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Review Article

Peste Des Petits Ruminants in Atypical Hosts and Wildlife: Systematic Review and Meta-Analysis of the Prevalence between 2001 and 2021

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Abstract

Peste des petits ruminants (PPR) or goat plague is considered a leading, highly contagious, and most lethal infectious viral disease of small ruminants affecting the worldwide livestock economy and international animal trade. Although sheep and goats are the primarily affected, the PPR Virus (PPRV) host range has expanded to other livestock (large ruminants) and wildlife animals over the last few decades, resulting in serious concern to the ongoing PPR global eradication program, which is primarily optimized, designed, and targeted towards accessible sheep and goat population. A systematic review and meta-analysis study was conducted to estimate the prevalence and spill-over infection of PPRV in large ruminants (bovine and camel) and wildlife. Published articles from 2001 to October 2021 on the "PPR" were searched in four electronic databases of PubMed, Scopus, Science direct, and Google Scholars. The articles were then selected using inclusion criteria (detection/prevalence of PPRV in bovine, camel, and wildlife population), exclusion criteria (only sheep or goats, lack of prevalence data, experimental trial, test evaluation, and reviews written in other languages or published before 2001), and the prevalence was estimated by random effect meta-analysis model. In the current study, all published articles belonged to Africa and Asia. The overall pooled prevalence of PPR estimates was 24% (95% CI: 15-33), with 30% in Asia (95% CI: 14-49) and 20% in Africa (95% CI: 11-30). The overall estimated pooled prevalence at an Africa-Asia level in bovine and camel was 13% (95% CI: 8-19), and in wildlife, it was 52% (95% CI: 30-74) with significant heterogeneity (I^2 = 97%) in most pooled estimates with a high prevalence in atypical hosts and wildlife across Asia and Africa. Over the last two decades, the host range has increased drastically in the wildlife population, even for prevalent PPR in the unnatural hosts only for a short time, contributing to virus persistence in multi-host systems with an impact on PPR control and eradication program. This observation on the epidemiology of the PPRV in unnatural hosts demands appropriate intervention strategies, particularly at the livestock-wildlife interface.

Keywords: PPR; Bovine; Camel; Wildlife; Systemic Review; Meta-analysis, Prevalence

1. Context

Peste des petits ruminants (PPR) as 'small ruminants plague' is one of the leading and most lethal infectious viral diseases of small ruminants, caused by *small ruminant morbillivirus* (*SRMV*) otherwise known as PPR Virus (PPRV), belonging to the genus *Morbillivirus* in the *Paramyxoviridae* family (http://ictvonline.org/virusTaxonomy.asp). Highly contagious nature results in classifying as Transboundary Animal Disease by Office International des Epizooties.

PPR also has high morbidity and mortality rates with a high number of outbreaks per year; therefore, a threat is to sustainable agricultural growth causing a severe socio-economic impact on the livestock industry, especially in developing and underdeveloped countries. Furthermore, PPR was first described in 1942 in the Republic Côte d'Ivoire in West Africa and then spread to more than 70 countries, such as Africa, the Middle East, the parts of Asia; in addition, the parts of Europe together have confirmed PPR affecting ~1.7 billion of the global sheep and goat population (4, 5). Considering the importance of small ruminants in ensuring food security and socio-economic growth in many parts of the world, mainly in Africa and Asia the Food and Agriculture Organization (FAO), and the World Organization for Animal Health (OIE) launched the PPR global eradication program (PPR-GEP) with the adoption of PPR Global Control and Eradication Strategy (GCES) for the global eradication of PPRV by 2030.

Sheep and goats are primary hosts for PPRV due to their highly contagious nature and ability to cross-species barrier similar to other members of morbillivirus (Rinderpest virus, Measles virus) with the mechanism for adapting to new hosts. In the last few decades, an increase was in reports on PPRV inter-species transmission to unnatural hosts. Such unknown mechanism of PPRV's propensity to transmit, expansion of susceptible hosts, and their epidemiological role raises concerns on the successful implementation of the PPR-GEP. Among the livestock, some reports are for confirmed PPRV infection with seroprevalence in large ruminants- in Asia and Africa (cattle, water buffalo, and camel) (11-14). Other than unusual livestock (bovine and camel), PPR is extensively reported in various wildlife and the first natural infection of PPR in wild Dorcas gazelle was reported by Furley, Taylor (17). The huge fatality documented in Mongolian wildlife (18) and mountain ungulates from the Middle East, South, and East Asia exemplifies the impact of PPR on the wildlife population (19-22). As per the literature based on antibody and viral detection, African wildlife often seems exposed to PPRV due to its large wildlife population density, compared to Asia (23-25).

Over the past few decades, the role of livestock and wildlife in PPR epidemiology is becoming clearer, with the majority of data supporting the effective disease transmission between livestock and wildlife with some gaps in knowledge (29, 30). PPRV spillover from a domestic source was observed in Tanzania's Serengeti habitat, with greater antibody prevalence in wild ungulates/cattle and without clinical symptoms or death (18, 19, 25). Furthermore, PPRV circulation in animals, even if only for a short time, can contribute to virus persistence in multi-host systems which increase virus propagation, and affect the intervention program (37). The current study aimed to conduct a systematic meta-analysis to determine the evidence of PPRV infection in atypical hosts (bovine and camel) and wildlife.

2. Evidence Acquisition

2.1. Literature Search Strategy

Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines of Cochran collaborations were used for systematic review and subsequently meta-analysis (38-40). A literature survey was systematically conducted to collect all relevant literature on the prevalence of PPRV in the bovine, camel, and wildlife. The published information was collected from the various electronic web database engines, including PubMed (https://pubmed.ncbi.nlm.nih.gov/), Scopus (www.scopus.com), ScienceDirect (https://www.sciencedirect.com/), and Google Scholars (https://scholar.google.com/). Some of the articles were added by the authors using hand-searching of references from the reviewed materials. Initial search string resulted in 552 articles from January 2001 to October 2021 using the different combinations of keywords "Prevalence OR Incidence OR Frequency OR Detection OR Occurrence OR Identification OR Isolation OR Characterization OR Investigation OR Survey OR Rate" AND "PPR OR Peste des petits ruminants OR Goat plague OR Kata OR ovine rinderpest OR Caprine rinderpest" AND "Large Ruminant OR Bovine OR Cattle OR Buffalo OR Camel Or Camelus OR Wild OR Wildlife OR feral Or unnatural host OR unusual host" (Table 1). Rayyan QCRI (the systematic reviews web app) was used for systematic reviews and compilations (40). Initially, a blind screening was performed by the two investigators independently and followed by resolving the conflict in the software (Rayyan QCRI). The reference management software Zotero desktop (version 5.0.96.3) was used to manage full articles and selected references. Furthermore, country and continent-wise distribution of PPR in atypical hosts and wildlife were depicted in the map using QGIS software (version 3.20.1), QGIS team, Switzerland.

2.2. Study Selection and Data Extraction

The schematic representation of the systematic review on the prevalence of PPR was depicted in figure 1. Out of 552 studies compiled during the literature search from the databases and duplicated entries, 153 articles were removed by screening titles and citation details. In the preliminary screening phase, studies were excluded based on irrelevance (n=357) (i.e., non-PPR study, non-bovine/camel/wildlife, lack of temporal and spatial information, lack of full text, article related to only sheep or goat, experimental trial, and articles in other languages than English). In total, seven articles were removed based on full-text screening due to lack of data on the sample tested, the test used, and species tested. Subsequently, three relevant articles were identified through a reference search based on the author's knowledge without an appearance in the search list. Accordingly, 48 studies were selected for the full-text reviews and subjected to the quality of bias assessment. Finally, a total of 37 articles were used for the meta-analysis and the determinants, such as the author, publication year, region, and species (wildlife, bovine, and camel); moreover, region and number of the sample tested, the number of positive samples, and tests used for the analysis were extracted from the selected articles.

2.3. Quality Assessment of Studies

The quality of the studies was assessed by two investigators independently, and the investigator used seven items with a 5-point Likert scale to judge the quality of each research paper. The maximum score of 5 indicates a likely and unlikely article. The scores of the investigators were further used to calculate the coefficient of the validity with the Aiken value (44-46).

2.4. Meta-Analysis

Meta-analysis was conducted using R open-source scripting software (Comprehensive R Archive Network; version 3.2.5) and the R package used was "meta" as reported earlier (48). The graphical representation of the effect size was done through a forest plot or confidence interval plot. In a meta-analysis, predominantly fixed effect and random effect models were used based on the variation in the studies and heterogeneity [I^2] values. The random-effect model was used when the heterogeneity among the studies was statistically significant in combining with inconsistency indices. The heterogeneity of the studies was calculated using Cochran's Q statistic, Tau square, H-value, and *P*-values obtained, and results are given in the last line of the forest plot (40, 44).

Meta-regression was conducted to analyze the influence of included studies and estimate variation in the studies (50). To predict the effect of a hypothesized moderator, a weighted linear regression model was applied in which the effect size (samples) was regressed onto the moderator (48, 51). The moderators in univariate meta-regression include the test, geographic region, years, species, and total. The variables with $P<0.05$ in univariate meta-regression were used for further subgroup analysis, and only factors significant at $P\leq0.05$ were retained in the final model. Meta-regression reduces the number of tests and estimations; therefore, the power of analysis is greater and the probability of false-positives findings is reduced (50).

