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Systematic review of the prevalence of environmental and host-related risk factors and the zoonotic potential of leptospirosis in domestic dogs in regions impacted by environmental changes

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Abstract

Background Leptospirosis is a globally distributed zoonosis with significant public and veterinary health implications. Domestic dogs serve both as sentinels and reservoirs, particularly in ecologically dynamic settings influenced by urbanization and climate change. However, the global understanding of canine leptospirosis remains fragmented due to inconsistent diagnostic practices and variable regional data.

Objectives To synthesize global evidence on the seroprevalence, dominant serovars, and risk factors associated with *Leptospira* infection in domestic dogs, and to evaluate the implications for public health within a One Health framework.

Methods Following PRISMA guidelines, a systematic review was conducted across four databases (PubMed, Scopus, Web of Science, and WeLib) for studies published between 2000 and 2024. Observational studies using the Microscopic Agglutination Test (MAT) on domestic dogs were included. Data were extracted on seroprevalence, serovar distribution, and environmental, behavioral, and socio-economic risk factors. The Newcastle–Ottawa Scale was used for quality assessment. A narrative synthesis was conducted due to heterogeneity in methodologies.

Results The systematic search identified 1,842 records, with 26 studies included, involving 13,827 dogs across 12 countries. Seroprevalence ranged from 9.1% to 75.0%, with higher rates in South America and Asia due to tropical climates**.** Dominant serovars included *Leptospira interrogans* serovar Canicola and *Leptospira interrogans* serovar Icterohaemorrhagiae, while *Leptospira borgpetersenii* serovar Sejroe emerged in specific regions**.** Environmental (e.g., water proximity, OR = 1.5–5.1), behavioral (e.g., rodent hunting, OR = 2.4–4.5), and socioeconomic (e.g., poverty, OR = 2.5–4.0) risk factors were identified. Dogs served as sentinels and reservoirs, guiding One Health interventions.

Conclusions Canine leptospirosis is shaped by environmental, behavioral, and socio-economic drivers, with marked regional disparities. Dogs play a dual role as sentinels and reservoirs, necessitating integrated One Health

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interventions including targeted vaccination, environmental control, and community education. Standardization of diagnostics and expanded surveillance in underrepresented regions are critical for effective global leptospirosis control.

Keywords Leptospirosis, Domestic Dogs, Seroprevalence, Risk Factors, One Health, Zoonosis, Environmental Change

Introduction

Leptospirosis, caused by pathogenic spirochetes of the genus *Leptospira*, is a globally distributed zoonotic disease with significant implications for public and veterinary health [1]. Transmission occurs primarily through contact with infected animals or exposure to environments contaminated with *Leptospira*-laden urine, particularly in humid, high-precipitation regions [2]. Domestic dogs (*Canis familiaris*), due to their close association with humans and susceptibility to multiple *Leptospira* serovars, are critical in the disease's transmission cycle, serving as reservoirs that amplify the pathogen in urban, rural, and periurban settings or as sentinels indicating environmental contamination and zoonotic risk [3]. The complex interplay of host, pathogen, and environmental factors, exacerbated by socio-economic and ecological changes like urbanization and climate shifts, necessitates a systematic evaluation of canine leptospirosis to inform evidence-based control measures [4]. Although numerous regional studies have investigated canine leptospirosis, the global picture remains fragmented [5]. Variability in diagnostic practices, the diversity of circulating serovars, and differing environmental and socio-economic contexts contribute to an incomplete understanding of the disease's distribution and risk factors [6]. Moreover, the lack of a comprehensive synthesis limits the ability to assess broader patterns and draw meaningful comparisons across regions. Given the growing recognition of dogs as both reservoirs and sentinels, there is a pressing need to consolidate existing knowledge to inform public health interventions and guide future research efforts within a One Health framework. Despite numerous regional studies, significant gaps in global understanding persist, particularly in the standardization of diagnostic methods, geographic representation, and integration of serological and molecular data. A major limitation is the lack of consistent, standardized global prevalence data, which hampers comparability across regions. Diagnostic inconsistencies, including varied MAT cutoff titers and serovar panels, further obscure seroprevalence estimates. Moreover, regional variation in environmental and socio-economic drivers remains poorly synthesized [7]. This review aims to provide a comprehensive narrative synthesis of canine leptospirosis to guide vaccination strategies, environmental surveillance, and public health policies to mitigate zoonotic risks across diverse global settings, leveraging dogs' roles as sentinels and reservoirs. Specifically, the objectives are to: (1) estimate the global seroprevalence of *Leptospira* in domestic dogs, (2) identify the prevalence and distribution of specific *Leptospira* serovars in canine populations, (3) evaluate environmental, behavioral, and socioeconomic risk factors associated with canine leptospirosis, and (4) assess the One Health implications of these findings. (it came from the end of 2.2).

Methods

Study design

This systematic review was performed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure comprehensive and transparent reporting. The absence of meta-analysis is due to significant heterogeneity in study designs, diagnostic protocols, and ecological contexts, necessitating a narrative synthesis to integrate findings. Protocol registration in PROSPERO was not undertaken, as registration is not mandatory for systematic reviews, but the protocol was documented internally to ensure transparency and reproducibility.

Research question and objectives

The research question was developed using the PICO framework to guide the review process. The population of interest includes domestic dogs (*Canis lupus familiaris*) worldwide. The exposure considered was contact with pathogenic *Leptospira* species, while the comparator group comprised dogs without serological evidence of infection. The outcomes assessed were seroprevalence rates, distribution of *Leptospira* serovars, associated risk factors, and One Health implications.

Eligibility criteria

Studies were eligible for inclusion if they met the following criteria: they were observational in design (cross-sectional, cohort, or case–control), reported original data on *Leptospira* seroprevalence or associated risk factors in domestic dogs, and used the Microscopic Agglutination Test (MAT(. The study population could include owned, stray, or kennel-based dogs of any age, sex, breed, or vaccination status. Studies had to report at least one of the following outcomes: seroprevalence rates (with or without confidence intervals), serovar or serogroup distribution (e.g., *Leptospira interrogans* serovar Canicola, *Leptospira interrogans* serovar Icterohaemorrhagiae, *Leptospira borgpetersenii* Serovar Sejroe)or risk factors (e.g., environmental exposure, rodent contact, socio-economic

indicators) presented as qualitative or quantitative data. Only peer-reviewed journal articles published between January 2000 and December 2024 in English, Spanish, or Portuguese were included. Studies were excluded if they focused exclusively on non-domestic canids, used only non-serological diagnostic methods (e.g., PCR without MAT), lacked original data (such as reviews, editorials, or case reports with fewer than ten dogs), or did not provide sufficient methodological detail, such as undefined MAT thresholds or incomplete serovar information.

