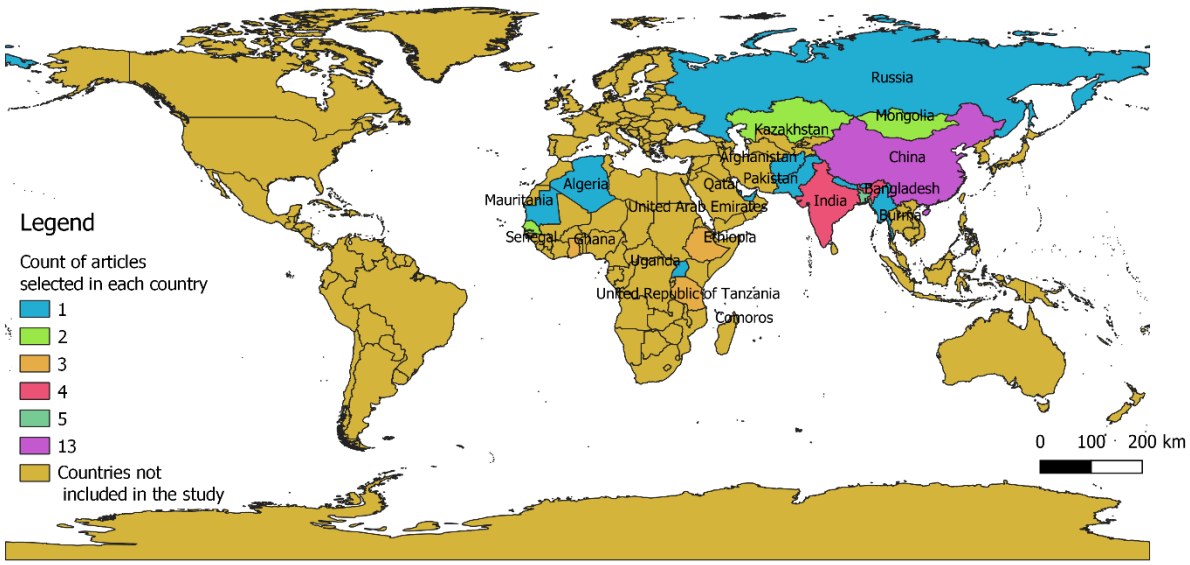
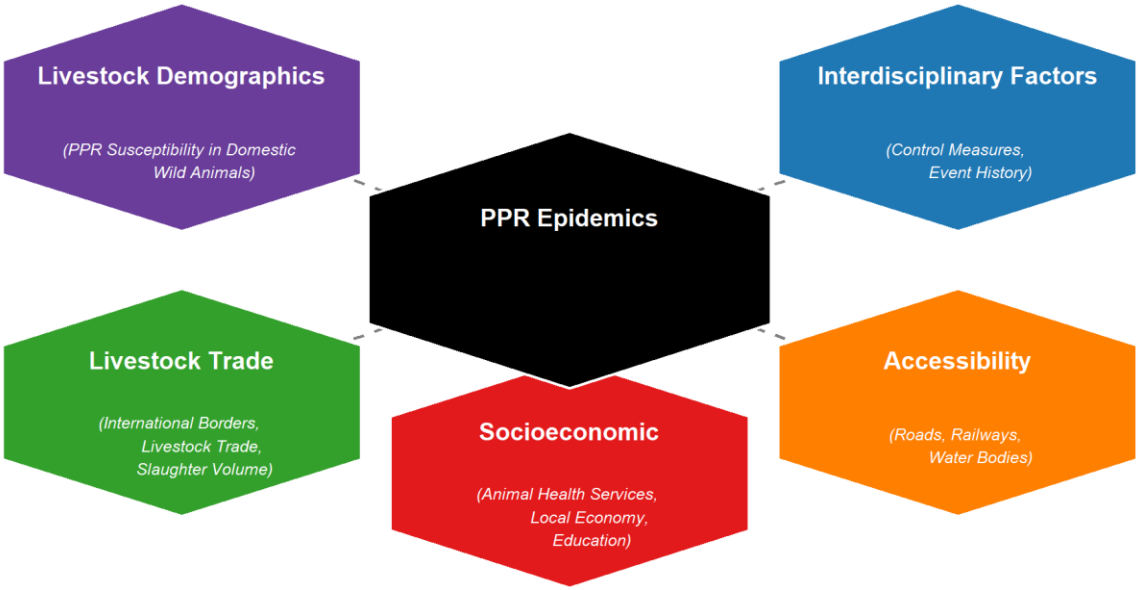
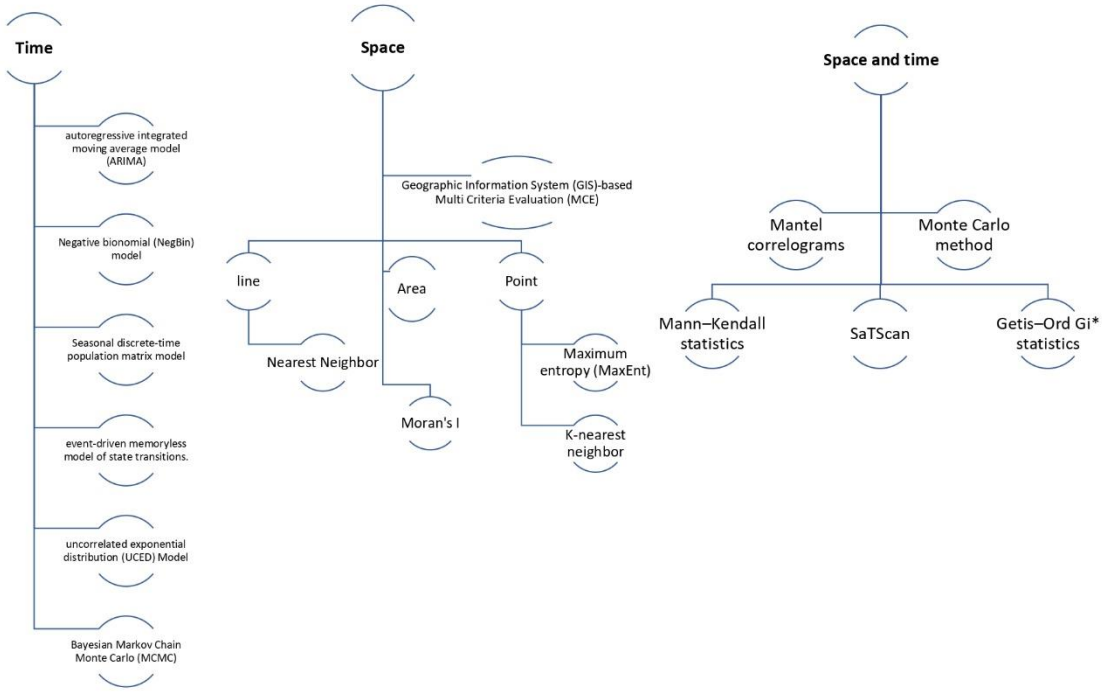
Flow diagram from bibliographic search of study records to final inclusion in the review