Subgroup analysis was conducted to assess the heterogeneity in the region (Asia and Africa), sample size, and the test included along with species (51). Sensitivity analysis was performed to identify the studies contributing to overall heterogeneity and measure the robustness of meta-analysis findings. The extent of publication bias in the selected studies was measured and demonstrated in a funnel plot with the Y-axis representing the standard error of each study and the X-axis representing the arcsine transformation of the proportion of the study (51).

Table 1. Evidence of PPRV infection in bovine, camel, and wildlife published during 2001-2021

Study	Year	Country	Continent	Animal	Species	Genus Species
*Roger, Yesus (6)	1995	Ethiopia	Africa	*Camel	Camel	*Camelus dromedarius*
*Haroun, Hajer (7)	2002	Sudan	Africa	*Camel	Camel	*Camelus dromedarius*
		United Arab Emirates	Asia	Bovine	Cattle	*Bos primigenius taurus*
Ozkul, Akca (10)	1999-2000	Turkey	Asia	Bovine	Cattle	*Bos primigenius taurus*
*Ogunsanmi, Awe (15)	Nil	Nigeria	Africa	*Wildlife	African grey duiker	*Sylvicapra grimmia*
Elzein, Housawi (26)	2002	Kingdom of Saudi Arabia (KSA)	Asia	Wildlife	Dorcas gazelles	*Gazella dorcus*
					Thomsons gazelles	*Gazella thomsoni*
*Lundervold, Milner-Gulland (28)	1997-1998	Kazakhstan	Asia	*Bovine	Cattle	*Bos primigenius taurus*
*Haque, Habib (35)	1997-1998	Bangladesh	Asia	*Bovine	Cattle	*Bos primigenius taurus*
*Abraham, Sintayehu (41)	2001	Ethiopia	Africa	*Camel	Camel	*Camelus dromedarius*
				*Bovine	Cattle	*Bos primigenius taurus*
Couacy-Hymann, Bodjo (23)	2005	Côte d'Ivoire	Africa	Wildlife	African buffalo	*Syncerus caffer*
					Defassa waterbuck	*Kobus defassa*
Khan, Siddique (42)	2008	Pakistan	Asia	Bovine	Cattle	*Bos primigenius taurus*
					Buffalo	*Bubalus bubalis*
*Maillard, Van (43)	Nil	Vietnam	Asia	*Bovine	Buffalo	*Bubalus bubalis*
					Cattle	*Bos primigenius taurus*
*Rashid, Asim (47)	Nil	Pakistan	Asia	*Bovine	Cattle	*Bos primigenius taurus*
*Albayrak and Gur (49)	2009	Turkey	Asia	*Bovine	Cattle	*Bos primigenius taurus*
*Gur and Albayrak (52)	2010	Turkey	Asia	*Wildlife	Goitered gazella	*Gazella subgutturosa*
*Kwiatek, Ali (53)	2000-2009	Sudan	Africa	*Camel	Camel	*Camelus dromedarius*
*Bao, Wang (54)	2007-2008	China	Asia	*Wildlife	Bharals	*Pseudois nayaur*
*Rajneesh, Kataria (55)	Nil	India	Asia	*Camel	Camel	*Camelus dromedarius*
*Balamurugan, Krishnamoorthy (11)	2009-2010	India	Asia	*Bovine	Buffalo	*Bubalus bubalis*
					Cattle	*Bos primigenius taurus*
Hoffmann, Wiesner (56)	2010-2011	Iraq	Asia	Wildlife	Wild goat	*Capra aegagrus*
Sen, Saravanan (76)	2012	India	Asia	Wildlife	Lion	*Panthera leo persica*
*Balamurugan, Krishnamoorthy (58)	2011	India	Asia	*Bovine	Buffalo	*Bubalus bubalis*
					Cattle	*Bos primigenius taurus*
*Lembo, Oura (59)	2011	Tanzania	Africa	*Bovine	Cattle	*Bos primigenius taurus*
El-Dakhly (60)	Nil	Libya	Africa	Camel	Camel	*Camelus dromedarius*
Abdul-Dahiru, Baba (61)	Nil	Nigeria	Africa	Bovine	Cattle	*Bos primigenius taurus*
				Camel	Camel	*Camelus dromedarius*
*Mahapatra, Sayalel (25)	2014	Tanzania	Africa	*Wildlife	African buffalo	*Syncerus caffer*
					Grant's gazelle	*Nanger granti*
					Wildebeest	*Connochaetes gnou*
					Impala	*Aepyceros melampus*
*Woma, Kalla (62)	2014	Nigeria	Africa	*Camel	Camel	*Camelus dromedarius*
*Saeed, Ali (63)	2002-2011	Sudan	Africa	*Camel	Camel	*Camelus dromedarius*
*Li, Li (20)	2013-2016	China	Asia	*Wildlife	Argali	*Ovis ammon*
					Ibex	*Capra ibex sibirica*
					Goitered gazella	*Gazella subgutturosa*
*Abubakar, Mahapatra (64)	2015	Pakistan	Asia	*Bovine	Buffalo	*Bubalus bubalis*
					Cattle	*Bos primigenius taurus*
*Intisar, Ali (65)	2008-2012	Sudan	Africa	Bovine	Cattle	*Bos primigenius taurus*
				*Wildlife	Dorcas gazelles	*Gazella dorcus*
				*Camel	Camel	*Camelus dromedarius*
*Jaisree, Aravindhbabu (66)	Nil	India	Asia	*Wildlife	Chowsingha	*Tetracerus quadricornis*
*Zhou, Wang (67)	2016	China	Asia	*Wildlife	Water deer	*Hydropotes inermis*
Ali, Osman (68)	2015-2016	Sudan	Asia	Bovine	Cattle	*Bos primigenius taurus*
Bello, Kazeem (70)	Nil	Nigeria	Africa	Camel	Camel	*Camelus dromedarius*
*Omani, Gitao (71)	2018	Kenya	Africa	*Camel	Camel	*Camelus dromedarius*

Study	Year	Country	Continent	Animal	Species	Genus Species
*Asil, Ludlow (1)	2018	Sudan	Africa	*Wildlife	Dorcas gazelles	*Gazella dorcus*
*Li, Cao (2)	2018	China	Asia	*Wildlife	Przewalski's gazelle	*Procapra przewalskii*
*Herzog, de Glanville (3)	2016	Tanzania	Africa	*Bovine	Cattle	*Bos primigenius taurus*
*Vj, Gitao (8)	Nil	Kenya	Africa	*Camel	Camel	*Camelus dromedarius*
*Agga, Raboisson (9)	2005-2006	Ethiopia	Africa	*Bovine	Cattle	*Bos primigenius taurus*
Hekal, Al-Gaabary (16)	2016-2018	Sudan	Africa	Bovine	Cattle	*Bos primigenius taurus*
*Abubakar, Sattorov (27)	2014	Pakistan	Asia	*Bovine	Yak	*Bos grunniens*
*Pruvot, Fine (18)	2017	Mongolia	Asia	*Wildlife	Ibex	*Capra ibex*
					Goitered gazella	*Gazella subgutturosa*
					Saiga antelope	*Saiga tatarica*
*Fernandez Aguilar, Mahapatra (31)	2013-2017	Sudan	Africa	*Wildlife	Elephant	*Loxodonta africana*
					Tiang	*Damaliscus lunatus tiang*
		Uganda	Africa		African buffalo	*Syncerus caffer*
					Uganda kob	*Kobus kob thomasi*
*Cosseddu, Doumbia (32)	2013	Mauritania	Africa	Bovine	Cattle	*Bos primigenius taurus*
*Liu, Liu (33)	2021	China	Asia	Wildlife	Alpacas	*Vicugna pacos*
*Jones, Mahapatra (34)	2015-2016	Tanzania	Africa	Wildlife	Kongoni	*Alcelaphus buselaphus*
					Grant's gazelle	*Nanger granti*
					African buffalo	*Syncerus caffer*
					Topi	*Damaliscus lunatus*
		Kenya	Africa		African buffalo	*Syncerus caffer*
					Wildebeest	*Connochaetes gnou*
					Grant's gazelle	*Nanger granti*
					Impala	*Aepyceros melampus*
					Thomsons gazelles	*Gazella thomsoni*
					Warthog	*Phacochoerus africanus*
					Gerenuk	*Litocranius walleri*
*Prajapati, Shrestha (36)	2021	Nepal	Asia	Bovine	Cattle	*Bos primigenius taurus*

* Study and animal included in the meta-analysis after exclusion of studies due to inter-rater disagreement