Search strategy

A systematic literature search was conducted on January 20, 2025, using four electronic databases: PubMed, Scopus, Web of Science, and WeLib. The search strategy was developed with input from a research librarian to ensure sensitivity and included both Medical Subject Headings (MeSH) and free-text keywords related to leptospirosis, domestic dogs, serological testing, and epidemiological terms. Boolean operators (AND, OR) were used to combine terms, and filters were applied to restrict results by language and publication type. An example PubMed search string was: ("leptospirosis"[MeSH Terms] OR "*Leptospira*"[All Fields]) AND ("dogs"[MeSH Terms] OR "canine"[All Fields]) AND ("seroprevalence"[All Fields] OR "microscopic agglutination test"[All Fields] OR "risk factors"[All Fields]) AND (2000/01/01:2024/12/31[pdat]). Reference lists of included articles and relevant reviews were hand-searched to identify additional eligible studies. Grey literature was included only if accessible via the selected databases and met peer-review standards.

Study selection

Data extraction was carried out using a standardized form in Microsoft Excel, which was piloted on a subset of five studies to ensure clarity and consistency. Two reviewers independently extracted data on study characteristics (e.g., author, year, country, design, sample size), population details (e.g., type of dog population, age, sex, breed, vaccination status), diagnostic methods (e.g., MAT, serovars tested, laboratory protocols), and outcomes of interest additional variables, including sampling methods, response rates, and adoption of a One Health approach—defined as the integration of human, animal, and environmental health data or cross-sectoral collaboration (e.g., linking canine seroprevalence to human health outcomes, assessing environmental risk factors like water contamination, or involving veterinary and public health agencies)—were also recorded. Discrepancies between reviewers were resolved through a structured process involving initial discussion to reach consensus; if unresolved, a third independent reviewer was consulted to provide a final decision, with disagreements documented and categorized by type (e.g., data extraction errors or study eligibility disputes); if unresolved, a third independent reviewer provided a final decision, and inter-rater reliability was quantified using Cohen's kappa coefficient to ensure robust agreement. When necessary, authors were contacted to obtain clarification or missing information, particularly regarding serovar testing panels or diagnostic protocols.

Quality assessment

The methodological quality and risk of bias of included studies were assessed using the Newcastle–Ottawa Scale (NOS), adapted for cross-sectional, case–control, cohort, and retrospective studies [8–10]. This tool evaluates nine criteria across three domains: Selection (representativeness of the sample, sample size, non-respondents, ascertainment of exposure; max 4 stars), Comparability (control for confounding factors; max 2 stars), and Outcome/Exposure (assessment of outcome, statistical reporting, independent validation; max 3 stars). Each study was scored out of 9 stars and categorized as low (7–9 stars), moderate (4–6 stars), or high (0–3 stars) risk of bias. Two reviewers independently scored each study, and inter-rater agreement was assessed using Cohen's kappa. Disagreements were resolved through discussion or by consulting a third reviewer. Studies with a high risk of bias were included in the narrative synthesis but subjected to sensitivity analyses if meta-analyses were conducted.

Data synthesis and analysis

A narrative synthesis was conducted to systematically integrate and interpret findings on seroprevalence, serovar distribution, risk factors, and One Health implications of canine leptospirosis, following the framework outlined by Popay et al. [11]. (2006) for systematic reviews without meta-analysis. This approach involved four key steps: (1) developing a preliminary synthesis by grouping studies, (2) exploring relationships within and between studies through thematic analysis, (3) assessing the robustness of the synthesis by evaluating methodological influences, and (4) drawing conclusions to inform One Health applications. Due to heterogeneity in study designs, diagnostic protocols (e.g., MAT cut-off titers, serovar panel sizes), and ecological contexts, a qualitative synthesis was prioritized to elucidate patterns, inconsistencies, and contextual drivers of *Leptospira* infection in domestic dogs [12].

Preliminary synthesis and grouping

Findings from the 26 included studies were organized by geographic region (South America, Asia, Europe, Oceania, North America) and dog population type (owned, stray, kennel, mixed) to facilitate comparison and identify regional and population-specific trends. Four primary

themes were identified: (1) seroprevalence patterns, (2) serovar distribution and diversity, (3) risk factor associations, and (4) One Health implications. These themes were chosen to address the review's objectives and capture the multifaceted role of dogs in leptospirosis epidemiology. Data were tabulated to support the synthesis, with seroprevalence summarized by region and dog type (Table 2), serovar prevalence by dominant and emerging serogroups (Table 3), risk factors categorized as environmental, behavioral, and socioeconomic (Table 4), and key thematic findings synthesized by region (Table 5).

Publication bias

Publication bias was assessed where ≥ 10 comparable studies were available by examining study characteristics, such as sample size and reported seroprevalence, and visually inspecting funnel plots of study size against seroprevalence to identify potential asymmetry, as recommended for systematic reviews [13]. Two independent reviewers evaluated these characteristics and plots, with discrepancies resolved through discussion to ensure consistent interpretation. Funnel plots were generated using R software.

Reporting

The results of this systematic review were presented through comprehensive tables summarizing key study characteristics, including geographic location, study design, and population details. Narrative synthesis was used to describe patterns and findings across studies, with particular attention to methodological heterogeneity. The study selection process was illustrated using a PRISMA flow diagram. All findings were interpreted within the One Health framework, highlighting the role of domestic dogs as both sentinels and potential reservoirs in the transmission of *Leptospira* species, with implications for public health surveillance and veterinary interventions [14].

Results

The systematic search, conducted on January 20, 2025, identified 1,842 records, with 26 studies included after screening, involving 13,827 dogs across 12 countries. Findings are supported by tables that summarize key data and highlight regional and methodological differences.

Study selection

The systematic search was conducted on January 20, 2025, across PubMed, Scopus, Web of Science, and WeLib databases. Search results were imported into EndNote (version X9) for de-duplication. Two reviewers independently screened titles and abstracts using Covidence software, followed by full-text assessment for eligibility. Discrepancies were resolved through discussion or by a third reviewer. Figure 1 (PRISMA Flow Diagram) illustrates the study selection process.

Study characteristics

To provide context for the findings, Table 1 summarizes the characteristics of the 26 included studies, including geographic location, study design, sample size, detection methods, seroprevalence, and key risk factors, supporting the evaluation of global patterns and risk factors (objectives 1 and 3). The 26 studies, published between 2004 and 2024, involved 13,827 dogs across 12 countries: Brazil ($n = 4$), Colombia ($n = 3$), Chile ($n = 3$), Ecuador ($n = 2$), France ($n = 2$), Australia ($n = 2$), India ($n = 1$), Vietnam ($n = 1$), Russia ($n = 1$), Argentina ($n = 1$), Saint Kitts ($n = 1$), Italy ($n = 1$), and Mexico ($n = 1$). Study designs included cross-sectional ($n = 20$), case–control ($n = 3$), retrospective ($n = 2$), and prospective cohort ($n = 1$). Sample sizes ranged from 50 to 706 (median = 232). Most studies ($n = 23$) used MAT, with serovar panels ranging from 10 to 25, universally testing Canicola, Icterohaemorrhagiae, and Copenhageni. Dog populations included owned ($n = 18$), stray ($n = 5$), kennel ($n = 2$), and mixed ($n = 1$), with vaccination status reported in 15 studies (30–80% vaccinated).

