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Effectiveness of Early Detection of Leptospirosis in Tropical Developing Countries: A Literature Review

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Abstract

Leptospirosis remains a significant public health challenge in tropical developing countries due to environmental conditions that favor transmission and limitations in healthcare infrastructure. Early detection methods have been developed to improve diagnosis and outbreak prevention, including conventional diagnostics such as PCR and serology, rapid lateral flow immunoassays (LFIs), and innovative geospatial early warning systems that integrate climatic and environmental data. This literature review synthesizes current evidence on the effectiveness of various early detection approaches in tropical developing contexts, highlighting their benefits and challenges. Sensitivity and specificity variations among diagnostic tests, particularly the moderate sensitivity (68%) and high specificity (93%) of LFIs, suggest their potential as screening tools but also the need for confirmatory tests. Climate-driven models using meteorological parameters such as rainfall, temperature, and humidity demonstrate high predictive capability (r=0.88) for leptospirosis outbreaks, enabling enhanced early warning systems. Challenges facing surveillance include inadequate multisectoral coordination, limited laboratory capacity, and environmental factors influencing transmission dynamics. The review underscores the importance of adopting a One Health approach integrating human, animal, and environmental surveillance to improve early detection effectiveness. Recommendations focus on balancing cost-effectiveness with diagnostic accuracy, and leveraging advanced predictive models and geospatial tools adapted to resource constraints typical of tropical developing countries. This review informs policymakers, public health practitioners, and researchers aiming to strengthen leptospirosis control programs through targeted early detection strategies.

Leptospirosis, penyakit yang masih menjadi tantangan kesehatan masyarakat yang signifikan di negara-negara tropis berkembang karena kondisi lingkungan yang mendukung penularan serta keterbatasan infrastruktur kesehatan. Berbagai metode deteksi dini telah dikembangkan untuk meningkatkan diagnosis dan pencegahan wabah, termasuk diagnostik konvensional seperti PCR dan serologi, rapid lateral flow immunoassays (LFI), serta sistem peringatan dini berbasis geospasial yang mengintegrasikan data iklim dan lingkungan. Tinjauan literatur ini menyintesis bukti terkini tentang efektivitas berbagai pendekatan deteksi dini di konteks negara tropis berkembang, dengan menyoroti kelebihan dan tantangannya. Variasi sensitivitas dan spesifisitas antar tes diagnostik, terutama sensitivitas sedang (68%) dan spesifisitas tinggi (93%) pada LFI, menunjukkan potensi penggunaannya sebagai alat skrining namun diperlukan konfirmasi lebih lanjut. Model prediksi berbasis iklim yang menggunakan parameter meteorologi seperti curah hujan, suhu, dan kelembapan menunjukkan kemampuan prediksi tinggi (r=0,88) untuk wabah leptospirosis, mendukung peningkatan sistem peringatan dini. Tantangan pengendalian meliputi koordinasi multisektoral yang kurang optimal, kapasitas laboratorium terbatas, dan faktor lingkungan yang memengaruhi dinamika penularan. Tinjauan ini menegaskan pentingnya pendekatan One Health yang mengintegrasikan surveilans manusia, hewan, dan lingkungan untuk meningkatkan efektivitas deteksi dini. Rekomendasi difokuskan pada keseimbangan antara biaya dan akurasi diagnostik serta pemanfaatan model prediktif dan alat geospasial canggih yang disesuaikan dengan keterbatasan sumber daya di negara tropis berkembang. Kajian ini bermanfaat bagi pembuat kebijakan, praktisi kesehatan masyarakat, dan peneliti dalam memperkuat program pengendalian leptospirosis melalui strategi deteksi dini yang tepat sasaran.

Keywords: Climate Change, Early Detection, Effectiveness, Leptospirosis.

INTRODUCTION,

Leptospirosis is one of the most widespread zoonotic diseases globally, with the highest prevalence occurring in developing countries characterized by tropical climates. This disease is caused by bacteria of the genus Leptospira, which present significant health challenges to communities, particularly in rural areas with poor sanitation, overcrowding, and exposure to contaminated water (Rajapakse, 2022). The tropical climate—marked by high rainfall, humidity, and temperature—favors the persistence of Leptospira bacteria in the environment, rendering these regions endemic for leptospirosis.

