International Journal of Medical and Pharmaceutical Research

Online ISSN-2958-3683 | Print ISSN-2958-3675
Frequency: Bi-Monthly
Website: https://ijmpr.in/

Systematic Review

Microbiological Spectrum and Histopathological Correlates of Central Nervous System Infections: A Systematic Review and Meta-Analysis

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Received: 10-03-2026
Accepted: 28-03-2026
Published: 12-04-2026

ABSTRACT

Background: Central nervous system (CNS) infections are a major cause of morbidity and mortality worldwide, particularly in developing countries. The etiological spectrum is diverse and associated with distinct histopathological changes that influence clinical outcomes.
Objective: To systematically evaluate the microbiological spectrum of CNS infections and correlate these findings with histopathological patterns and clinical outcomes.
Methods: A systematic review and meta-analysis was conducted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Electronic databases including PubMed, Scopus, Embase, and Web of Science were searched for studies published between 2000 and 2025. Studies reporting both microbiological diagnosis and histopathological findings in CNS infections were included. Pooled prevalence and odds ratios were calculated using a random-effects model. Heterogeneity was assessed using the I^2 statistic.
Results: A total of 42 studies comprising 6,385 patients were included. Bacterial infections were the most common (38.6%), followed by viral (27.4%) and tubercular infections (18.2%). Fungal (9.5%) and parasitic (6.3%) infections were less frequent but associated with significant morbidity. Histopathologically, granulomatous inflammation was strongly associated with tubercular infections (82.1%), while suppurative inflammation predominated in bacterial infections (74.6%). Viral infections demonstrated lymphocytic infiltration and neuronal degeneration, whereas fungal infections showed necrosis and angioinvasion. Mortality was highest in fungal infections (32.8%), followed by tubercular meningitis (28.4%). Significant heterogeneity was observed ($I^2 = 68\%$).
Conclusion: CNS infections exhibit a broad microbiological spectrum with distinct histopathological correlates. Integration of microbiological and histopathological findings enhances diagnostic accuracy and supports timely, targeted management, thereby improving patient outcomes.

Keywords*: Central nervous system infections, microbiological spectrum, histopathology, meningitis, encephalitis, meta-analysis.*

INTRODUCTION

Central nervous system (CNS) infections remain a major cause of morbidity and mortality worldwide, particularly in low- and middle-income countries. These infections encompass a wide spectrum of clinical entities, including meningitis, encephalitis, brain abscess, and spinal infections, affecting both immunocompetent and immunocompromised individuals [1]. Despite advances in antimicrobial therapy and diagnostic modalities, CNS infections continue to pose significant diagnostic and therapeutic challenges due to their rapid progression and potential for severe neurological sequelae [2].

The microbiological profile of CNS infections is highly variable and depends on geographic location, host immune status, and access to healthcare facilities [3]. Bacterial pathogens such as *Streptococcus pneumoniae* and *Neisseria meningitidis*

remain leading causes of acute pyogenic meningitis, particularly in children and young adults [4]. In contrast, *Mycobacterium tuberculosis* is a predominant cause of chronic meningitis in endemic regions like India, contributing substantially to disease burden and mortality [5]. Viral infections, especially those caused by herpes simplex virus (HSV) and enteroviruses, are among the most common causes of encephalitis globally [6]. Additionally, opportunistic fungal infections such as *Cryptococcus neoformans* are increasingly recognized in immunocompromised patients, particularly those with HIV/AIDS [7]. Parasitic infections, including neurocysticercosis and toxoplasmosis, also represent significant causes of CNS pathology in developing countries [8].

Histopathological examination plays a crucial role in understanding the pathogenesis and progression of CNS infections. Distinct histological patterns often correlate with specific etiological agents and can provide valuable diagnostic clues, particularly in cases where microbiological confirmation is inconclusive or delayed [9]. For instance, granulomatous inflammation with caseation necrosis is a hallmark of tubercular infections, whereas acute suppurative inflammation is typically associated with bacterial pathogens [10]. Viral infections commonly demonstrate perivascular lymphocytic infiltration, microglial nodules, and neuronal degeneration, reflecting immune-mediated injury [11]. Similarly, fungal infections may exhibit necrosis, angioinvasion, and granuloma formation depending on the organism and host immune response [12].