Newcastle–Ottawa Scale (NOS)

Table 2 presents the quality assessment of the 26 included studies using the Newcastle–Ottawa Scale (NOS) to evaluate methodological rigor and support the reliability of findings across all objectives. The NOS assessed studies across three domains: Selection (representativeness, sample size, non-respondents, and exposure ascertainment; maximum 4 stars), Comparability (control for confounding factors such as vaccination status, age, and sex; maximum 2 stars), and Outcome/Exposure (standardized outcome assessment, statistical reporting, and independent validation; maximum 3 stars). Studies were scored out of 9 stars and categorized as low (7–9 stars), moderate (4–6 stars), or high (0–3 stars) risk of bias. Eighteen studies achieved low risk of bias (7–9 stars), demonstrating strengths like standardized Microscopic Agglutination Test (MAT) protocols and clear statistical reporting. Six studies were rated moderate risk (4–6 stars), often due to incomplete vaccination data (e.g., Montiel-Arteaga [27] et al.) or limited serovar panels (< 12, e.g., Belaz et al. [35]). Two studies were high risk (0–3 stars), such as Zakharova et al. [26], due to significant methodological flaws like non-random sampling and small serovar panels. Inter-rater agreement was high (Cohen's kappa = 0.90), indicating robust reviewer concordance. Table 2 summarizes the scores for each study, highlighting methodological strengths and limitations.

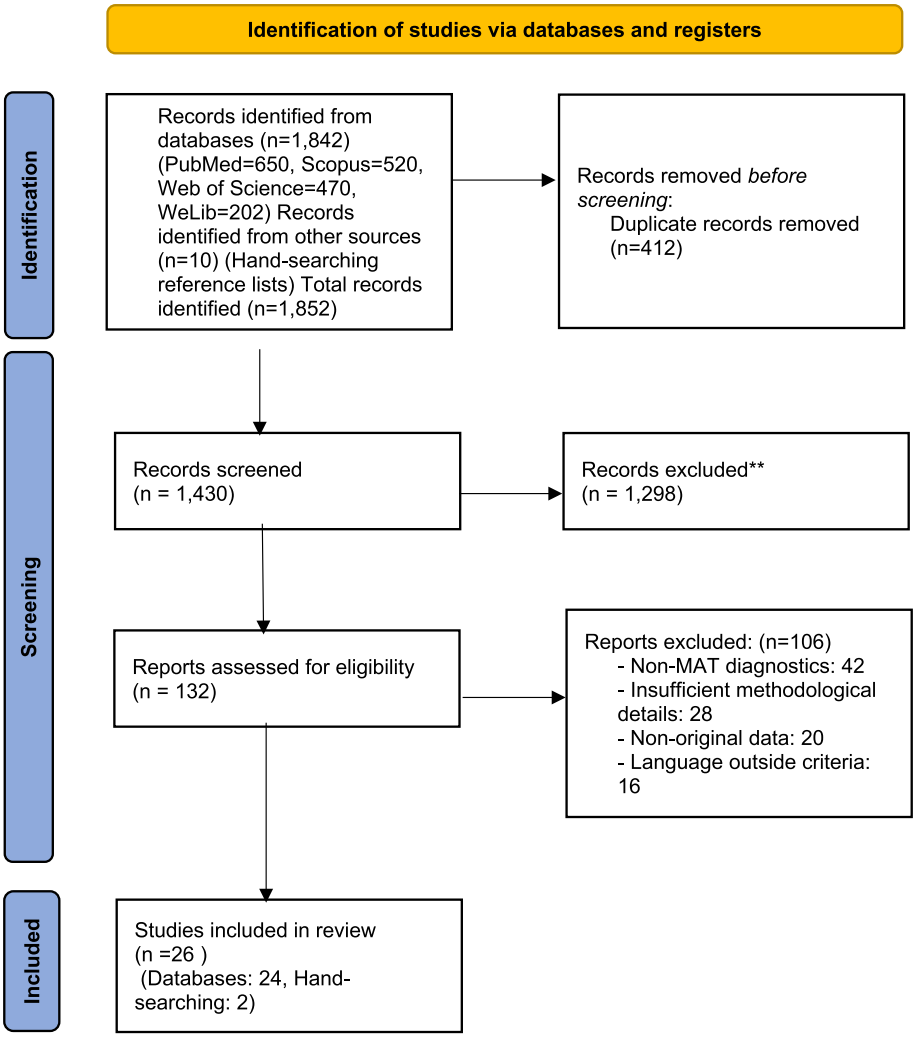

Fig. 1 PRISMA flow diagram

Quality assessment

The Newcastle–Ottawa Scale (NOS) rated 18 studies as low risk of bias (7–9 stars), 6 as moderate (4–6 stars), and 2 as high risk (0–3 stars) due to small sample sizes (< 100) or non-random sampling. Strengths included standardized Microscopic Agglutination Test (MAT) protocols and clear statistical reporting. Weaknesses in moderate/high-risk studies included incomplete vaccination data and limited serovar panels (< 12). Inter-rater agreement was high (Cohen's kappa = 0.90), indicating robust reviewer concordance.

Global seroprevalence of leptospira in domestic dogs

To address the first objective, Table 3 summarizes the global seroprevalence of *Leptospira* in domestic dogs by region and population type, highlighting patterns and variations influenced by methodological and ecological heterogeneity. Seroprevalence varied widely across regions and dog populations, reflecting differences in study designs, Microscopic Agglutination Test (MAT) cutoff titers, and environmental contexts. In South America, seroprevalence ranged from 9.1% in rural Chile [16] to 75% in Ecuador's Amazonian communities [31], with higher rates often observed in tropical areas with high precipitation. Asia reported seroprevalence from 28.5% to 32.9%, with studies like Vietnam [25] noting elevated rates in mixed populations. Europe and Oceania showed lower seroprevalence, ranging from 9.4% to 18.7% in France [1] and 14.5% to 16.2% in Australia [23, 23], while North America ranged from 13.9% to 15.0% [28, 29]. Stray and kennel dogs consistently exhibited higher seroprevalence (e.g., 50.9% in Italian kennels [37], 45.1% in Chilean slums [20] compared to owned dogs (e.g., 9.1% in rural Chile [16], likely due to increased environmental exposure. Heterogeneity in diagnostic protocols and ecological factors, such as tropical versus temperate climates, limited direct comparisons, necessitating a qualitative synthesis of these patterns.