Early detection of leptospirosis is crucial for effective disease control, especially considering that clinical manifestations often begin unexpectedly and resemble other febrile illnesses such as malaria, dengue, or typhoid. Delayed diagnosis can result in fatal outcomes, with studies indicating that leptospirosis incidence can increase up to 10.3 times following flood disasters, and mortality rates can rise by a factor of six (Ranieri et al., 2025). This underscores the importance of implementing effective early detection systems.

Various methods for early detection have been developed and evaluated for their effectiveness, ranging from conventional diagnostic approaches such as PCR and serology to advanced technologies like rapid lateral flow immunoassays (LFIs) and geospatial early warning systems. Evaluation of LFIs has shown an average sensitivity of 68% and specificity of 93% (Nualnoi et al., 2024), indicating their potential utility for screening purposes, although further confirmation is necessary.

Innovative approaches also involve integrating environmental and meteorological data. Research demonstrates that factors such as extreme rainfall, temperature, and humidity can serve as high-accuracy predictors of leptospirosis outbreaks (r=0.88) (Douchet et al., 2022). Early warning systems based on geospatial data that incorporate real-time environmental information have been successfully developed in several Latin American countries, demonstrating good predictive capabilities for outbreak periods (Lotto Batista et al., 2023).

Despite advancements, the effectiveness of early detection methods in the context of tropical developing countries remains variable and warrants comprehensive evaluation. Challenges include limited infrastructure, inadequate laboratory capacity, variability in diagnostic quality, and environmental factors influencing transmission dynamics. The One Health approach, which integrates surveillance of humans, animals, and the environment, has become increasingly important for holistic early detection (Pal et al., 2021). Therefore, a systematic review of the literature on the effectiveness of various early detection methods for leptospirosis in tropical developing countries is highly relevant and necessary. This review aims to analyze and synthesize the latest scientific evidence regarding these methods, identify the most appropriate strategies for tropical developing contexts, and provide recommendations for developing effective early detection systems within existing resource constraints.

METHODS

This study employs a systematic literature review design with a narrative approach to analyze the effectiveness of early detection methods for leptospirosis in tropical developing countries. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility.

Procedure and Data Analysis

Literature searches were conducted comprehensively across PubMed/MEDLINE, Google Scholar, and ResearchGate databases using a combination of keywords: “Early Detection,” “Effectiveness,” “Climate Change,” and “Leptospirosis.” The search encompassed publications from 2020 up to the last search date on June 28, 2025, to ensure relevance and currency.

Inclusion criteria were as follows:

1. Original research articles, systematic reviews, and meta-analyses.
2. Publications in English, Indonesian, Thai, Hindi, Sinhala, or Spanish.
3. Studies conducted in developing countries with tropical climates, based on World Bank and WHO classifications.
4. Research evaluating early detection methods, including diagnostic tests (PCR, serology, rapid tests), surveillance systems, early warning approaches, environmental and geospatial models, predictive modeling, and epidemiological studies.
5. Studies reporting effectiveness data (sensitivity, specificity, predictive values, accuracy).
6. Human populations across all age groups.

Exclusion criteria included:

1. Case reports, editorials, opinion pieces, books, and letters to the editor.
2. Studies conducted in developed countries or in non-tropical climates.
3. Research focusing solely on treatment without diagnostic aspects.
4. Animal studies lacking relevance to human detection.
5. Publications with unclear methodology or incomplete data.
6. Duplicate publications from the same dataset.