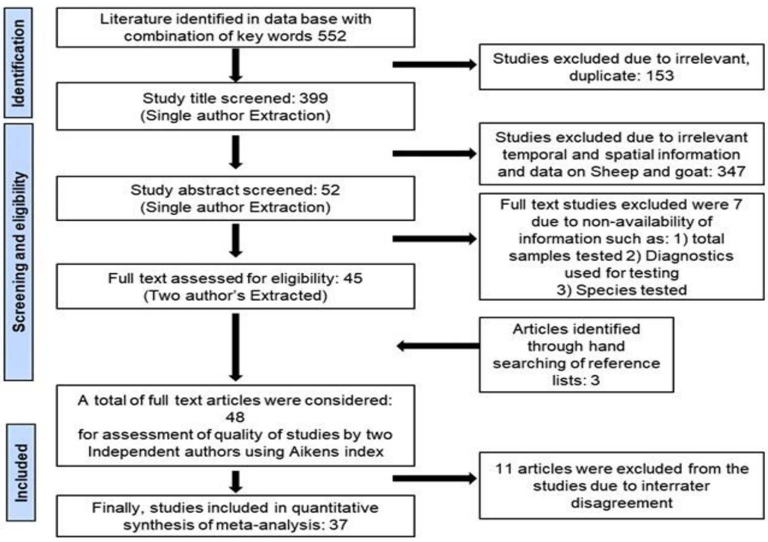

Figure 1. PRISMA checklist flow diagram of the selection of eligible studies for inclusion in the meta-analysis

3. Results

3.1. Information on the Included Studies and Quality of Bias Assessment

Out of 552 studies, a total of 48 studies (Table 1) were selected for full-text reviews and subjected to the quality of bias assessment. For the selection of articles, inter-rater agreement and consensus using Aiken's V-value index were performed to reduce bias. Additionally, the quality of the studies was assessed based on the score given by the two independent authors to seven items using the Likert scale. Based on the ratings calculated, Aiken's V-value for all the studies was more than 0.75, indicating the acceptable quality of the study. Finally, 37 articles were selected for meta-analysis (1-3, 6-9, 11,15, 18, 20, 24, 28, 31-36, 41, 43, 47, 49, 52-55, 58-59, 62-68, 71, 83) (Table 1) with the details presented in the PRISMA flow chart (Figure 1). The prevalence of PPRV was calculated using a total sample size of 12,337 out of which Bovine alone contributed to 7,962 cases followed by camel (n=3,577) and wildlife (n=798).

3.2. Publication Bias

Publication bias is a critical problem in systematic review and meta-analysis, affecting the validity and generalization of conclusions (57). In this study, funnel plot-based methods include a visual examination of a funnel plot, regression, and rank test used to assess publication bias. A funnel plot was plotted with arcsine transformation proportion in the X-axis and standard error in Y-axis. The arcsine-based transformation has the important advantage of stabilizing variance (57) which is likely the main reason included in our study. In figure 2, most of the studies were scattered and a few of the studies fall into the funnel, showing the publication bias. Moreover, the presence of asymmetry in the funnel plot was tested using Begg's rank correlation test and Egger's regression test. To deal with the presence of publication bias, the meta-regression was employed with sample size as the risk of bias factor, proving the non-significance (P>0.05) nullifying the effect of publication bias on the study.

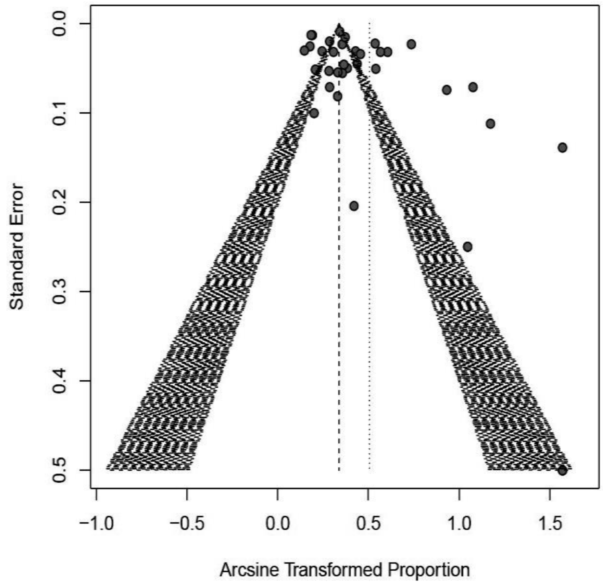

Figure 2. Funnel plot for the examination of publication bias of the prevalence estimates of PPR in bovine, camel, and wildlife during 2001-2021

3.3. Meta-Regression to Identify the Factors Affecting the Heterogeneity

Univariate meta-regression was used to identify potential covariates likely the magnitude and direction of the overall estimate of heterogeneity. The result of the meta-regression (Table 2) revealed that detection techniques had a significant impact on the overall heterogeneity at a 5% level. Variables, such as test, species, sample sizes, and year were statistically significant, and the estimated results revealed that the subgroup analysis and sensitivity analysis were required for further fine-tuning of prevalence rates of PPR.

3.4. Subgroup and Sensitivity Analysis

Subgroup analysis was conducted for the covariates, such as antigen/antibody test with a level of sample size further based on region and animal group due to the effect on heterogeneity (Table 3). Subgroup analysis of antigen/antibody test revealed the percentage prevalence of 90% with I^2 = 88% and $\tau 2$= 0.1882 (95% CI: 0.67-1.0) in PCR assay, followed by antibody prevalence of 25.71% (Figure 3).

Table 2. Univariate meta-regression analysis of PPR in large ruminants and wildlife

Predictors	Estimate	SE	z value	$\tau 2$	I^2 (%)	H^2	R^2 (%)	Qm	*P*- Value
Region	0.45	0.07	6.19	0.10	99.11	112.59	0.00	0.99	0.3192
Test	0.29	0.16	1.76	0.05	97.87	46.86	45.89	40.53	0.0001***
Species	0.33	0.07	4.66	0.07	98.71	77.62	27.31	17.28	0.0002***
Sample Size	0.56	0.06	9.16	0.09	98.90	90.76	5.22	3.72	0.0538
Year	-38.99	17.15	-2.27	0.08	98.97	97.09	9.06	5.30	0.0214*

Where* indicates the 5% level of significance, *** 0.1% level of significance

Table 3. Estimated pooled prevalence of PPR in large ruminants and wildlife

Group	Variables	No. of study	No. of animal sampled	No. of positive animal	Pooled estimate %	95% CI	Heterogeneity chi-squared (τ^2)	I^2%	*P*-value
Continent	Africa	18	8811	1025	20	11-30	0.0684	98	<0.01
	Asia	19	3526	527	30	14- 49	0.1599	95	<0.01
Animal	Bovine	14	7962	900	11	8-14	0.0090	94	<0.01
	Camel	10	3577	425	15	4-31	0.0936	99	<0.01
	Estimate Livestock (Bovine and camel)	23	11539	1325	13	8-19	0.0403	98	<0.01
	Wildlife	15	798	227	52	30-74	0.1568	91	<0.01
Study years	Livestock in 2001-2010	10	3426	336	15	5-28	0.0642	97	<0.01
	Wildlife in 2001-2010	3	124	17	24	2-61	0.0952	74	<0.02
	Estimate livestock and wildlife 2001-2010	13	3550	353	16	7-27	0.0601	97	<0.01
	Livestock in 2011-2021	13	8113	989	12	7-19	0.0272	98	< 0.01
	Wildlife in 2011-2021	12	674	210	60	35-83	0.1580	92	< 0.01
	Estimate livestock and wildlife 2011-2021	24	8787	1199	29	16-44	0.1298	97	<0.01
Overall estimate		37	12337	1552	24	15- 33	0.1005	97	<0.01

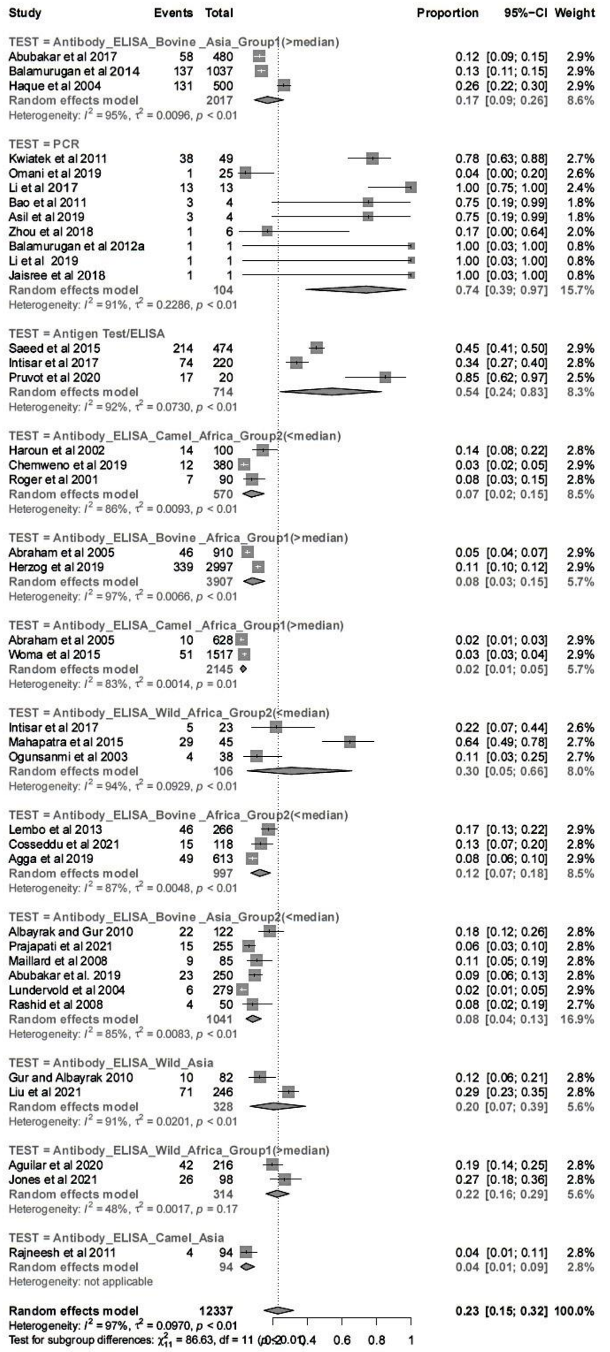

Figure 3. Forest plot of the subgroup and sensitivity analysis of PPR in bovine, camel and wildlife during 2001-2021