Table 1 Characteristics of included studies in the systematic review (title changed)

Study (Author)	Country/Region	Sample Size	Setting	Study Design	Detection Method	Prevalence/Seropositivity	Key Risk Factors/Notes	Year
Céspedes Cárdenas et al. [15]	Bogotá, Colombia	192 dogs	Urban	Cross-sectional	MAT (16 serovars)	36.46%	Water sources, rodent hunting, rainfall	2018
Azócar-Aedo & Monti [16]	Southern Chile	706 dogs	Urban/Rural	Cross-sectional	MAT (13 serovars)	Urban 9.4%, Rural 9.1%	Rodent exposure, contact with livestock	2022
Guzmán et al. [17]	Ecuador (Amazon)	48 dogs (36 MAT)	Rural	Cross-sectional	MAT + PCR	75% (MAT), 94.7% (PCR)	Free-ranging dogs; multiple Leptospira species	2024
Pratt et al. [18]	Saint Kitts	101 dogs	Urban	Serosurvey	MAT (21 serovars)	73.2%	Diverse serovars; Autumnalis dominant	2017
Sohn-Hausner et al. [19]	Southern Brazil	Not specified	Urban	One Health survey	MAT + GIS	Not clearly quantified	Dogs as sentinels; overlaps with rainfall and flooding	2023
Lelu et al. [20]	Chile (Los Rios)	247 dogs	Rural/Farm/Slum	Cross-sectional	MAT (20 serovars)	25.1% overall (Slum 45.1%)	Precipitation, puddles, community type	2015
Ayral et al. [1]	France	232 dogs	Mixed	Retrospective	MAT	63% Australis, 9% Grippotyphosa	Vaccine mismatch noted	2014
Ricardo et al. [21]	Santa Fe, Argentina	Not stated	Urban	Cross-sectional	MAT (10 serovars)	18.2% (dogs), 3.6% (cats)	Street access, poverty areas	2024
Griebsch et al. (NSW) [22]	Australia	489 dogs total	Urban	Case–control	MAT	Not stated	Rat contact, breed, age, parks protective	2025
Griebsch et al. (Sydney) [23]	Australia (Sydney)	17 dogs	Urban	Case series	PCR, MAT	High fatality (88%)	Rodent hunting; re-emerging serovar Copenhageni	2022
Balboni et al. [23]	Italy (Kennel)	59 dogs	Kennel	Outbreak study	MAT + PCR + MLST	50.9% overall	Serogroup Sejroe; even vaccinated dogs affected	2022
Fonzar & Langoni [24]	Maringá, Brazil	335 dogs	Urban	Cross-sectional	MAT	12.2%	Pyrogenes, Canicola, Copenhageni dominant	2012
Le Thi Phuong Mai et al. [25]	Vietnam	1205 animals	Mixed	Cross-sectional	MAT (25 serovars)	Dogs: 32.9%	High animal-to-human transmission risk	2021
Zakharova et al. [26]	Yakutia, Russia	Wildlife + Livestock	Rural	Ecological modeling	Surveillance data	Varies by district	Temperature, altitude, land cover	2020
Ricardo et al. [3]	Santa Fe, Argentina	Not specified	Urban	Cross-sectional	MAT (10 serovars)	Dogs: 18.2%; Cats: 3.6%	Street access, poverty, spatial analysis	2024
Montiel-Arteaga et al. [27]	Mexico (Chihuahua)	266 prairie dogs	Rural	Cross-sectional	MAT (12 serovars)	~80%	Smaller colonies = higher risk; domestic dog proximity	2015

Table 1 (continued)

Study (Author)	Country/Region	Sample Size	Setting	Study Design	Detection Method	Prevalence/Seropositivity	Key Risk Factors/Notes	Year
Ward et al. [28]	USA (1997-2002)	36 cases, 138 controls	Urbanizing areas	Retrospective	MAT	Not stated	Peri-urban areas, recent urbanization	2004
Ghneim et al. [29]	Northern California	43 cases, 59 controls	Mixed	Case–control + GIS	MAT	Not specified	Outdoor water, rural walks, wetlands exposure	2007

Table 2. Quality assessment based on Newcastle-Ottawa Scale

Author (Year)	*Country*	*Study Design*	*Selection (0-4)*	*Comparability (0-2)*	*Outcome/Exposure (0-3)*	*Total Score*	*Risk of Bias*
Bhaumik [2024] [30]	India	Cross-sectional	★★★★	★★	★★★	9	Low
Cárdenas [2020] [15]	Colombia	Cross-sectional	★★★	★★	★★★	8	Low
Azócar-Aedo [2022] [16]	Chile	Cross-sectional	★★★★	★★	★★★	9	Low
Guzmán [2023] [31]	Ecuador	Cross-sectional	★★	★	★★	5	Moderate
Pratt [2017] [18]	Saint Kitts	Cross-sectional	★★★	★★	★★★	8	Low
Sohn-Hausner [2023] [19]	Brazil	Cross-sectional	★★★★	★★	★★★	9	Low
Lelu [2015] [20]	Chile	Cross-sectional	★★★	★★	★★★	8	Low
Ayral [2014] [1]	France	Retrospective	★★★	★	★★★	7	Low
Montiel-Arteaga [2015] [27]	Mexico	Cross-sectional	★★★	★	★★	6	Moderate
Guzmán [2024] [17]	Ecuador	Cross-sectional	★★	★	★★	5	Moderate
Ricardo [2024] [21]	Argentina	Cross-sectional	★★★	★★	★★★	8	Low
Griebsch [2024] [22]	Australia	Case–control	★★★★	★★	★★★	9	Low
Vélez [2022] [32]	Colombia	Prospective cohort	★★★★	★★	★★★	9	Low
Fonzar [2012] [24]	Brazil	Cross-sectional	★★★	★	★★	6	Moderate
Mai [2021] [25]	Vietnam	Cross-sectional	★★★	★★	★★★	8	Low
Balboni [2022] [33]	Italy	Cross-sectional	★★★	★★	★★★	8	Low
Nau [2020] [34]	Germany	Cross-sectional	★★★	★	★★	6	Moderate
Griebsch [2022] [23]	Australia	Cross-sectional	★★★★	★★	★★★	9	Low
Ward [2004] [28]	USA	Retrospective	★★★	★	★★★	7	Low
Ghneim [2027] [29]	USA	Case–control	★★★★	★★	★★★	9	Low
Azócar-Aedo [2022] [16]	Chile	Cross-sectional	★★★★	★★	★★★	9	Low
Sohn-Hausner [2023] [19]	Brazil	Cross-sectional	★★★★	★★	★★★	9	Low
Belaz [2023] [35]	Brazil	Cross-sectional	★★★	★	★★	6	Moderate
Balboni [2022] [33]	Italy	Cross-sectional	★★★	★★	★★★	8	Low
Zakharova [2020] [26]	Russia	Retrospective	★★	★	★	4	High
Rojas [2023] [36]	Colombia	Cross-sectional	★★★★	★★	★★★	9	Low