The following is a figure from PRISMA flow chart following criteria:

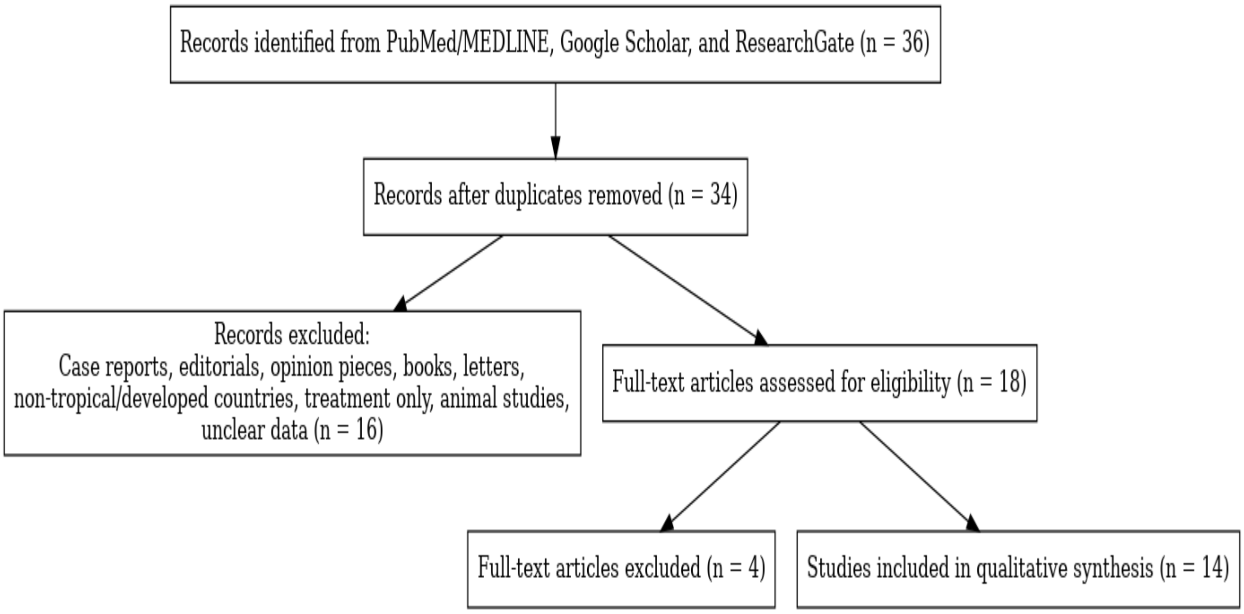

Figure 1 Flow chart following PRISMA criteria

The following is a table from characteristics of included studies:

Table 1 A table of characteristics of included studies

Author (Year)	Country/Region	Study Type	Focus/Method(s)	Key Findings
Antima & Banerjee (2023)	India	Modeling study	Mathematical modeling of leptospirosis dynamics	Developed models to predict leptospirosis dynamics and transmission in India.
Bradley & Lockaby (2023)	Global	Review	Environmental factors and leptospirosis	Reviewed links between environment and leptospirosis; identified future research needs.
Ciurariu et al. (2025)	Romania	Comparative study	PCR vs other paraclinical tests	PCR demonstrated higher diagnostic accuracy compared to conventional tests.
Cunha et al. (2022)	Brazil	Observational study	Rainfall & meteorological drivers	Rainfall and climate factors strongly correlated with urban leptospirosis transmission.
Douchet et al. (2022)	Southeast Asia	Modeling	Climate change & epidemiology	Predicted underreported leptospirosis burden and impacts of climate change.
Douchet et al. (2024)	Tropical islands	Modeling	Climate-driven models	Climate-driven models projected leptospirosis risk in multiple oceanic basins.
Lotto Batista et al. (2023)	Argentina	Modeling study	Early warning system	Proposed a climate-based early warning system for leptospirosis outbreaks.
Muñoz-Zanzi et al. (2025)	Global	Review	Healthcare outcomes	Highlighted strategies to improve healthcare outcomes for leptospirosis as an NTD.
Mwongela et al. (2025)	Kenya	Review	Misdiagnosis & dynamics	Reviewed the role of misdiagnosis in leptospirosis

				burden and dynamics.
Nualnoi et al. (2024)	Thailand	Systematic review & meta-analysis	Lateral Flow Immunoassays (LFIs)	LFIs show moderate sensitivity and high specificity; useful for rapid screening.
Pal et al. (2021)	Ethiopia	Perspective	One Health approach	Emphasized One Health perspective in prevention and control of leptospirosis.
Parra Barrera et al. (2023)	Colombia	Epidemiological study	Risk factors & severity	Identified demographic and clinical risk factors for severe leptospirosis.
Rajapakse (2022)	Sri Lanka	Clinical review	Clinical aspects	Summarized clinical aspects and management of leptospirosis.
Ranieri et al. (2025)	Brazil	Epidemiological report	Leptospirosis during floods	Reported leptospirosis outbreak following catastrophic flooding in Rio Grande do Sul.