3.5. Region and Animal Species Reported

A total of 37 articles covering 16 countries in two continents (Asia and Africa) were included in this study. The number of articles published (mentioned in parenthesis) from African countries was: Ethiopia (3), Kenya (3), Mauritania (1), Nigeria (2), Sudan (6), Tanzania (4), Uganda (1), and from Asian countries was Bangladesh (1), China (5), India (4), Kazakhstan (1), Mongolia (1), Nepal (1), Pakistan (3), Turkey (2), and Vietnam (1) from 2001 to 2021 (Table 1 and Figure 4). Totally, 29 animal species among which livestock species included in the study, were Cattle (*Bos primigenius taurus*), Water Buffalo (*Bubalus bubalis*), Yak (*Bos grunniens*), and Camel (*Camelus dromedarius*), and among the wildlife, African buffalo (*Syncerus caffer*), African grey duiker (*Sylvicapra grimmia*), Alpacas (*Vicugna pacos*), Argali (*Ovis ammon*), Bharals (*Pseudois nayaur*), Chowsingha (*Tetracerus quadricornis*), Dorcas gazelles (*Gazella dorcus*), Elephant (*Loxodonta africana*), Gerenuk (*Litocranius walleri*), Goitered gazella (*Gazella subgutturosa*), Grant's gazelle (*Nanger granti*), Ibex (*Capra ibex* and *Capra ibex sibirica*), Impala (*Aepyceros melampus*), Kongoni (*Alcelaphus buselaphus*), Lion (*Panthera leo persica*), Przewalski's gazelle (*Procapra przewalskii*), Saiga antelope (*Saiga tatarica*), Thomsons gazelles (*Gazella thomsoni*), Tiang (*Damaliscus lunatus tiang*), Topi (*Damaliscus lunatus*), Uganda kob (*Kobus kob thomasi*), Warthog (*Phacochoerus africanus*), Water deer (*Hydropotes inermis*), and Wildebeest (*Connochaetes gnou*) (Table 1 and Figure 4).

3.6. Prevalence Estimates

The random effect meta-analysis of bovine, camel, and wildlife showed that pooled prevalence of PPR was 24% (95% CI: 15-33) with heterogeneity I^2 =97%, $\tau 2$=0.1005, P<0.01 (Table 3, Figure 5). Furthermore, in the case of the specific region, the studies showed that the prevalence of PPRV in Asia was 30% (95% CI: 0.14-0.49) followed by Africa with 20% (95% CI: 0.11-0.30) (Figures 6). Animal species category wise pooled prevalence showed 11% (95% CI: 8-14) for bovine (cattle and buffaloes), 15% (95% CI: 4-31) for camel, and 52% (95% CI: 30-74) for wildlife (Figure 7). However, the pooled prevalence of livestock (bovine and camel combined) was 13%. Furthermore, the articles were sub grouped into the studied period (2001-2010 and 2011-2021) to understand the prevalence of PPR in the last two decades. From 2001 to 2010, the estimated prevalence was 15% (95% CI: 5-28) and 24% (95% CI: 2-61) for livestock and wildlife, respectively, with an overall estimated pooled prevalence of 16% (95% CI: 7-27) during 2001-2010. Similarly, from 2011 to 2021, the prevalence was 12% (95% CI: 7-19) and 60% (95% CI: 35-83) for livestock and wildlife, respectively, and overall estimate pooled prevalence showed 29% (95% CI: 16-44) during 2011-2021.

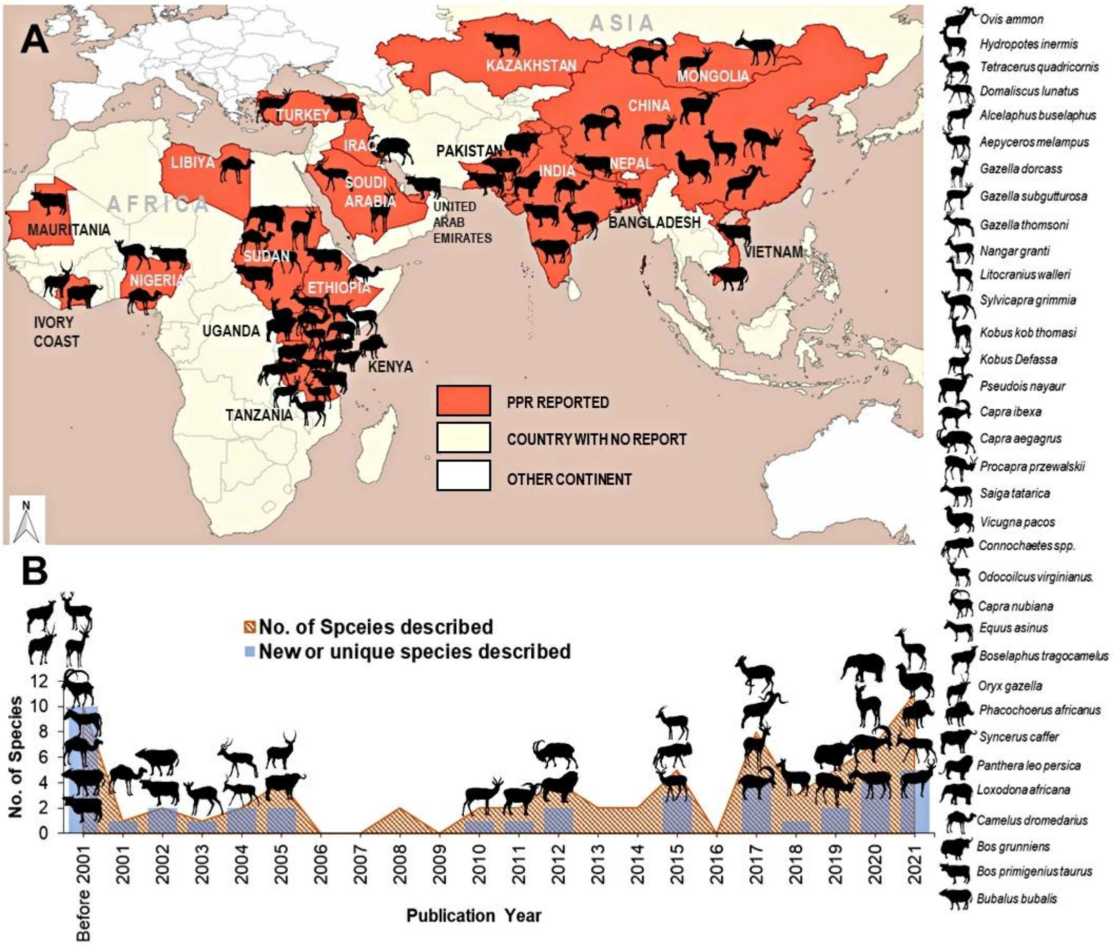

Figure 4. A. PPR affected countries in Asia and Africa to bovine, camel, and wildlife animals and animal species distribution. B. Graph depicting the number of species described in the year-wise publication, and the frequency of new or unique species described for the first time.

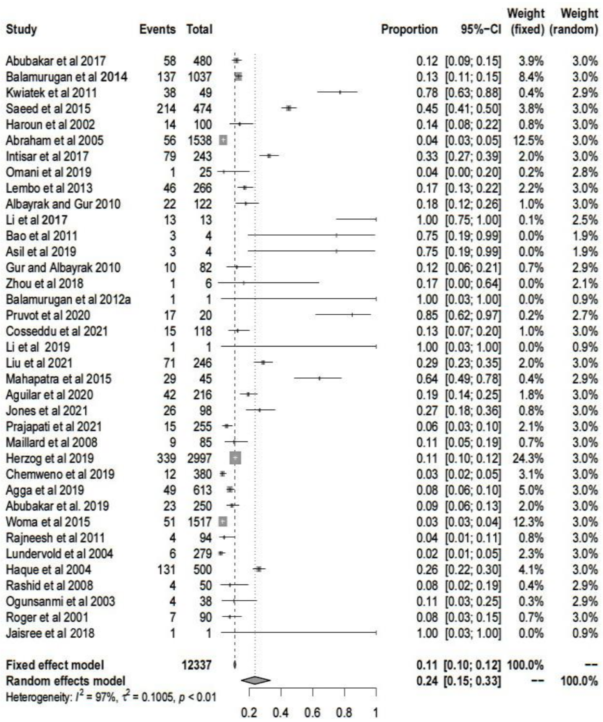

Figure 5. Forest plot of the prevalence estimates of PPR in bovine, camel, and wildlife during 2001-2021