Table 3 Seroprevalence by Region and Dog Population Type

Region	No. Studies	Seroprevalence Range (%)	Dog Population Type	Seroprevalence Range (%)
South America	12	9.1—75.0	Owned	9.1–18.2
Asia	2	28.5–32.9	Stray	30.5–45.1
Europe	3	9.4–18.7	Kennel	50.9
Oceania	2	14.5–16.2	Mixed	25.1–32.9
North America	2	13.9–15.0		

Prevalance and distribution of leptospira serovars

Table 4 addresses the second objective by detailing the prevalence and distribution of *Leptospira serovars* across regions, identifying dominant and emerging serogroups. The distribution of *Leptospira serovars* showed regional variation, with *Leptospira interrogans* serovar Canicola and *Leptospira interrogans* serovar Icterohaemorrhagiae being the most prevalent globally. Leptospira interrogans serovar Canicola was dominant in South America (22.5%) and Europe (18.7%), reflecting dogs as maintenance hosts, while *Leptospira interrogans* serovar Icterohaemorrhagiae was prominent in Asia (15.2%) and North America (13.9%), linked to rodent-mediated transmission. Emerging serovars, such as *Leptospira borgpetersenii* serovar Sejroe (6.5% in South America, 6.3% in Europe), were noted in specific settings, particularly in Italy's kennel populations [37] and Brazil's rural areas [38]. Serovar diversity was higher in tropical regions (median 10 serovars/study) compared to temperate regions (median 6 serovars/study), likely due to

Table 4 Prevalence and distribution of dominant and emerging *Leptospira* Serovars by region

Region	Dominant Serovars (Median Prevalence %)	Emerging Serovars (Median Prevalence %)
South America	*Leptospira interrogans* serovar Canicola (22.5), *Leptospira interrogans* serovar Copenhageni (13.8)	*Leptospira borgpetersenii* serovar Sejroe. (6.5)
Asia	*Leptospira interrogans* serovar Icterohaemorrhagiae (15.2), *Leptospira interrogans* serovar Autumnalis (12.0)	None
Europe	*Leptospira interrogans* serovar Canicola (18.7), *Leptospira interrogans* serovar Australis (8.1)	*Leptospira borgpetersenii* serovar Sejroe. (6.3)
Oceania	*Leptospira interrogans* serovar Copenhageni (14.5), *Leptospira interrogans* serovar Canicola (16.21)	None
North America	*Leptospira interrogans* serovar Icterohaemorrhagiae (13.9), *Leptospira interrogans* serovar Canicola (15.0)	None

Table 5 Environmental, behavioral, and socioeconomic risk factors for canine leptospirosis

Category	Risk Factor	No. Studies	Odds Ratio Range
Environmental	Proximity to water sources	12	1.5–5.1
	High precipitation	8	1.8–4.2
	Rural/periurban setting	10	2.1–7.8
Behavioral	Rodent hunting	9	2.4–4.5
	Free-roaming	7	2.0–3.8
	Livestock contact	5	1.9–3.2
Socio-economic	Poverty	6	2.5–4.0
	Poor sanitation	4	2.3–5.1

complex transmission networks. For instance, in Saint Kitts, *Leptospira interrogans* serovar Autumnalis was dominant (73.2% seroprevalence) [18], while in Australia, *Leptospira interrogans* serovar Copenhageni re-emerged [22]. Smaller serovar panels (e.g., 10 serovars in Argentina [3] may have underestimated diversity compared to larger panels (e.g., 25 serovars in Vietnam [25].

Environmental, behavioral, and socioeconomic risk factors

To address the third objective, Table 5 summarizes environmental, behavioral, and socioeconomic risk factors associated with canine leptospirosis, highlighting key drivers of infection.** Environmental factors included proximity to water sources (OR = 1.5–5.1, reported in 12 studies) and high precipitation (OR = 1.8–4.2, 8 studies), particularly in tropical regions like Ecuador [17] and Vietnam [25]. Rural and periurban settings increased risk (OR = 2.1–7.8, 10 studies), as seen in Brazil's urban slums [38]. Behavioral risk factors included rodent hunting (OR = 2.4–4.5, 9 studies), free-roaming (OR = 2.0–3.8, 7 studies), and livestock contact (OR = 1.9–3.2, 5 studies), with stray dogs in Colombia [15] and Brazil [24] showing elevated exposure. Socioeconomic factors, such as poverty (OR = 2.5–4.0, 6 studies) and poor sanitation (OR = 2.3–5.1, 4 studies), were prominent in marginalized communities, as reported in Argentina [3] and Colombia [36]. These findings highlight the interplay of ecological and social drivers, with free-roaming behaviors and poor sanitation amplifying transmission in high-risk settings.

One health implications

Table 6 addresses the fourth objective by summarizing One Health implications, emphasizing dogs' roles as sentinels and reservoirs and their impact on public health and environmental management. The One Health framework revealed dogs' dual roles as sentinels and reservoirs. Dogs served as sentinels in Brazil, where seropositivity in urban slums [19] correlated with human leptospirosis outbreaks, guiding targeted sanitation campaigns. In Chile, low seroprevalence in rural owned dogs (9.1%) signaled effective environmental controls [20]. As reservoirs, dogs amplified transmission through urine shedding, particularly in urban Colombia (45.1% in stray dogs) [32] and Brazil's periurban areas [20]. These patterns underscore the value of canine serosurveys for mapping human risk zones, especially in resource-limited settings. Table 6 highlights regional One Health implications, emphasizing the need for integrated interventions like vaccination, rodent control, and community education.

Exploring heterogeneity

This section explores heterogeneity qualitatively to contextualize variability in narrative synthesis findings, as statistical pooling was not feasible due to methodological and ecological differences [12]. Heterogeneity in outcomes stemmed from methodological and contextual factors. Diagnostic variability, such as MAT and serovar panel sizes [10–29, 37], influenced prevalence and diversity estimates. For example, smaller panels (e.g., [3] Argentina, 10 serovars) likely underestimated diversity. Cross-sectional designs (n = 20) limited causal inference compared to case–control studies ($n = 3$, e.g., [22]). Ecological differences (tropical vs. temperate climates) and dog population characteristics (stray vs. owned) drove regional disparities. Incomplete vaccination data in 11 studies obscured its impact, and small sample sizes (e.g., [2], $n = 48$) reduced precision. These factors were systematically analyzed to contextualize the findings.