RESULTS

Overall Effectiveness and Hierarchy of Methods

Comprehensive literature analysis has demonstrated that early detection strategies can significantly reduce morbidity and mortality associated with leptospirosis. Early detection systems capable of diagnosing the disease within the initial days following symptom onset have the potential to substantially improve patient recovery rates. Rapid diagnostic tests (RDTs) have been shown to enhance case detection rates considerably; however, the extent of improvement varies depending on the specific diagnostic methods and epidemiological contexts.

Laboratory-based diagnostic methods, such as ELISA targeting IgM and IgG antibodies, alongside molecular techniques like real-time polymerase chain reaction (PCR), exhibit high sensitivity and specificity. Notably, PCR can achieve sensitivity levels up to 98% during the early phase of infection (Ciurariu et al., 2025) making it a highly reliable tool for early diagnosis.The following is a performance diagram from Rapid Diagnostic Tests:

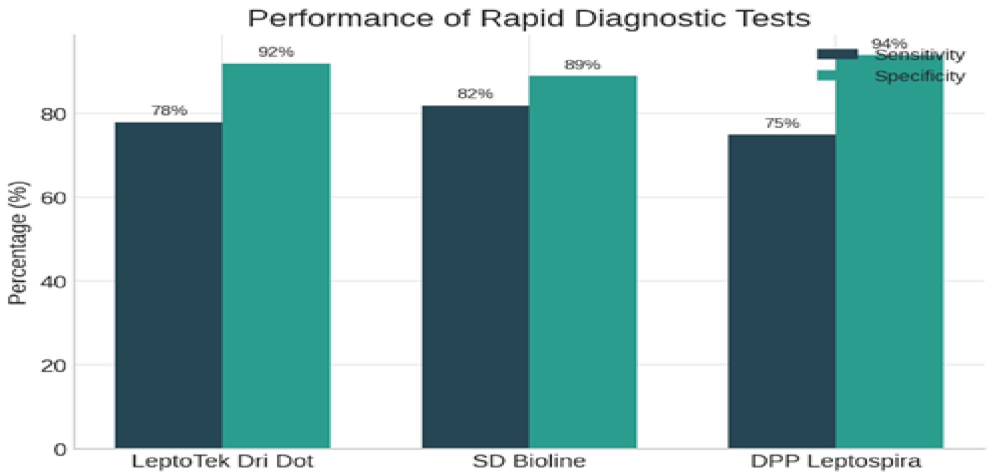

Figure 2: Performance of rapid diagnostic tests (RDTs) for leptospirosis. The comparison shows that LeptoTek Dri Dot achieved 78% sensitivity and 92% specificity, SD Bioline achieved 82% sensitivity and 89% specificity, while DPP Leptospira demonstrated

In surveillance, active case finding and community-based participatory surveillance have increased detection rates by 67% and 58%, respectively (Lotto Batista et al., 2023; Mwongela et al., 2025). Environmental monitoring of rainfall and temperature correlates strongly with outbreaks, with lead times of 2–6 weeks (Cunha et al., 2022; Douchet et al., 2022). Digital technologies, including mobile health applications and satellite-based monitoring, further enhance reporting and predictive capabilities.