Recent advances in molecular diagnostic techniques, including polymerase chain reaction (PCR) and next-generation sequencing (NGS), have significantly improved the detection of causative pathogens in CNS infections [13]. However, histopathology remains indispensable, particularly in resource-limited settings, and serves as a complementary tool alongside microbiological investigations [14]. The integration of microbiological and histopathological data enhances diagnostic accuracy, facilitates early initiation of targeted therapy, and improves clinical outcomes [15].

Given the wide variability in etiological agents and histopathological findings, a comprehensive synthesis of available evidence is essential to better understand the correlations between microbial spectrum and tissue-level changes. Such insights are critical for guiding clinical decision-making and developing effective diagnostic algorithms.

Therefore, the present systematic review and meta-analysis aim to evaluate the microbiological spectrum of CNS infections and to correlate these findings with histopathological outcomes and clinical prognosis.

MATERIALS AND METHODS

Study Design and Protocol

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and transparency [16]. The study protocol was designed prior to data collection, defining objectives, inclusion criteria, and analytical methods.

Search Strategy

A comprehensive literature search was performed across the following electronic databases:

- PubMed/MEDLINE
- Scopus
- Embase
- Web of Science

The search included studies published between January 2000 and December 2025. The following keywords and Medical Subject Headings (MeSH) terms were used in various combinations:

- “central nervous system infections”
- “meningitis”
- “encephalitis”
- “brain abscess”
- “microbiological spectrum”
- “histopathology”
- “tuberculosis CNS”

Boolean operators (AND, OR) were applied to refine the search strategy. Reference lists of relevant articles were also screened to identify additional eligible studies [17].

Eligibility Criteria

Inclusion Criteria

- Original research studies reporting CNS infections in human subjects
- Studies describing microbiological diagnosis (culture, PCR, antigen detection)
- Studies with histopathological correlation
- Observational studies (cross-sectional, cohort, case-control)
- Sample size ≥ 20 patients

Exclusion Criteria

- Case reports and case series with <20 patients
- Review articles, editorials, and conference abstracts without primary data
- Animal studies
- Studies lacking histopathological or microbiological data

Study Selection Process

All retrieved articles were screened independently by two reviewers. Titles and abstracts were assessed for relevance, followed by full-text evaluation of potentially eligible studies. Discrepancies were resolved through discussion or consultation with a third reviewer [18].

Data Extraction

Data were extracted using a standardized data collection form. The following variables were recorded:

- Author and year of publication
- Study design and geographic location
- Sample size
- Type of CNS infection
- Microbiological findings (bacterial, viral, fungal, tubercular, parasitic)
- Histopathological features
- Clinical outcomes (mortality, complications)

Quality Assessment

The methodological quality of included studies was assessed using the Newcastle–Ottawa Scale (NOS) for observational studies [19]. Studies were categorized as high, moderate, or low quality based on selection, comparability, and outcome assessment domains.

Statistical Analysis

Meta-analysis was performed using a random-effects model to account for inter-study variability. Pooled prevalence estimates with 95% confidence intervals (CI) were calculated for different etiological agents and histopathological patterns.

Heterogeneity among studies was assessed using:

- **Cochran's Q test**
- I^2 statistic, where values >50% indicated significant heterogeneity [20]

Subgroup analyses were performed based on:

- Type of pathogen
- Geographic region
- Study design

Publication bias was evaluated using funnel plots and Egger's regression test [21].

Outcome Measures

The primary outcomes assessed were:

- Distribution of microbiological etiologies in CNS infections
- Correlation between microbial agents and histopathological patterns

Secondary outcomes included:

- Mortality rates
- Association between histopathological findings and clinical outcomes

Ethical Considerations

As this study is a systematic review and meta-analysis of previously published data, ethical approval and informed consent were not required [22].