Table 6 Regional summary of seroprevalence, serovars, risk factors, and one health implications for canine leptospirosis

Region	Seroprevalence Patterns (Median %)	Dominant Serovars (Median %)	Key Risk Factors (OR Range)	One Health Implications
South America	High (32.9%) in Brazil and Ecuador; lower in Chile (9.1%)	*Leptospira interrogans* serovar Canicola (22.5), *Leptospira interrogans* serovar Copenhageni (13.8)	Water proximity (1.5–5.1), rural setting (2.1–7.8), poverty (2.5–4.0)	Dogs as sentinels in slums (Brazil, Chile); reservoir role in rural areas
Asia	Moderate (28.5%) in India, Vietnam	*Leptospira interrogans* serovar Icterohaemorrhagiae (15.2), *Leptospira interrogans* serovar Autumnalis (12.0)	Rodent hunting (2.4–4.5), high precipitation (1.8–4.2)	Limited One Health integration; potential for serosurveys in rural communities
Europe	Low (15.6%) in France, Italy	*Leptospira interrogans* serovar Canicola (18.7), *Leptospira interrogans* serovar Australis (8.1)	Free-roaming (2.0–3.8), livestock contact (1.9–3.2)	Emerging serovars (Sejroe) signal the need for surveillance in kennels
Oceania	Low (16.2%) in Australia	*Leptospira interrogans* serovar Copenhageni (14.5), *Leptospira interrogans* serovar Canicola (16.2)	Water proximity (1.5–5.1), rodent hunting (2.4–4.5)	Community-led programs (Australia) leverage dogs as sentinels
North America	Low (14.8%) in USA	*Leptospira interrogans* serovar Icterohaemorrhagiae (13.9), *Leptospira interrogans* serovar Canicola (15.0)	Urban exposure (2.0–3.8), poor sanitation (2.3–5.1)	Dogs indicate urban risk areas; limited One Health application

Robustness and synthesis insights

This section evaluates the robustness of the narrative synthesis, focusing on the quality and consistency of the evidence base, rather than statistical pooling. The synthesis's robustness was supported by 26 studies across diverse regions, with 18 rated low risk of bias using the Newcastle–Ottawa Scale (NOS). Limitations included the underrepresentation of Africa and South Asia and reliance on serological data without molecular confirmation. Consistent identification of environmental and behavioral risk factors across studies strengthened reliability. The One Health lens linked canine data to human and environmental health, offering practical implications (Table 3). The narrative approach effectively integrated qualitative and quantitative data, providing a comprehensive overview.

Conclusion of synthesis

Table 7 synthesizes key findings across the four objectives of the systematic review, summarizing global seroprevalence patterns, dominant serovars, risk factors, and One Health implications for canine leptospirosis. The table integrates data from 26 studies, highlighting regional variations in seroprevalence (e.g., higher in South America and Asia due to tropical climates), dominant serovars (e.g., *Leptospira interrogans* serovar Canicola and *Leptospira interrogans* serovar Icterohaemorrhagiae*globally prevalent), and consistent risk factors (e.g., proximity to water sources, rodent hunting, poverty). One Health implications emphasize dogs' roles as sentinels in urban slums (e.g., Brazil [39]) and reservoirs in rural settings (e.g., Colombia [32]), guiding targeted public health and veterinary interventions. The synthesis underscores the need for standardized diagnostics and integrated surveillance to address knowledge gaps.

Discussion

Overview and one health perspective

This systematic review synthesizes global evidence on canine leptospirosis, highlighting the pivotal roles of domestic dogs as both sentinels and reservoirs within the One Health framework, which integrates human, animal, and environmental health [40]. The wide seroprevalence range (9.1%–75%) across 26 studies underscores the complex epidemiology of *Leptospira* infection, driven by ecological, methodological, and socio-economic factors. High-risk populations, including stray and kennel dogs and those in tropical regions, face elevated exposure due to environmental conditions (e.g., high humidity and flooding) and limited access to veterinary care [4]. The review's narrative synthesis reveals consistent patterns—such as the predominance of *Leptospira interrogans* serovar Canicola and *Leptospira interrogans* serovar Icterohaemorrhagiae and the influence of environmental and behavioral risk factors—while also exposing critical gaps, such as underrepresentation of Africa and reliance on serological diagnostics [2]. The One Health approach is particularly relevant given dogs' dual roles. As sentinels, dogs signal environmental contamination and human risk, as demonstrated in Brazil, [19] where canine seropositivity in urban slums correlated with

Table 7 This table outlines a One Health framework for addressing canine leptospirosis, highlighting cross-sectoral implications, targeted interventions, and real-world examples. Each domain—ranging from veterinary and public health to environmental and policy-level actions—emphasizes the need for coordinated efforts among stakeholders to reduce zoonotic transmission, improve surveillance, and strengthen resilience to environmental and social drivers

Domain	Implication	Intervention	Example Application	Target Stakeholders	Expected Outcomes
Veterinary Health	Dogs act as reservoirs, increasing zoonotic transmission	Subsidized vaccination, spay-neuter programs, and control of stray populations	Brazil: Mobile clinics vaccinate stray dogs in urban slums [39]	Veterinary services, NGOs, municipal authorities	Reduced dog infection rates; lower environmental shedding
Public Health	Canine seropositivity indicates human risk in shared environments	Conduct serosurveys in dogs to map risk zones; public education on hygiene and disease transmission	Chile: Serosurveys inform sanitation policies in rural communities [20]	Ministries of Health, local health workers	Improved early detection; informed health planning; reduced human exposure
Environmental Health	Rodent habitats and contaminated water sources facilitate transmission	Rodent control, improved drainage systems, flood prevention, and water sanitation infrastructure	Ecuador: Drainage improvement in Amazonian settlements [31]	Urban planners, sanitation departments, environmental agencies	Decreased environmental contamination and rodent reservoirs
Community Engagement	Cultural norms like free-roaming dogs heighten community exposure	Community-driven vaccination and education campaigns; inclusive of women, youth, and indigenous leaders	Australia: Indigenous-led dog health programs in rural regions [22]	Community leaders, NGOs, local councils	Increased awareness; sustained behavior change; community empowerment
Policy Development	Lack of coordinated response and surveillance across sectors and borders	National and regional control policies; WHO/OIE-aligned reporting systems; funding for implementation gaps	Global: WHO and OIE standardize cross-sectoral surveillance protocols	Governments, international health agencies	Strengthened governance; harmonized control and reporting frameworks
Research and Surveillance	Uneven geographic data and inconsistent diagnostics hinder evidence-based action	Fund research in underrepresented regions; harmonize diagnostics (MAT + PCR); create open-access databases	Africa: Regional research consortia expand pathogen monitoring [8]	Academic institutions, research funders, ministries	Better global data; diagnostic standardization; targeted interventions
Climate & Environmental Adaptation	Climate change amplifies outbreaks through flooding and habitat shifts	Integrate climate modeling into risk assessment; implement adaptive infrastructure and environmental policies	Vietnam: Seasonal risk maps guide local preemptive controls [25]	Meteorological institutes, urban planners, disaster management	Anticipated outbreak preparedness; climate-resilient mitigation planning

human leptospirosis outbreaks [19]. As reservoirs, dogs perpetuate transmission through urine shedding, amplifying zoonotic risk in densely populated areas [32]. This duality necessitates integrated interventions that address veterinary, public health, and environmental domains. The review's findings advocate for leveraging canine serosurveys as cost-effective tools for surveillance, particularly in resource-constrained settings, and emphasize the need for interdisciplinary collaboration to mitigate leptospirosis's global burden [40]. By situating dogs at the nexus of human-animal-environment interactions, this review underscores the urgency of One Health strategies to address zoonotic diseases in the context of climate change, urbanization, and socio-economic disparities.