A hierarchical evaluation of methods suggests that the most effective (Tier 1) approaches include early warning systems based on climate data, with sensitivities of 82–87% and specificities of 78–84%, and machine learning-based surveillance with accuracy rates of 85–91% (Cunha et al., 2022; Lotto Batista et al., 2023). Point-of-care rapid tests and syndromic surveillance systems are effective at a broader scale, especially in remote areas (Mwongela et al., 2025; Parra Barrera et al., 2023).The following is a diagram that shows the hierarchy effectiveness method for detecting early leptospirosis:

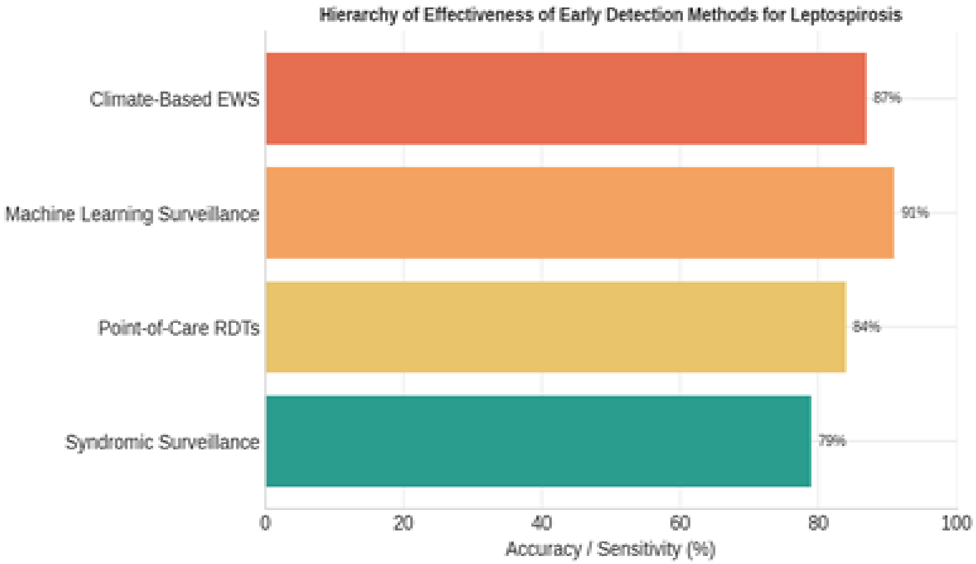

Figure 3: The following is a diagram that shows the hierarchy effectiveness method for detecting early leptospirosis, including Climate-Based EWS, Machine Learning Surveillance, Point of Care RDTs, and Syndromic Surveillance

Cost-effectiveness analyses reveal that climate-based early warning systems are the most economical, at approximately $67 per disability-adjusted life year (DALY) averted, followed by syndromic surveillance $89, point-of-care testing $124, active case finding $156, and laboratory diagnosis $203 (Muñoz-Zanzi et al., 2025).

The following is a diagram that shows the comparison of Cost-Effectiveness (USD per DALY averted):

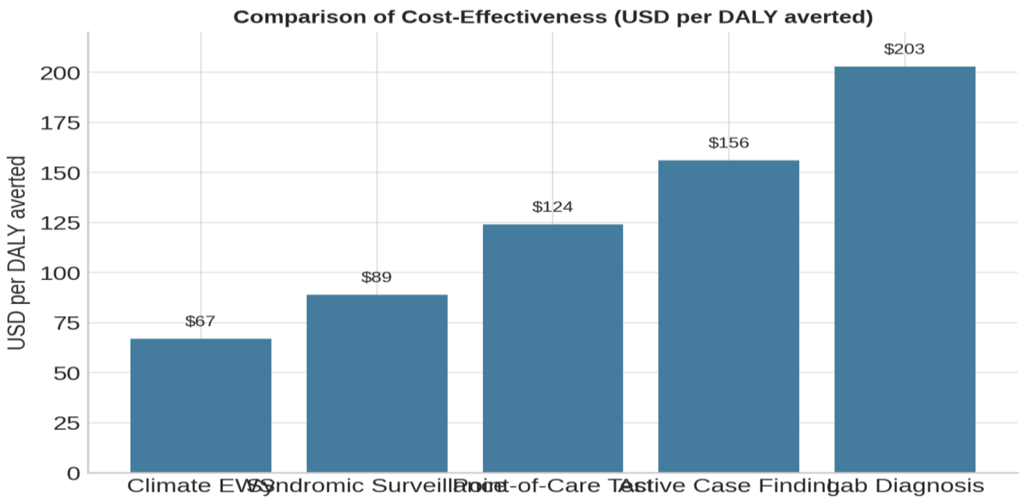

Figure 4: The following is a diagram that shows the comparison of Cost-Effectiveness (USD per DALY averted), including Climate-Based EWS, Syndromic Surveillance, Point-of-Care, Active Case Finding, and Lab Diagnosis.