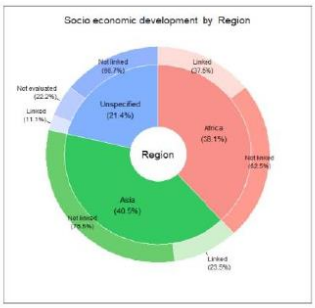
Geographical coverage of the studies included in the scoping review

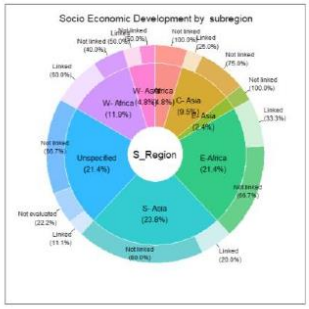


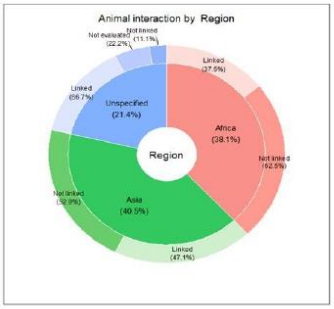
Conceptual frameworks used to classify the risk factors for Peste des petits ruminants epidemics.

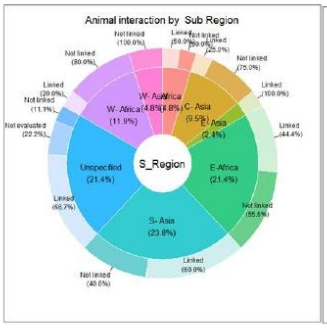


Dimensions and data forms for classification of cluster analysis modified from (25)


Socio economic development by Region
Region
Africa (38.1%)
Asia (40.5%)
Unspecified (21.4%)


Socio Economic Development by subregion
S_Region
E-Africa (21.4%)
S- Asia (23.8%)
Unspecified (21.4%)
W- Africa (11.9%)
C- Asia (9.5%)
E Asia (2.4%)


Animal interaction by Region
Region
Africa (38.1%)
Asia (40.5%)
Unspecified (21.4%)


Animal interaction by Sub Region
S_Region
E-Africa (21.4%)
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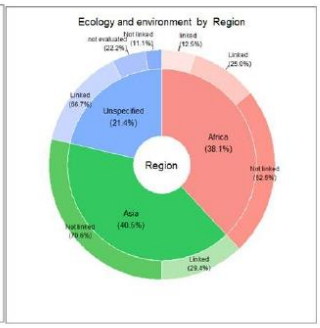
Ecology and environment by Region
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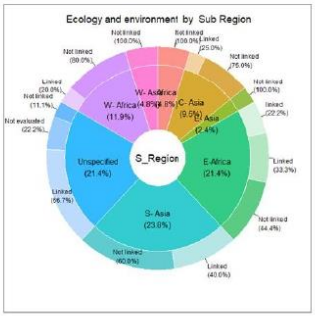
Asia (40.5%)
Unspecified (21.4%)


Ecology and environment by Sub Region
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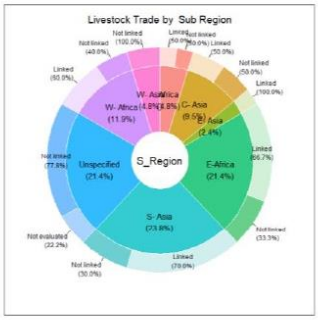
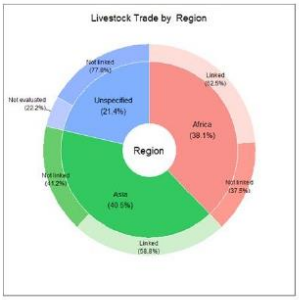
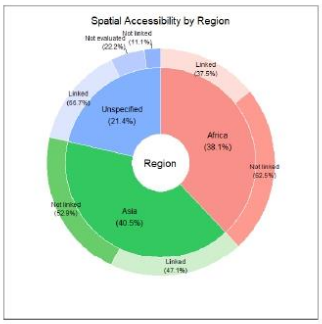
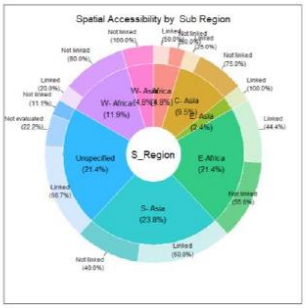
E Asia (2.4%)


Livestock Trade by Sub Region
S_Region
E-Africa (21.4%)
S- Asia (23.8%)
Unspecified (21.4%)
W- Africa (11.9%)
C- Asia (9.5%)
E Asia (2.4%)


Livestock Trade by Region
Region
Africa (38.1%)
Asia (40.5%)
Unspecified (21.4%)


Spatial Accessibility by Region
Region
Africa (38.1%)
Asia (40.5%)
Unspecified (21.4%)


Spatial Accessibility by Sub Region
S_Region
E-Africa (21.4%)
S- Asia (23.8%)
Unspecified (21.4%)
W- Africa (11.9%)
C- Asia (9.5%)
E Asia (2.4%)

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Distribution of models, at regional and subregional, containing variables from every category in the conceptual framework