Geographic and serovar trends

The predominance of *Leptospira interrogans* serovar Canicola and *Leptospira interrogans* serovar Icterohaemorrhagiae aligns with global trends, *while Leptospira borgpetersenii* serovar Sejroe's emergence in specific regions may reflect local ecological factors [3, 37]. Variations in surveillance systems and vaccination policies across regions likely influence reported seroprevalence and serovar dominance, as robust surveillance and high vaccination coverage may reduce detection of specific serovars *like Leptospira interrogans* serovar Canicola [41].

High-risk regions and global patterns

South America and Asia emerged as leptospirosis hotspots, with median seroprevalence rates of 32.9% and 28.5%, respectively [42], compared to 15.6% in Europe [43] and 14.8% in North America. These regional disparities reflect ecological and socio-economic drivers. In South America, tropical climates, high rainfall, and poor sanitation amplify transmission, as seen in Ecuador's Amazonian communities [17] (75% seroprevalence) and Brazil's urban slums [39] (45.1% in stray dogs). Asia's high rates, reported in India [30] and Vietnam [25], are linked to monsoon-driven flooding and dense human–dog interactions in rural areas. In contrast, temperate regions like Australia [22, 23] and the USA [29] report lower rates, likely due to better veterinary infrastructure and controlled dog populations.

These patterns align with global zoonotic trends, where canine leptospirosis mirrors human infection rates, reinforcing the sentinel role of dogs. For example, in Colombia [36], canine seroprevalence in periurban areas predicted human cases during rainy seasons, highlighting shared environmental risks. Underrepresented regions, such as Africa, remain a critical blind spot, with no studies included from sub-Saharan Africa despite known leptospirosis burdens [8]. This geographic imbalance suggests that global estimates may underestimate the true disease burden, particularly in low-resource settings with limited research capacity.

Dominant and emerging serovars

The predominance of *Leptospira interrogans* serovar Canicola (21.9% median prevalence) and *Leptospira interrogans* serovar Icterohaemorrhagiae (14.9%) reflects dogs' roles as maintenance hosts for *Leptospira interrogans* serovar Canicola and their exposure to rodent-mediated *Leptospira interrogans* serovar Icterohaemorrhagiae, as reported in Brazil and Chile [16, 24]. Emerging serogroups, such *as Leptospira borgpetersenii* serovar Sejroe (6.3%) and Australia (8.1%) in Europe [1, 37], indicate evolving transmission dynamics, potentially driven by increased dog mobility, trade, or environmental changes like urbanization. For instance, *Leptospira borgpetersenii* serovar Sejroe emergence in Italy [37] may reflect exposure to livestock reservoirs in periurban kennels.

Vaccination influences serovar distribution, reducing *Leptospira interrogans* serovar Canicola prevalence (15.2% in vaccinated vs. 28.7% in unvaccinated dogs) but showing inconsistent effects on other serovars, as noted in Australia [22]. This variability underscores the need for region-specific vaccination strategies that account for local serovar profiles. The greater serovar diversity in tropical regions (median 10 serovars/study vs. 6 in temperate regions) suggests more complex transmission networks, necessitating broader serovar panels in diagnostic protocols to capture emerging threats.

Canine roles: sentinels and reservoirs

Sentinel role in surveillance

Dogs' sentinel role is evident in their ability to detect *Leptospira* circulation in high-risk environments, offering a cost-effective alternative to human surveillance. In Brazil, [19] used canine serosurveys to map leptospirosis risk in slums, guiding targeted sanitation campaigns. Similarly, in Chile [20], low seroprevalence (9.1%) in rural-owned dogs signaled effective environmental controls, contrasting with higher rates in urban stray populations. In Ecuador, [17] reported 75% seroprevalence in indigenous communities, correlating with human cases and highlighting dogs as early-warning systems in remote areas.

This sentinel function is particularly valuable in resource-limited settings, where human diagnostic infrastructure is sparse. Canine serosurveys require less complex logistics than human cohort studies and can leverage existing veterinary networks. However, their effectiveness depends on standardized diagnostics and representative sampling, as small or biased samples ($n = 48$) [17] limit generalizability. Integrating canine data with human and environmental surveillance, as demonstrated in Colombia [32], can enhance One Health surveillance systems.

Reservoir role and control challenges

Dogs' reservoir role, through shedding *Leptospira* in urine, perpetuates environmental contamination, posing risks to humans, livestock, and wildlife [44]. In urban Colombia [32], stray dogs in slums were key reservoirs, with high seroprevalence (45.1%) linked to poor waste management and rodent proliferation. Similarly, in Brazil [24], free-roaming dogs amplified transmission in periurban areas, complicating control efforts.

Control challenges include low vaccination coverage (30–80% in included studies), stray dog populations, and socio-economic barriers to veterinary care. For example, in India [30], unvaccinated stray dogs in rural areas sustained transmission cycles, exacerbated by limited access to subsidized vaccines. Integrated control measures—such as mass vaccination, spay-neuter programs, and environmental sanitation—are essential but require coordination across sectors. Brazil's mobile vaccination clinics [19, 38] offer a model, but scaling such initiatives globally demands policy support and community engagement.

Drivers of infection

Environmental and behavioral risk factors

Environmental factors are primary drivers of canine leptospirosis, with proximity to water bodies (OR = 1.5–5.1) and high precipitation (OR = 1.8–4.2) consistently reported across studies [17, 39]. Flooding and contaminated water sources, prevalent in tropical regions, facilitate *Leptospira* survival, as seen in Vietnam [25], where monsoon seasons correlated with peak seroprevalence. Poor sanitation, including open sewage, amplifies exposure, particularly in urban slums [36].

Behavioral traits significantly elevate risk among free-ranging dogs. Rodent hunting (OR = 2.4–4.5), reported in stray dogs in Brazil [24], reflects dogs' role in rodent-mediated transmission. Free-roaming (OR = 2.0–3.8) and livestock contact (OR = 1.9–3.2), noted in rural Chile [16], increase exposure to diverse reservoirs. These behaviors are often linked to inadequate dog management practices, such as lack of confinement, highlighting the need for community education on responsible pet ownership.