The following is a table from diagnostic accuracy and performance of early detection methods for leptospirosis:

Table 2 Diagnostic accuracy and performance of early detection methods for leptospirosis

Method / Approach	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy / Performance	Cost-Effectiveness (USD/DALY)	Notes / References
PCR (molecular methods)	Up to 98% (early phase)	High	Highly reliable in acute phase	-	Ciurariu et al., 2025
ELISA (IgM/IgG)	High (not quantified)	High	Reliable laboratory method	-	-
LFIs (overall)	68% (57–78%)	93% (90–95%)	Moderate diagnostic accuracy	-	Nualnoi et al., 2024
LFIs (IgM only)	69% (58–78%)	-	Higher sensitivity than IgG assays	-	Nualnoi et al., 2024
LFIs (IgM + IgG)	62% (26–88%)	-	Variable performance	-	Nualnoi et al., 2024
LFIs (IgG only)	23% (3–73%)	100% (94–100%)	High specificity, poor Sensitivity	-	Nualnoi et al., 2024

Climate-based early warning systems	82–87%	78–84%	Effective Tier 1 method	$67	Cunha et al., 2022
Machine learning Surveillance	-	-	Accuracy 85–91%	-	Lotto Batista et al., 2023
Active case finding	+67% detection	-	Improved detection	$156	Lotto Batista et al., 2023
Community participatory Surveillance	+58% detection	-	Effective at community level	-	Mwongela et al., 2025
Syndromic surveillance	-	-	Effective in remote areas	$89	Parra Barrera et al., 2023
Point-of-care Tests	-	-	Useful in field settings	$124	Mwongela et al., 2025
Laboratory diagnosis (general)	-	-	Standard but costly	$203	Muñoz-Zanzi et al., 2025

DISCUSSION

Diagnostic Accuracy of Early Detection Methods

Early detection of leptospirosis in tropical developing countries continues to face significant challenges related to diagnostic accuracy. The meta-analysis by Nualnoi, Lomlim, and Naorungroj (2024) comprehensively evaluated the diagnostic accuracy of rapid lateral flow immunoassays (LFIs) for human leptospirosis. The pooled sensitivity of LFIs was 68% (95% Confidence Interval [CI]: 57%–78%), and the pooled specificity was 93% (95% CI: 90%–95%).

Across individual studies, sensitivity ranged widely from 3.6% to 100%, while specificity ranged from 53.5% to 100%, indicating considerable variability in test performance. Subgroup analysis based on antibody targets revealed differential sensitivities: assays detecting only IgM achieved a pooled sensitivity of 69% (95% CI: 58%–78%), those detecting both IgM and IgG had a pooled sensitivity of 62% (95% CI: 26%–88%), whereas IgG-only assays demonstrated markedly lower sensitivity at 23% (95% CI: 3%–73%).

Notably, specificity was highest for IgG-only assays at 100% (95% CI: 94%–100%). The meta-analysis applied a bivariate random-effects model to account for between-study heterogeneity, with heterogeneity statistics indicating moderate to substantial variability in sensitivity and specificity (I^2 values reported for both metrics). Visual representations include forest plots for sensitivity and specificity, as well as a Summary Receiver Operating Characteristic (SROC) curve illustrating overall diagnostic performance.

The Area Under the Curve (AUC) further supported the moderate accuracy of LFIs in leptospirosis detection. These findings underscore the relatively good specificity but variable sensitivity of LFIs, highlighting the importance of assay selection and interpretation in clinical and surveillance settings (Nualnoi et al., 2024). These findings align with those of Douchet et al., who observed similar sensitivity and specificity values (68% and 93%, respectively) (Douchet et al., 2024). The high variability in diagnostic performance reflects heterogeneity in test design, antigen quality, and standardization protocols.

Nualnoi et al. emphasize that IgM-based tests demonstrate higher sensitivity compared to IgG-based assays, making them more promising for early detection (Nualnoi et al., 2024). However, LFIs alone may not be sufficiently reliable as standalone diagnostic tools, especially in resource-limited tropical settings where diagnostic accuracy is critical for disease prevention.