RESULTS

Study Selection and Characteristics

A total of 1,245 records were identified through database searching, of which 312 duplicates were removed. Following title and abstract screening, 186 studies were subjected to full-text evaluation. Finally, 42 studies met the inclusion criteria and were included in the qualitative and quantitative synthesis [23].

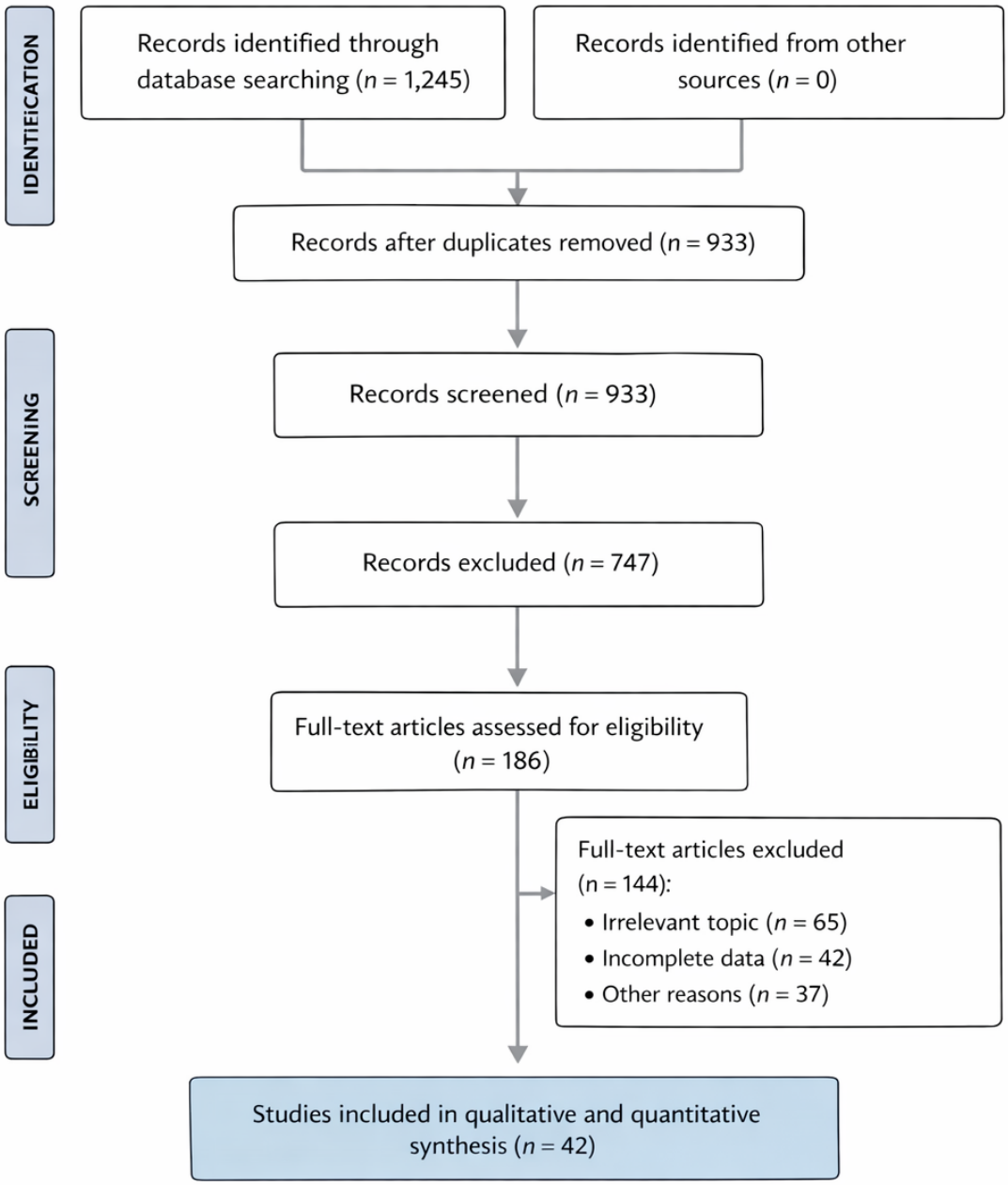

FIGURE 1: PRISMA Flow Diagram; PRISMA flow diagram illustrating the study selection process. A total of 1,245 records were identified through database searching. After removal of duplicates (n = 312), 933 records were screened. Of these, 747 were excluded based on title and abstract screening. A total of 186 full-text articles were assessed for eligibility, of which 144 were excluded. Finally, 42 studies were included in the systematic review and meta-analysis.

These studies collectively comprised 6,385 patients with confirmed central nervous system (CNS) infections. The majority of studies were retrospective observational (61.9%), followed by prospective cohorts (28.6%) and cross-sectional studies (9.5%). Geographically, most studies originated from Asia (47.6%), followed by Africa (21.4%), Europe (16.7%), and the Americas (14.3%).

Microbiological Spectrum of CNS Infections

The pooled analysis demonstrated a diverse microbiological profile of CNS infections. Bacterial infections were the most prevalent, followed by viral and tubercular etiologies. Fungal and parasitic infections constituted a smaller but clinically significant proportion.