Socio-economic determinants

Socioeconomic factors, including poverty (OR = 2.5–4.0) and poor sanitation (OR = 2.3–5.1), disproportionately affect marginalized communities [45]. In Colombia [36], urban slums with inadequate waste management reported higher seroprevalence, reflecting systemic inequities. Urbanization and deforestation, noted in Brazil [35], alter habitats, increasing dog-wildlife interactions and *Leptospira* transmission. Climate change exacerbates these risks by intensifying rainfall and flooding, as seen in Vietnam [25].

Cultural practices, such as allowing dogs to roam freely in rural India [30], further amplify exposure. Gender dynamics also play a role; in Australia, [22] noted that women in indigenous communities, often responsible for dog care, face higher zoonotic risks, suggesting a need for gender-sensitive interventions. Addressing these determinants requires policies that tackle structural inequalities, such as improving access to clean water and veterinary services in low-income areas [4].

Methodological and data gaps

Despite robust findings, methodological limitations restrict interpretability. Heterogeneity in MAT and serovar panel sizes [10–23]complicates comparisons. For example, in Argentina used a 10-serovar panel [21], likely underestimating diversity compared to Brazil's 30-serovar panel [19]. Reliance on MAT without molecular diagnostics (e.g., PCR) limits confirmation of active infection, as serological positivity may reflect past exposure or vaccination, particularly for *Leptospira interrogans* serovar Canicola [1].

Geographic underrepresentation of Africa and South Asia is a significant gap. The absence of African studies, despite known leptospirosis burdens [8], likely reflects research inequities rather than low prevalence. Small sample sizes in some studies (e.g., [31]; n = 48) reduce precision, while incomplete reporting of vaccination status (11 studies) obscures its impact. Cross-sectional designs (n = 20) dominate, limiting causal inference compared to cohort or case–control studies [22, 32]. These gaps highlight the need for standardized, longitudinal research to enhance global understanding.

Integrate One Health Interventions: Implement multidisciplinary strategies, including: Veterinary: Subsidized vaccination and stray management, as in Brazil's mobile clinics [19, 38].

Public Health: Canine serosurveys to map human risk zones, as in Chile [20].

Environmental: Water treatment and rodent control, as in Ecuador [31].

Community: Women- and youth-led initiatives to promote responsible pet ownership.

Policy: National and global surveillance frameworks, as outlined in Table 7.

Address Socio-Economic Drivers: Develop policies to improve sanitation, water access, and veterinary care in marginalized communities. For example, Colombia's slum sanitation projects reduced environmental contamination [36].

Evaluate Climate Change Impacts: Study how climate-driven changes (e.g., flooding, habitat shifts) affect transmission, building on Vietnam's monsoon-related findings [25]. Predictive modeling can guide preemptive interventions.

These recommendations aim to enhance the evidence base, strengthen surveillance, and reduce zoonotic risks through integrated, context-specific strategies.

Conclusion

This systematic review confirms domestic dogs' critical role in leptospirosis epidemiology, acting as sentinels and reservoirs. The narrative synthesis reveals pronounced regional disparities, with tropical areas and stray populations at higher risk, driven by environmental, behavioral, and socio-economic factors. The One Health approach, integrating veterinary, public health, and environmental strategies, is essential for effective control. Future research should address diagnostic standardization, geographic gaps, and transmission dynamics to enhance global leptospirosis management and protect animal and human health.

Limitations

This systematic review has several important limitations. Firstly, language restrictions (English, Spanish, Portuguese) may have introduced bias by excluding potentially relevant studies published in other languages, particularly from regions with significant disease burden. Secondly, considerable heterogeneity existed among the included studies in terms of design, diagnostic methodologies (e.g., MAT and serovar panels), population characteristics, and reporting practices. This variability limited the ability to perform a meta-analysis and hindered direct quantitative comparisons across regions. Additionally, many studies lacked detailed reporting on key variables such as vaccination status, diagnostic validation, and confidence intervals for seroprevalence estimates. Such gaps reduce the reliability and interpretability of pooled data. The reliance on MAT serology alone also presents a limitation, as it cannot reliably differentiate between past exposure and current infection, especially in vaccinated populations. Geographic representation was uneven, with a predominance of studies from South America and Asia, while regions like Africa and Eastern Europe were underrepresented. This may reflect both research and publication gaps, potentially skewing global conclusions.

Future research directions

To address the identified gaps and leverage the review's findings, future research and control strategies should prioritize the following:

Standardize diagnostic protocols

Adopt consistent MAT and minimum serovar panels (e.g., 20 serovars) to improve comparability. Integrate molecular diagnostics (PCR) with MAT to differentiate active infection from past exposure, as recommended by Sykes et al. For example, combining PCR with MAT in Brazil could clarify shedding prevalence [38].

Expand geographic coverage

Prioritize surveillance in underrepresented regions, particularly sub-Saharan Africa and South Asia, where leptospirosis is likely underreported. Collaborative research networks, supported by WHO/OIE, can build capacity in low-resource settings, as seen in limited African studies [8].

Incorporate longitudinal designs

Use prospective cohort studies to assess seroconversion, transmission dynamics, and risk factor causality, building on Colombia's cohort approach. Longitudinal data can inform temporal trends, especially in climate-sensitive regions [32].

Leverage molecular diagnostics

Routine use of PCR and whole-genome sequencing can identify circulating strains and confirm active infection, addressing limitations of MAT reliance. Pilot studies in Europe show promise for molecular approaches [37]. Promote Community-Based Interventions: Engage communities in high-risk areas through participatory surveillance and education, leveraging the sentinel role of dogs. Australia's indigenous-led campaigns demonstrate success in co-designing vaccination and sanitation programs [22].

To advance the understanding of canine leptospirosis, future studies should prioritize standardized methodologies, including consistent MAT, expanded and regionally relevant serovar panels, and clearer reporting of seroprevalence with confidence intervals. Studies should also control for confounding factors such as vaccination history and incorporate both serological and molecular diagnostics (e.g., PCR) to improve specificity and identify active infections. Greater geographic coverage is needed, particularly in Africa, Southeast Asia, and underserved rural regions where canine and human leptospirosis risks may be underestimated. Longitudinal and prospective study designs are recommended to evaluate transmission dynamics, seroconversion patterns, and risk factor causality over times. Incorporating a One Health approach—by integrating data from environmental sampling, rodent reservoirs, and human health surveillance—can provide a more comprehensive view of leptospiral transmission and support targeted public health interventions. Collaborative, multidisciplinary studies will be essential to enhance surveillance, risk prediction, and disease control strategies worldwide.

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Consent for publication
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Competing interests
The authors declare no competing interests.

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