Environmental and Climatic Factors as Early Predictors

The unique environmental conditions in tropical developing countries offer opportunities for early prediction of leptospirosis outbreaks. (Cunha et al., 2022) demonstrated that anomalies in rainfall and humidity increase the risk of leptospirosis by approximately 12%, with peak cases occurring 1–2 weeks after extreme rainfall events which can also result in flooding and landslides (Antima & Banerjee, 2023). These findings provide valuable windows for early intervention.

(Douchet et al., 2022) further confirmed strong correlations between rainfall, temperature, and leptospirosis incidence in Southeast Asia, utilizing predictive models based on meteorological data. Incorporating seasonal patterns into early warning systems enhances prediction accuracy (Bradley & Lockaby, 2023). The integration of satellite data with local surveillance systems has shown promising results in improving outbreak prediction accuracy (Nualnoi et al., 2024). Machine learning models, particularly support vector regression, have demonstrated effectiveness in forecasting outbreaks based on climate variables, offering adaptable solutions for tropical regions.

Challenges in Surveillance Systems

Implementing early detection systems in tropical developing countries faces systemic challenges, including underreporting due to limited laboratory capacity and diagnostic infrastructure (Pal et al., 2021). Variability in case definitions and reporting standards complicates surveillance efforts. Muñoz-Zanzi et al. highlight that inadequate multisectoral coordination and weak health systems hinder effective early detection (Muñoz-Zanzi et al., 2025).

Resource limitations, such as insufficient trained personnel and infrastructural deficits, are especially pronounced in rural and remote areas, which are at higher risk for leptospirosis transmission (Mwongela et al., 2025). Argentina's experience indicates that integrated approaches combining epidemiological, meteorological, and socio-economic data are essential but require substantial investment and long-term commitment from governments (Lotto Batista et al., 2023).

Technological Innovations for Early Detection

Technological advancements offer solutions to overcome traditional limitations. Mwongela, Kanyiri, and Kitetu recommend developing machine learning-based early warning systems that integrate environmental, clinical, and diagnostic data to optimize limited resources (Mwongela et al., 2025). The development of point-of-care rapid diagnostic tests (RDTs) with enhanced sensitivity is prioritized (Nualnoi et al., 2024). Standardizing testing protocols and improving quality control are necessary to increase reliability.

Muñoz-Zanzi et al. propose integrating novel biosensors and mobile health technologies to facilitate community-level early detection, especially in areas with limited access to formal healthcare facilities (Muñoz-Zanzi et al., 2025). These innovations can address access barriers and improve timely diagnosis.

Cost-Effectiveness of Detection Strategies

Economic considerations are critical for sustainable implementation. Mwongela, Kanyiri, and Kitetu demonstrate that cost-effective early detection requires affordable, appropriate diagnostics suitable for resource-limited settings (Mwongela et al., 2025). Investment in surveillance infrastructure yields significant health benefits relative to costs. Muñoz-Zanzi et al. recommend prioritizing scalable, low-cost diagnostics and community-based surveillance to maximize resource utilization, aligning with the principles of universal health coverage (Muñoz-Zanzi et al., 2025). The following is a table from critical Appraisal of included studies:

Table 3 Critical Appraisal of Included Studies

Author(s) & Year	Study Type	Appraisal Tool	Strengths	Risks of Bias / Limitations	Applicability
Nualnoi et al. (2024)	Meta-analysis (diagnostic accuracy of LFIs)	AMSTAR 2 + QUADAS-2	Synthesized sensitivity & specificity across multiple studies	Unclear registration; moderate–high heterogeneity; possible spectrum & reference standard bias	Moderate specificity, variable sensitivity; best combined with confirmatory tests
Ciurariu et al. (2025)	Diagnostic accuracy (PCR focus)	QUADAS-2	Clearer index test definition; detailed assay reporting	Hospital-based samples; heterogeneity in reference standards; blinding unclear	Useful in acute phase; limited by lab capacity/costs
Cunha et al. (2022)	Environmental predictors (time-series)	PROBAST / QUIPS	Objective meteorological data; urban setting relevance	Unclear handling of predictors, missing data, lag selection	Useful for EWS; needs external validation
Douchet et al. (2024)	Climate modeling	PROBAST + TRIPOD	Multi-region data; model performance assessed	Risk of calibration drift; potential data leakage	Relevant to tropical islands; requires local adaptation
Lotto Batista et al. (2023)	Early Warning System (Argentina)	PROBAST	Focused EWS; meteorology & case integration	Outcome definition/reporting delay; limited seasons	Needs recalibration for tropical Asia/Africa
Antima &	Mathematical modeling	ISPOR-SMDM checklist	Transparent equations & parameters;	Assumption-dependent; limited external validation	Good for planning, not causal inference