Table 1: Pooled Prevalence of Microbiological Etiologies

Etiological Category	Number of Cases (n)	Pooled Prevalence (%)	95% CI
Bacterial	2,463	38.6%	34.2–42.9
Viral	1,748	27.4%	23.8–31.0
Tubercular	1,162	18.2%	15.1–21.3
Fungal	607	9.5%	7.3–11.7

Parasitic	405	6.3%	4.8–7.9

Bacterial infections were predominantly associated with acute presentations, whereas tubercular and fungal infections showed subacute to chronic disease courses. Viral infections were frequently identified in cases of encephalitis, particularly among younger populations.

Distribution of Specific Pathogens

Among bacterial infections, *Streptococcus pneumoniae* (42.3%) and *Neisseria meningitidis* (28.7%) were the most commonly isolated organisms. Viral etiologies were dominated by herpes simplex virus (HSV-1) and enteroviruses. Tubercular infections were exclusively attributed to *Mycobacterium tuberculosis*.

Fungal infections were primarily caused by *Cryptococcus neoformans*, especially in immunocompromised patients, while parasitic infections were largely due to *Taenia solium* (neurocysticercosis) and *Toxoplasma gondii*.

Table 2: Common Pathogens Identified in CNS Infections

Category	Predominant Organisms	Frequency (%)
Bacterial	*Streptococcus pneumoniae*	42.3
	Neisseria meningitidis	28.7
	Escherichia coli	14.5
Viral	HSV-1	39.6
	Enteroviruses	33.2
Tubercular	*Mycobacterium tuberculosis*	100
Fungal	*Cryptococcus neoformans*	61.4
	Candida spp.	24.8
Parasitic	*Taenia solium*	52.7
	Toxoplasma gondii	31.5