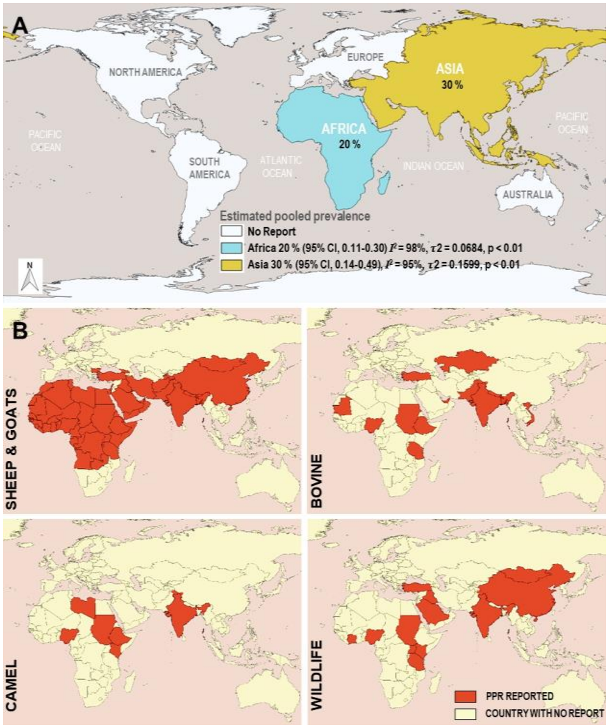

Figure 6. A. Estimated pooled prevalence of PPR in studied animals in Asia and Africa

B. Showing reported countries for PPR in sheep and goats (as per OIE 2018), bovine, camel, and wildlife

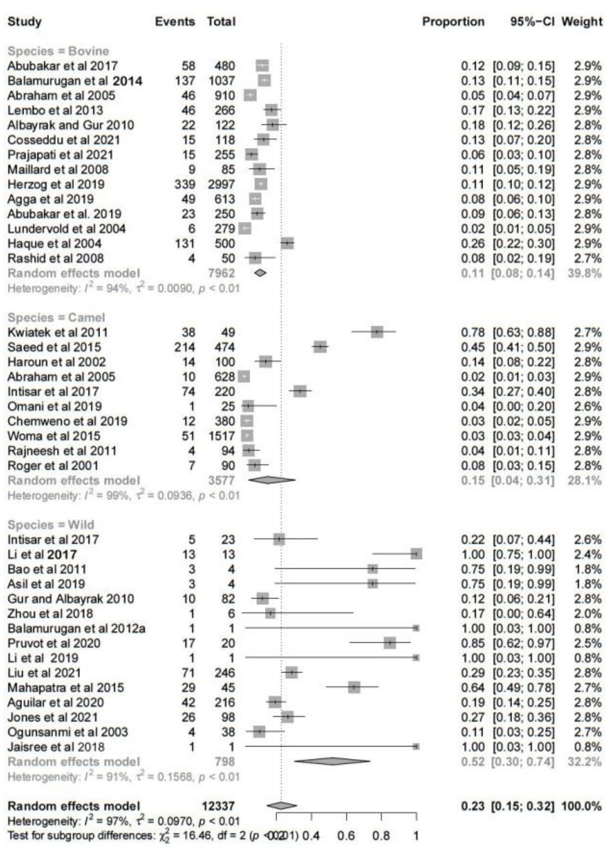

Figure 7. Forest plot subgroup analysis of prevalence estimates of PPR in bovine, camel, and wildlife

4. Conclusions

Contagious viral infection of PPRV has been reported in different parts of the world, including Asia, Africa, and some parts of Europe (18-22). However, for the meta-analysis, only 37 articles were selected from 48 eligible articles due to inter-rater disagreement. All 48 articles on bovine, camel, and wildlife from 2001 to 2021 were listed in table 1. An article published in 2001 by Roger, Yesus (6) based on the study conducted in 1995 was also included, and the systemic review and meta-analysis summarize the prevalence of PPR in bovine, camels, and wildlife based on the population size (n=12,337). An earlier meta-analysis study by Ahaduzzaman (69) using the random-effect model on PPR prevalence in sheep and goats from 34 countries shows an overall estimated pooled prevalence of 39.46% so that all data included in the study belonged to Asia and Africa with the prevalence of 38.63% and

40.16%, respectively. In the present study, the overall estimated pooled prevalence was 24% in three groups of unnatural hosts bovine, camel, and wildlife, which is lower than the prevalence of the primary host sheep and goat observed by Ahaduzzaman (69). The prevalence in bovine, camel, and wildlife was significantly higher in Asia (30%) and Africa (20%) (Table 3, Figures 6), which was contrary to the continent wise prevalence in compared to sheep and goats observed by Ahaduzzaman (69).

The present study under PCR assay grouping had I^2=91% and $\tau2$=0.2286 with a high prevalence of 74% (95 % CI: 39-97) (Figure 3). The chance of positivity was attributed to the low sample size as the outbreak samples were collected only in case of the onset of animal deaths and analyzed by RT-PCR. Furthermore, subgroup analyses of the enzyme-linked immunosorbent assay were classified by PPRV antigen and antibody detection with species, continents, and sample size above or below the median for better understanding. The result of antibody detection had a wide range of prevalence from 2 % above-median in camels from Africa to 30% below-median in the wildlife of Africa.

PPR in sheep and goats is reported from more than 70 countries, mostly of African and Asian origin (Figure 6) (4, 69). In the present review, PPR in the atypical/unnatural hosts (bovine, camel) and wildlife were observed in 22 countries from Africa (9) and Asia (13) (Table 1, Figure 4); however, the pooled prevalence was estimated for only 16 countries in the present meta-analysis. Only three enzootic countries, such as Nigeria, Sudan, and India were reported for all three groups of animals (bovine, camel, and wildlife) in the study period (Figure 6). Moreover, Bangladesh, Ethiopia, Kazakhstan, Libya, Mauritania, Nepal, Pakistan, and United Arab Emirates (UAE) were only reported in the atypical hosts (bovine and camel), and Côte d'Ivoire, Iraq, Saudi Arabia, Mongolia, China, and Uganda were reported only wildlife (Table 1, Figure 6B). Evidence of PPRV was in bovine in Vietnam without any official OIE reports on the prevalence of PPR in sheep and goats. Apart from these countries listed in this review, other reports conducted to detect the PPRV in wildlife were in Pakistan (72), Kurdistan, Iran (21, 56), UAE (73), and Egypt (74) as reviewed earlier (19, 22). Out of 70 countries with PPR in sheep and goats, only about 22 countries (31%) studied or reported the prevalence of PPR in atypical and wildlife hosts, showing a huge knowledge gap in understanding the role of these animals in the PPR spread and transmission.

In the present study, overall estimated pooled prevalence rates of 11%, 15%, and 52% were observed for bovine, camel, and wildlife, respectively. Prevalence in wildlife was higher than that in the bovine and camel, leading to concerns; however, the study population size of the wildlife was only 798, compared to 7,962 in bovine and 3,577 in camel as these low numbers are attributed to the lack of systematic study, limiting to outbreaks responses and lack of reporting in the wildlife setup.

A significant difference was also observed between the number of studies and prevalence of PPR in wildlife in two decades, 24% (3 studies) in 2001-2010 and 60% (12 studies) in 2011-2021 (Table 3). A cumulative time-scale map of the reported countries for PPR in the atypical hosts (bovine and camel) and wildlife during 2001-2021 is shown in figures 8 indicating the significance of wildlife recognized in recent years and the increasing frequency of PPR in wildlife.

Furthermore, large ruminants, such as cattle, water buffalo, and yaks are reported for seroconversion to PPRV in Asia and Africa; however, Govindarajan, Koteeswaran (13) observed rare clinical infection with high case fatality (96%) in bovine with fever, conjunctival congestion, hypersalivation, and depression. Experimental clinical infection was established in buffalo calves, whereas cattle were susceptible without clinical signs (75, 76). The cattle are also considered dead-end hosts for PPRV as no evidence of virus shedding was observed in body secretion and excretions (9, 14); however, transmission by water buffalo cannot be ruled out (13, 14). Clinical PPRV infection and seroconversion in camels are frequently reported from Africa and Asia. Here, clinical signs have been similar to sheep and goats (14, 77, 78), and the signs include fever, diarrhea, conjunctivitis with ocular discharges, loss of body condition, and general weakness, resembling PPR in small ruminants consequently. Additionally, evidence supporting viral shedding in faces and nasal discharges is considered as source of infection. It should be noted that the possible risk of camel transmission needs more studies. Both bovine and camel PPRV infections are attributed to the cohabitation of sheep and goats (14).