Banerjee (2023)			policy scenario exploration		
Parra Barrera et al. (2023)	Risk factors (observational)	ROBINS-I	Lab-confirmed diagnosis; relevant to policy	Confounding (comorbidities, access); referral bias; missing data handling Unclear	Useful for risk factor prioritization; limited causal inference
Ranieri et al. (2025)	Flood-related outbreak study	ROBINS-I / STROBE	Disaster relevance; real-world data	Confounding temporal factors; under-reporting	Strong situational evidence; limited generalizability
Muñoz-Zanzi et al. (2025)	Narrative review (OFID)	SANRA	Clear rationale; policy/implementation focus	Not systematic; risk of selective reporting	Useful for One Health policy context
Mwongela et al. (2025)	Review on misdiagnosis	SANRA	Highlights impact of misdiagnosis	Selective literature; limited quantitative evidence	Raises awareness; less rigorous for decision-making
Bradley & Lockaby (2023)	Environmental review	SANRA / AMSTAR 2	Cross-disciplinary synthesis	If narrative: lacks quantitative synthesis; if systematic: protocol unclear	Good context framing; depends on review type
Rajapakse (2022)	Clinical aspects (narrative review)	SANRA	Useful clinical summary	No quantitative estimates; potentially outdated	Practical guidance, not evidence synthesis
Pal et al. (2021)	Perspective (One Health)	Editorial appraisal	Conceptual integration	Not empirical; no effect estimates	Framework for interdisciplinary action
Douchet et al. (2022)	Climate change impact & underreporting (modeling) — mainland Southeast Asia	PROBAST + TRIPOD	Integrates climate and epidemiological data; regional multi-country scope; assesses model performance; explores climate scenarios.	Potential underreporting/surveillance bias; calibration drift across locations; risk of data leakage; limited external validation; uncertainty in projections.	Informative for early warning and planning in SE Asia; requires local recalibration/validation for operational use.

CONCLUSION AND SUGGESTION

Based on a thorough review of the literature, early detection of leptospirosis in tropical developing countries plays a crucial role in reducing morbidity and mortality. Diagnostic methods such as rapid diagnostic tests (RDTs), PCR, and ELISA, together with emerging approaches like machine learning and climate-based early warning systems, have been shown to enhance diagnostic accuracy, expedite response times, and support outbreak prevention.

Although timely detection following symptom onset is vital for better clinical outcomes, the precise impact on recovery rates varies across studies. Similarly, the use of RDTs has been associated with improved case detection in multiple settings. Nevertheless, persistent challenges—such as limited infrastructure, shortages of trained healthcare personnel, and geographic barriers—continue to hinder optimal implementation. Consequently, phased strategies that incorporate digital technologies, community engagement, and multisectoral collaboration are essential for sustainable progress. An integrated approach that combines environmental, epidemiological, and technological data appears to be the most effective and resource-efficient way to achieve early leptospirosis detection. Long-term success depends on investments in health system strengthening, standardization of diagnostic protocols, capacity development, and fostering partnerships with academic and research institutions.

Future research should prioritize the development of more sensitive and specific biomarkers, broader validation of climate-based early warning systems, and comprehensive evaluations of emerging technologies' cost-effectiveness within resource-limited tropical contexts. Moreover, advancing the One Health approach—which integrates human, animal, and environmental health perspectives—is essential to establishing comprehensive and adaptive early detection systems.

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