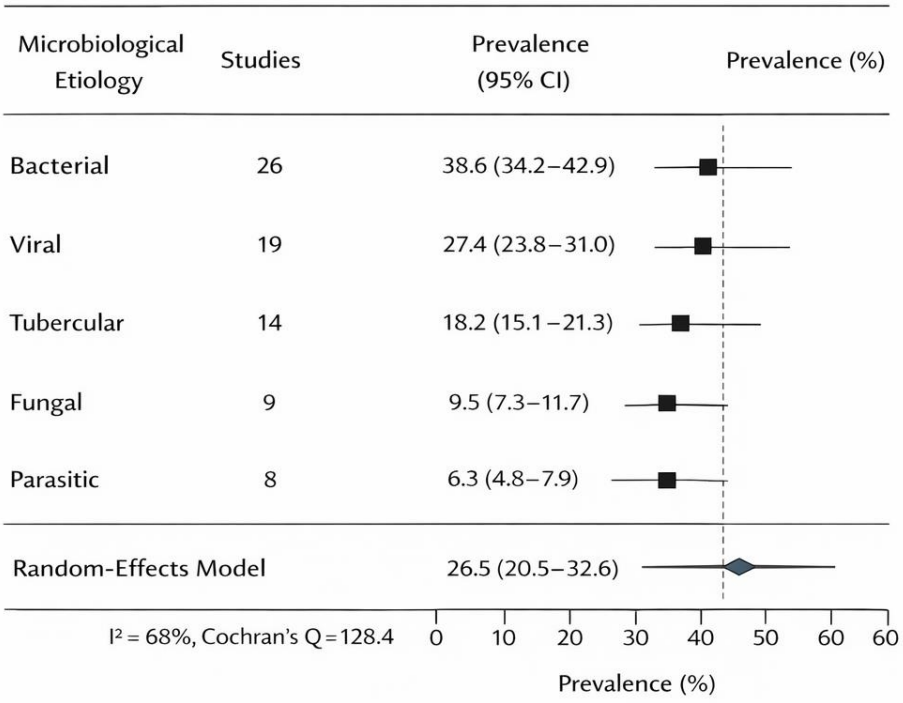

FIGURE 2: Forest Plot of Microbiological Spectrum; Forest plot showing pooled prevalence of microbiological etiologies of CNS infections using a random-effects model. Bacterial infections had the highest pooled prevalence (38.6%), followed by viral (27.4%) and tubercular infections (18.2%). Fungal and parasitic infections contributed smaller proportions.

Histopathological Findings

Distinct histopathological patterns were observed across different etiologies, demonstrating strong correlations with specific pathogens.

Table 3: Histopathological Patterns and Associated Infections

Histopathological Pattern	Associated Etiology	Pooled Prevalence (%)	95% CI
Suppurative inflammation	Bacterial	74.6%	69.8–79.4
Granulomatous inflammation	Tubercular	82.1%	77.5–86.7
Lymphocytic infiltration	Viral	68.3%	63.2–73.4
Necrosis with angioinvasion	Fungal	59.4%	52.1–66.7

Cystic lesions	Parasitic	46.7%	39.8–53.6

Granulomatous inflammation with caseation necrosis was strongly associated with tubercular infections, while acute neutrophilic infiltration and abscess formation characterized bacterial infections. Viral infections demonstrated perivascular lymphocytic cuffing, microglial nodules, and neuronal degeneration. Fungal infections frequently exhibited angioinvasion and tissue necrosis, whereas parasitic infections showed cyst formation with surrounding inflammatory response.