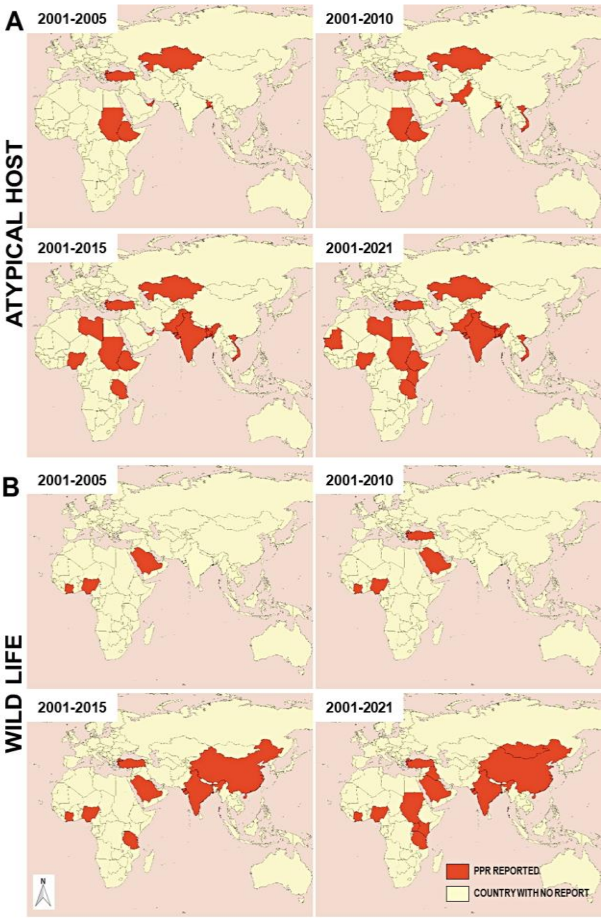

Figure 8. Cumulative reported countries for PPR in atypical hosts -bovine and camel- for the period 2001-2005, 2001-2010, 2001-2015 and 2001-2021 (A), in wildlife for the period 2001-2005, 2001-2010, 2001-2015 and 2001-2021 (B)

Hamdy and Dardiri (79) first reported in 1976 that wild ruminants were also sensitive to PPRV. Since then most reports of PPRV-related deaths focused on wild ruminants, such as bharals, wild goats, dorcas gazelles, bubal hartebeests, and waterbucks (22, 80). Before 2001, PPR was reported in cattle, water buffalo, camel, and in a few wildlife species, including Gazella dorcass (*Dorcas gazelles*), Nubian ibex (*Capra nubiana*), White-tailed deer (*Odocoileus virginianus*), Asinus (*Equus asinus*), Gemsbok (*Oryx gazella*), Laristan sheep (*Ovis gmelina*), and Nilgai (*Boselaphus tragocamelus*) (14, 17, 19, 22, 79, 81).

Since 2001, a drastic increase in the reports of atypical hosts and wildlife, and around 25 new species of animals (mostly in the wildlife) are reported, (Figure 4B). Prevalence of PPR in 25 wildlife species was covered in the present systematic review in Asia and Africa (Figure 4A) that include *Aepyceros melampus* (25), *Alcelaphus buselaphus* (34, 82), *Capra ibex* (18, 20), *Connochaetes* spp. (25), *Damaliscus lunatus* tiang (31), *Defassa waterbuck* (23), *Eudorcas thomsonii*, *Phacochoerus africanus Litocranius walleri* (34), *Gazella subgutturosa* (20, 26, 52), *Gazella thomsoni* (52), *Kobus kob leucotis*, *Kobus kob thomasi*, *Loxodonta africana* (31), *Nanger granti* (25, 34), *Ovis ammon* (20), *Panthera leo persica* (76), *Procapra przewalskii* (2), *Saiga tatarica* (18), *Syncerus caffer* (59), *Vicugna pacos* (33), *Capra aegagrus* (56), *Hydropotes inermis* (67), *Sylvicapra grimmia* (15), and *Tetracerus quadricornis* (66). Apart from these, PPR was also reported in other wildlife species, including *Gazella gazella cora* (Arabian mountain gazelle), *Antidorcas marsupialis* (Springbuck), *Gazella gazella* (Arabian gazelle), *Ammotragus lervia* (Barbary), *Tragelaphus scriptus* (Bushbuck), *Capra falconeri* (Afghan Markhor goat) (73), and *Ovis orientalis* (wild sheep) (21) without any data regarding prevalence in these reports. There is also reports with evidence of PPRV detection in lions (76) and elephant (31) from Asia and Africa, respectively. The frequency of PPR reporting in new hosts increased over the years and the year-wise species diversity and detection of new hosts are shown in figure 4B. Due to high animal density, most of the enzootic regions of Asia and Africa are likely to have a higher risk of PPR, for eg. the countries like Sudan, Kenya, and Tanzania have the highest species diversity. Moreover, because of a vast host range and heterogeneities in different host ranges and animal population density, the difference in susceptibility of the host to PPRV infection, disease control, and eradication seem cumbersome. As a result, the strategies employed cannot solely rely on or be limited to the vaccination of sheep and goats.

In the PPR GCES of the "Global Program-Transboundary Animal Diseases (GF-TADs)", the focus is considered vital on the prevention of cross-species and transmission from the typical hosts to unnatural hosts, including wildlife through strengthened disease surveillance, coupled with appropriate diagnostics and vaccination. More research on the pathogenesis of PPR in wildlife species is needed to explain this phenomenon; additionally, the function of infective strains, migration, stress, co-infections, environmental conditions, and other ecological elements of the disease must be thoroughly examined. However, wild ruminants can sustain and bridge viruses between wildlife and livestock (80), thereby eradicating PPRV may be hindered. For effective eradication, the program should focus on understanding the transmission of PPRV among the atypical hosts/wildlife. Modern molecular tools should also help in understanding virus virulence, an adapted ability for diverse hosts (80).

The limitation of the present analysis is that most of the studies on unnatural hosts, such as large ruminants and wildlife, were based on few samples, leading to high positivity. The systematic review was conducted on articles only from countries of Africa and Asia within the search range. Demographic characteristics (age, gender) and risk factors were also absent or not uniform in the selected articles. The review excluded some kinds of articles, including non-English, unpublished articles, retro perspective, method-validation articles, and also experimental-trial results. Finally, heterogeneity in models was significant that showed other ignored factors might have substantial effects.

To the best of our knowledge, this paper is the first study to estimate the prevalence of PPR among unusual hosts (bovine, camel) and wildlife using systematic review and meta-analysis. The estimated pooled prevalence was high and different between the two continents, which was contrary to observation on sheep and goats in Asia than Africa. The results show that the host range is widening over time and the frequency of discovery of new hosts has increased in recent years; moreover, the screening tests for PPR, effective preventive, and control measures should be routinely conducted in all susceptible animals (livestock and wildlife) in regions with a high disease prevalence to control the spill-over outbreaks. The outbreak in unnatural hosts may cause morbidity and mortality in economically important livestock and be also fatal to the wildlife populations in the sanctuaries and national parks. Controlling disease transmission to other unnatural hosts from sheep and goats is as much important as in sheep and goats. Furthermore, epidemiological surveillance is needed for estimating the disease burden and its elimination in many regions, in which the virus may be circulating in multiple hosts. Additionally, the contributing factors to the prevalence heterogeneity should be handled suitably in the survey for an accurate estimate. The findings of the current study are significant as Asia and Africa are responsible for the majority of the world's bovine, camel, and wildlife populations. Due to human activities and global climate change, wildlife has less access to food and water, resulting in poor nutritional status and habitat disturbance, increasing the probability of wildlife-livestock interactions. This interaction either directly or indirectly via other livestock animal persistence transmission can jeopardize the ongoing control program in the sheep and goat population. Therefore, surveillance mechanisms should be considered at the interface between the livestock and wildlife to identify the spillover mechanism of the PPRV infection. Furthermore, the surveillance should be strengthened to ensure mild clinical cases as PPR reported in sheep and goat vaccinated regions (due to the impact of vaccination, changing pattern of the disease in sheep and goats). Syndromic surveillance should be also used for knowing the status of clinical diseases, if any in the interface, and identifying the undetected mild cases during the PPR control and eradication program.

Authors' Contribution

S. S. K. carried out the literature search, analysis of data, and wrote the rough draft of the manuscript. K. V. K. and P. P. B. interpreted the data, wrote the draft, and prepared the GIS map, figures, and tables. S. S. K., B. A. P., and A. N. analyzed the data and carried out the meta-analysis in R software. K. P. S. designed, analyzed, and interpreted the data. BRS provided guidance and support to carry out the research. V. B. designed and conceptualized the idea, interpreted the data, rewritten the draft, and edited the manuscript. All authors read and approved the final edited manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