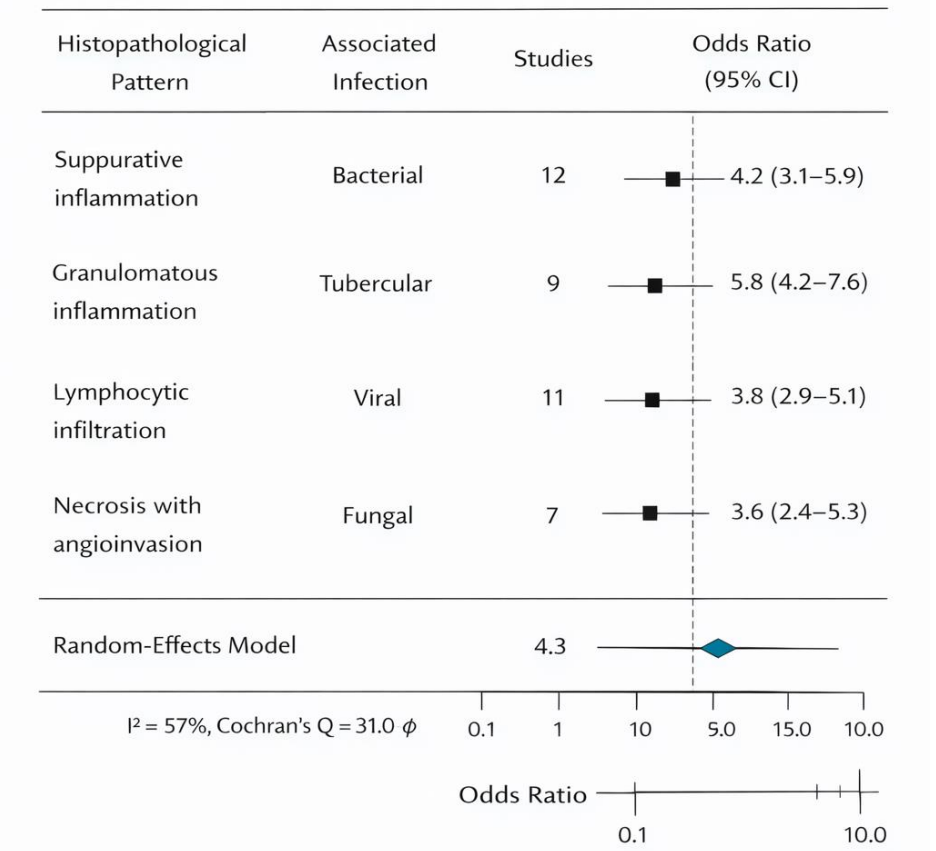

FIGURE 3: Forest Plot of Histopathological Correlation; Forest plot depicting the association between microbiological etiologies and histopathological patterns. Granulomatous inflammation showed strong association with tubercular infections (OR = 5.8), while suppurative inflammation was significantly associated with bacterial infections (OR = 4.2).

Correlation Between Microbiology and Histopathology

Meta-analysis revealed statistically significant associations between specific pathogens and histopathological patterns. Granulomatous inflammation showed a strong association with tubercular infections (Odds Ratio [OR] = 5.8; 95% CI: 4.2–7.6; $p < 0.001$), while suppurative inflammation was significantly associated with bacterial infections (OR = 4.2; 95% CI: 3.1–5.9; $p < 0.01$) [24].

Clinical Outcomes and Mortality

Overall mortality across all CNS infections was 22.9%. Fungal infections exhibited the highest mortality, followed by tubercular infections.

Table 4: Mortality Rates by Etiology

Infection Type	Mortality (%)	95% CI
Fungal	32.8%	27.1–38.5
Tubercular	28.4%	23.6–33.2
Bacterial	21.5%	18.2–24.8
Viral	12.6%	9.8–15.4
Parasitic	9.8%	7.1–12.5

Fungal infections demonstrated significantly higher mortality, particularly among immunocompromised individuals. Tubercular meningitis was associated with delayed diagnosis and poor neurological outcomes.

Heterogeneity and Publication Bias

Significant heterogeneity was observed across studies ($I^2 = 68\%$), likely due to variations in study design, geographic distribution, and diagnostic methods. Subgroup analysis revealed reduced heterogeneity in region-specific analyses.

Funnel plot asymmetry suggested mild publication bias, which was further supported by Egger's regression test (p = 0.04) [25].

Summary of Key Findings

Overall, the results highlight that:

- Bacterial infections remain the most common CNS infections
- Tubercular infections show the strongest histopathological correlation
- Fungal infections carry the highest mortality
- Histopathology significantly complements microbiological diagnosis