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References

1. Asil RM, Ludlow M, Ballal A, Alsarraj S, Ali WH, Mohamed BA, et al. First detection and genetic characterization of peste des petits ruminants virus from dorcas gazelles "Gazella dorcas" in the Sudan, 2016-2017. Arch Virol. 2019;164(10):2537-43.
2. Li L, Cao X, Wu J, Dou Y, Meng X, Liu D, et al. Epidemic and evolutionary characteristics of peste des petits ruminants virus infecting Procapra przewalskii in Western China. Infect Genet Evol. 2019;75:104004.
3. Herzog CM, de Glanville WA, Willett BJ, Kibona TJ, Cattadori IM, Kapur V, et al. Pastoral production is associated with increased peste des petits ruminants seroprevalence in northern Tanzania across sheep, goats and cattle. Epidemiol Infect. 2019;147:e242.
4. Balamurugan V, Vinod Kumar K, Dheeraj R, Kurli R, Suresh KP, Govindaraj G, et al. Temporal and Spatial Epidemiological Analysis of Peste Des Petits Ruminants Outbreaks from the Past 25 Years in Sheep and Goats and Its Control in India. Viruses. 2021;13(3).
5. FAO. Supporting Livelihoods and Building Resilience through Peste des Petits Ruminants (PPR) and Small Ruminant Diseases Control Rome: Animal Production and Health Position Paper; 2013 [Available from: http://www.fao.org/ppr/en/
6. Roger F, Yesus M, Libeau G, Diallo A, Yigezu LM, Yilma T. Detection of antibodies of rinderpest and peste des petits ruminants viruses (Paramyxoviridae, Morbillivirus) during a new epizootic disease in Ethiopian camels (Camelus dromedarius). Rev Med Vet. 2001;152:265-8.
7. Haroun M, Hajer I, Mukhtar M, Ali BE. Detection of antibodies against peste des petits ruminants virus in sera of cattle, camels, sheep and goats in Sudan. Vet Res Commun. 2002;26(7):537-41.
8. Vj C, Gitao G, Gachohi J, Soi R, Ndungu E, Khalif A, et al. PPR in Camels Sero-Prevalence and Socio-Economics. Int J Vet Sci. 2019;8.
9. Agga GE, Raboisson D, Walch L, Alemayehu F, Semu DT, Bahiru G, et al. Epidemiological Survey of Peste des Petits Ruminants in Ethiopia: Cattle as Potential Sentinel for Surveillance. Front Vet Sci. 2019;6:302.
10. Ozkul A, Akca Y, Alkan F, Barrett T, Karaoglu T, Dagalp SB, et al. Prevalence, distribution, and host range of Peste des petits ruminants virus, Turkey. Emerg Infect Dis. 2002;8(7):708-12.
11. Balamurugan V, Krishnamoorthy P, Veeregowda BM, Sen A, Rajak KK, Bhanuprakash V, et al. Seroprevalence of Peste des petits ruminants in cattle and buffaloes from Southern Peninsular India. Trop Anim Health Prod. 2012;44(2):301-6.

12. Fakri FZ, Bamouh Z, Jazouli M, Omari Tadlaoui K, Elharrak M. Experimental infection of dromedary camels with virulent virus of Peste des Petits Ruminants. Vet Microbiol. 2019;235:195-8.

13. Govindarajan R, Koteeswaran A, Venugopalan AT, Shyam G, Shaouna S, Shaila MS, et al. Isolation of pestes des petits ruminants virus from an outbreak in Indian buffalo (Bubalus bubalis). Vet Rec. 1997;141(22):573-4.

14. Rahman AU, Dhama K, Ali Q, Hussain I, Oneeb M, Chaudhary U, et al. Peste des petits ruminants in large ruminants, camels and unusual hosts. Vet Q. 2020;40(1):35-42.

15. Ogunsanmi AO, Awe EO, Taiwo TU. Peste des petits ruminants (PPR)virus antibodies in African grey duiker(Sylvicapra Grimmia). African Journal of Biomedical Research (ISSN: 1119-5096). 2010;6(1).

16. Hekal SHA, Al-Gaabary MH, El-Sayed MM, Sobhy HM, Fayed AAA. Seroprevalence of some Infectious transboundry diseases in cattle imported from Sudan to Egypt. J Adv Vet Anim Res. 2019;6(1):92-9.

17. Furley CW, Taylor WP, Obi TU. An outbreak of peste des petits ruminants in a zoological collection. Vet Rec. 1987;121(19):443-7.

18. Pruvot M, Fine AE, Hollinger C, Strindberg S, Damdinjav B, Buuveibaatar B, et al. Outbreak of Peste des Petits Ruminants among Critically Endangered Mongolian Saiga and Other Wild Ungulates, Mongolia, 2016-2017. Emerg Infect Dis. 2020;26(1):51-62.

19. Aziz Ul R, Wensman JJ, Abubakar M, Shabbir MZ, Rossiter P. Peste des petits ruminants in wild ungulates. Trop Anim Health Prod. 2018;50(8):1815-9.

20. Li J, Li L, Wu X, Liu F, Zou Y, Wang Q, et al. Diagnosis of Peste des Petits Ruminants in Wild and Domestic Animals in Xinjiang, China, 2013-2016. Transbound Emerg Dis. 2017;64(6):e43-e7.

21. Marashi M, Masoudi S, Moghadam MK, Modirrousta H, Marashi M, Parvizifar M, et al. Peste des Petits Ruminants Virus in Vulnerable Wild Small Ruminants, Iran, 2014-2016. Emerg Infect Dis. 2017;23(4):704-6.

22. Munir M. Role of wild small ruminants in the epidemiology of peste des petits ruminants. Transbound Emerg Dis. 2014;61(5):411-24.

23. Couacy-Hymann E, Bodjo C, Danho T, Libeau G, Diallo A. Surveillance of wildlife as a tool for monitoring rinderpest and peste des petits ruminants in West Africa. Rev Sci Tech. 2005;24(3):869-77.

24. Kock R. Mongolia Investigation of Peste des Petits Ruminants (PPR) among wild animals and its potential impact on the current PPR situation in livestock. 2019.

25. Mahapatra M, Sayalel K, Muniraju M, Eblate E, Fyumagwa R, Shilinde L, et al. Spillover of Peste des Petits Ruminants Virus from Domestic to Wild Ruminants in the Serengeti Ecosystem, Tanzania. Emerg Infect Dis. 2015;21(12):2230-4.

26. Elzein EM, Housawi FM, Bashareek Y, Gameel AA, Al-Afaleq AI, Anderson E. Severe PPR infection in gazelles kept under semi-free range conditions. J Vet Med B Infect Dis Vet Public Health. 2004;51(2):68-71.

27. Abubakar M, Sattorov N, Manzoor S, Khan EuH, Hussain M, Zahur AB, et al. Detection of antibodies to peste-des-petits-ruminants virus in the semi-domesticated yak. Eur J Wildl Res. 2019;65(6):88.

28. Lundervold M, Milner-Gulland EJ, O'Callaghan CJ, Hamblin C, Corteyn A, Macmillan AP. A serological survey of ruminant livestock in Kazakhstan during post-Soviet transitions in farming and disease control. Acta Vet Scand. 2004;45(3-4):211.

29. Meunier NV, Sebulime P, White RG, Kock R. Wildlife-livestock interactions and risk areas for cross-species spread of bovine tuberculosis. Onderstepoort J Vet Res. 2017;84(1):e1-e10.

30. Miguel E, Grosbois V, Caron A, Boulinier T, Fritz H, Cornélis D, et al. Contacts and foot and mouth disease transmission from wild to domestic bovines in Africa. 2013;4(4):art51.

31. Fernandez Aguilar X, Mahapatra M, Begovoeva M, Kalema-Zikusoka G, Driciru M, Ayebazibwe C, et al. Peste des Petits Ruminants at the Wildlife-Livestock Interface in the Northern Albertine Rift and Nile Basin, East Africa. Viruses. 2020;12(3).

32. Cosseddu GM, Doumbia B, Scacchia M, Pinoni C, Di Provvido A, Polci A, et al. Sero-surveillance of emerging viral diseases in camels and cattle in Nouakchott, Mauritania: an abattoir study. Trop Anim Health Prod. 2021;53(2):195.

33. Liu Q, Liu L, Meng YK, Wang C, Gao Y, Zheng FG, et al. Serological evidence of bovine viral diarrhea virus and peste des petits ruminants virus infection in alpacas (Vicugna pacos) in Shanxi Province, northern China. Trop Anim Health Prod. 2021;53(2):299.

34. Jones BA, Mahapatra M, Mdetele D, Keyyu J, Gakuya F, Eblate E, et al. Peste des Petits Ruminants Virus Infection at the Wildlife-Livestock Interface in the Greater Serengeti Ecosystem, 2015-2019. Viruses. 2021;13(5).

35. Haque M, Habib S, M.R I, K.A K, A.S.M.A H, Anower AKM, et al. Sero-monitoring of Peste Des Petits Ruminants (PPR) Antibodies in Small and Large Ruminants in Bangladesh. J Anim Vet Adv. 2004.
36. Prajapati M, Shrestha SP, Kathayat D, Dou Y, Li Y, Zhang Z. Serological investigations of Peste des Petits Ruminants in cattle of Nepal. Vet Med Sci. 2021;7(1):122-6.
37. Fenton A, Pedersen AB. Community epidemiology framework for classifying disease threats. Emerg Infect Dis. 2005;11(12):1815-21.
38. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535.
39. Shamseer L, Moher D, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. BMJ. 2015;350:g7647.
40. Sushma B, Shedole S, Suresh KP, Leena G, Patil SS, Srikantha G. An Estimate of Global Anthrax Prevalence in Livestock: A Meta-analysis. Vet World. 2021;14(5):1263-71.
41. Abraham G, Sintayehu A, Libeau G, Albina E, Roger F, Laekemariam Y, et al. Antibody seroprevalences against peste des petits ruminants (PPR) virus in camels, cattle, goats and sheep in Ethiopia. Prev Vet Med. 2005;70(1-2):51-7.
42. Khan HA, Siddique M, Sajjad ur R, Abubakar M, Ashraf M. The detection of antibody against peste des petits ruminants virus in sheep, goats, cattle and buffaloes. Trop Anim Health Prod. 2008;40(7):521-7.
43. Maillard JC, Van KP, Nguyen T, Van TN, Berthouly C, Libeau G, et al. Examples of probable host-pathogen co-adaptation/co-evolution in isolated farmed animal populations in the mountainous regions of North Vietnam. Ann N Y Acad Sci. 2008;1149:259-62.
44. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med. 2002;21(11):1539-58.
45. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ. 2003;327(7414):557-60.
46. Schwarzer G. meta: An R Package for Meta-Analysis. 2007;7:40-5.
47. Rashid A, Asim M, Hussain A. Seroprevalence of peste des petits ruminants (PPR) virus in goats, sheep and cattle at Livestock Production Research Institute Bahadurnagar Okara. J Anim Plant Sci. 2008;18.
48. Krishnamoorthy P, Akshatha L, Jacob S, Suresh K, Roy P. Theileriosis prevalence status in cattle and buffaloes in India established by systematic review and meta-analysis. Indian J Anim Sci. 2021;91(4):269–79.
49. Albayrak H, Gur S. A serologic investigation for Peste des petits ruminants infection in sheep, cattle and camels (Camelus dromedarius) in Aydin province, West Anatolia. Trop Anim Health Prod. 2010;42(2):151-3.
50. Fagerland MW. Chapter 12 - Evidence-Based Medicine and Systematic Reviews. In: Laake P, Benestad HB, Olsen BR, editors. Research in Medical and Biological Sciences (Second Edition). Amsterdam: Academic Press; 2015. p. 431-61.
51. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(7109):629-34.
52. Gur S, Albayrak H. Seroprevalance of peste des petits ruminants (PPR) in goitered gazelle (Gazella subgutturosa subgutturosa) in Turkey. J Wildl Dis. 2010;46(2):673-7.
53. Kwiatek O, Ali YH, Saeed IK, Khalafalla AI, Mohamed OI, Obeida AA, et al. Asian lineage of peste des petits ruminants virus, Africa. Emerg Infect Dis. 2011;17(7):1223-31.
54. Bao J, Wang Z, Li L, Wu X, Sang P, Wu G, et al. Detection and genetic characterization of peste des petits ruminants virus in free-living bharals (Pseudois nayaur) in Tibet, China. Res Vet Sci. 2011;90(2):238-40.
55. Rajneesh, Kataria A, Tanwar RK. Prevalence of some infectious diseases in dromedary camel from Bikaner region in Rajasthan. Vet Pract. 2011;12:50-3.
56. Hoffmann B, Wiesner H, Maltzan J, Mustefa R, Eschbaumer M, Arif FA, et al. Fatalities in wild goats in Kurdistan associated with Peste des Petits Ruminants virus. Transbound Emerg Dis. 2012;59(2):173-6.
57. Lin L, Xu C. Arcsine-based transformations for meta-analysis of proportions: Pros, cons, and alternatives. Health Sci Rep. 2020;3(3):178.
58. Balamurugan V, Krishnamoorthy P, Raju DS, Rajak KK, Bhanuprakash V, Pandey AB, et al. Prevalence of Peste-des-petits-ruminant virus antibodies in cattle, buffaloes, sheep and goats in India. Virusdisease. 2014;25(1):85-90.
59. Lembo T, Oura C, Parida S, Hoare R, Frost L,

Fyumagwa R, et al. Peste des petits ruminants infection among cattle and wildlife in northern Tanzania. Emerg Infect Dis. 2013;19(12):2037-40.
60. El-Dakhly A. Serological Survey for Peste Des Petits Ruminants Virus (PPRv) in Camel from Different Regions in The West of Libya. Int J Sci Researh. 2013;4:1455-9.
61. Abdul-Dahiru E-Y, Baba SS, Ambali A-G, Egwu G. Seroprevalence of peste des petits ruminants among domestic small and large ruminants in the semi-arid region of North-eastern Nigeria. Vet World. 2013;6:807-11.
62. Woma TY, Kalla DJ, Ekong PS, Ularamu HG, Chollom SC, Lamurde, II, et al. Serological evidence of camel exposure to peste des petits ruminants virus (PPRV) in Nigeria. Trop Anim Health Prod. 2015;47(3):603-6.
63. Saeed IK, Ali YH, AbdulRahman MB, Mohammed ZA, Osman HM, Taha KM, et al. Mixed infection of peste des petits ruminants virus (PPRV) and other respiratory viruses in dromedary camels in Sudan, an abattoir study. Trop Anim Health Prod. 2015;47(5):995-8.
64. Abubakar M, Mahapatra M, Muniraju M, Arshed MJ, Khan EH, Banyard AC, et al. Serological Detection of Antibodies to Peste des Petits Ruminants Virus in Large Ruminants. Transbound Emerg Dis. 2017;64(2):513-9.
65. Intisar KS, Ali YH, Haj MA, Sahar MA, Shaza MM, Baraa AM, et al. Peste des petits ruminants infection in domestic ruminants in Sudan. Trop Anim Health Prod. 2017;49(4):747-54.
66. Jaisree S, Aravindhbabu RP, Roy P, Jayathangaraj MG. Fatal peste des petits ruminants disease in Chowsingha. Transbound Emerg Dis. 2018;65(1):e198-e201.
67. Zhou XY, Wang Y, Zhu J, Miao QH, Zhu LQ, Zhan SH, et al. First report of peste des petits ruminants virus lineage II in Hydropotes inermis, China. Transbound Emerg Dis. 2018;65(1):e205-e9.
68. Ali WH, Osman NA, Asil RM, Mohamed BA, Abdelgadir SO, Mutwakil SM, et al. Serological investigations of peste des petits ruminants among cattle in the Sudan. Trop Anim Health Prod. 2019;51(3):655-9.
69. Ahaduzzaman M. Peste des petits ruminants (PPR) in Africa and Asia: A systematic review and meta-analysis of the prevalence in sheep and goats between 1969 and 2018. Vet Med Sci. 2020;6(4):813-33.
70. Bello MB, Kazeem HM, Oladele SB, Fatihu MY, Tambuwal FM, Jibril AH. Seroprevalence of peste des petits ruminants among unvaccinated small ruminants in Sokoto State, northwestern Nigeria. Comp Clin Path. 2018;27(5):1141-6.
71. Omani RN, Gitao GC, Gachohi J, Gathumbi PK, Bwihangane BA, Abbey K, et al. Peste Des Petits Ruminants (PPR) in Dromedary Camels and Small Ruminants in Mandera and Wajir Counties of Kenya. Adv Virol. 2019;2019:4028720.
72. Abubakar M, Rajput ZI, Arshed MJ, Sarwar G, Ali Q. Evidence of peste des petits ruminants virus (PPRV) infection in Sindh Ibex (Capra aegagrus blythi) in Pakistan as confirmed by detection of antigen and antibody. Trop Anim Health Prod. 2011;43(4):745-7.
73. Kinne J, Kreutzer R, Kreutzer M, Wernery U, Wohlsein P. Peste des petits ruminants in Arabian wildlife. Epidemiol Infect. 2010;138(8):1211-4.
74. TM I. Studies on prevalence of rinderpest and pests des petits ruminants antibodies in camel sera in Egypt. Vet Med J. 1992;40:49-53.
75. Couacy-Hymann E, Bodjo C, Danho T, Libeau G, Diallo A. Evaluation of the virulence of some strains of peste-des-petits-ruminants virus (PPRV) in experimentally infected West African dwarf goats. Vet J. 2007;173(1):178-83.
76. Sen A, Saravanan P, Balamurugan V, Bhanuprakash V, Venkatesan G, Sarkar J, et al. Detection of subclinical peste des petits ruminants virus infection in experimental cattle. Virusdisease. 2014;25(3):408-11.
77. Khalafalla AI, Saeed IK, Ali YH, Abdurrahman MB, Kwiatek O, Libeau G, et al. An outbreak of peste des petits ruminants (PPR) in camels in the Sudan. Acta Trop. 2010;116(2):161-5.
78. Zakian A, Nouri M, Kahroba H, Mohammadian B, Mokhber-Dezfouli MR. The first report of peste des petits ruminants (PPR) in camels (Camelus dromedarius) in Iran. Trop Anim Health Prod. 2016;48(6):1215-9.
79. Hamdy FM, Dardiri AH. Response of white-tailed deer to infection with peste des petits ruminants virus. J Wildl Dis. 1976;12(4):516-22.
80. Dou Y, Liang Z, Prajapati M, Zhang R, Li Y, Zhang Z. Expanding Diversity of Susceptible Hosts in Peste Des Petits Ruminants Virus Infection and Its Potential Mechanism Beyond. Front Vet Sci. 2020;7:66.
81. Rahman AU, Munir M, Shabbir MZ. A comparative phylogenomic analysis of peste des petits ruminants virus isolated from wild and unusual hosts. Mol Biol Rep. 2019;46(5):5587-93.
82. Jones BA, Mahapatra M, Chubwa C, Clarke B,

Batten C, Hicks H, et al. Characterisation of Peste Des Petits Ruminants Disease in Pastoralist Flocks in Ngorongoro District of Northern Tanzania and Bluetongue Virus Co-Infection. Viruses. 2020;12(4).