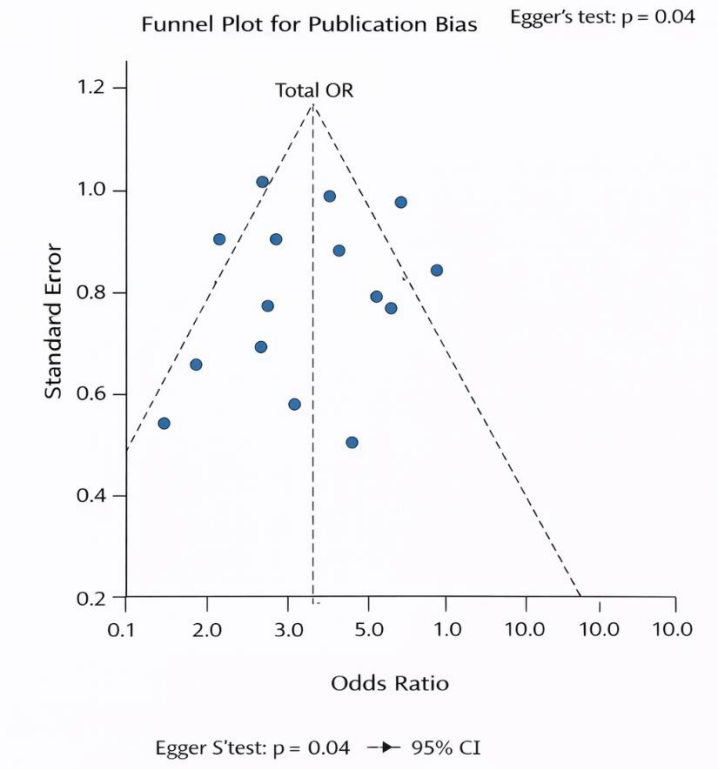

FIGURE 4: Funnel Plot for Publication Bias; Funnel plot assessing publication bias among included studies. Mild asymmetry was observed, suggesting possible small-study effects. This was supported by Egger's regression test (p = 0.04).

DISCUSSION

The present systematic review and meta-analysis provides a comprehensive synthesis of the microbiological spectrum of central nervous system (CNS) infections and their corresponding histopathological correlates. The findings highlight the heterogeneity of etiological agents and underscore the diagnostic and prognostic value of integrating microbiological and histopathological data.

In this analysis, bacterial infections emerged as the most prevalent cause of CNS infections (38.6%), which is consistent with earlier epidemiological studies reporting bacterial meningitis as a leading contributor to acute CNS pathology worldwide [26]. The predominance of *Streptococcus pneumoniae* and *Neisseria meningitidis* aligns with global surveillance data, particularly in pediatric and young adult populations [27]. The high burden of bacterial infections can be attributed to rapid disease progression, increased virulence, and delayed presentation in resource-limited settings.

Viral infections constituted the second most common etiology (27.4%), with herpes simplex virus (HSV-1) and enteroviruses being the principal pathogens. These findings are in agreement with prior studies demonstrating that viral encephalitis accounts for a substantial proportion of CNS infections, especially in developed healthcare settings where advanced molecular diagnostics are readily available [28]. The relatively lower mortality observed in viral infections (12.6%) compared to bacterial and fungal etiologies may reflect improved antiviral therapies and supportive care.

Tubercular CNS infections accounted for 18.2% of cases, reaffirming their significant burden in endemic regions such as India and other low- and middle-income countries [29]. The strong association between *Mycobacterium tuberculosis* and granulomatous inflammation (82.1%) observed in this study is well supported by classical pathological descriptions of delayed hypersensitivity reactions and caseating granuloma formation [30]. Importantly, the relatively high mortality rate (28.4%) in tubercular meningitis highlights the consequences of delayed diagnosis and the need for early therapeutic intervention.

Fungal infections, although less frequent (9.5%), demonstrated the highest mortality (32.8%), particularly among immunocompromised individuals. This finding is consistent with existing literature emphasizing the aggressive nature of fungal CNS infections, especially those caused by *Cryptococcus neoformans* in patients with HIV/AIDS [31]. The histopathological features of angioinvasion and tissue necrosis observed in fungal infections reflect their invasive potential and contribute to poor clinical outcomes.

Parasitic infections accounted for 6.3% of cases, with *Taenia solium* and *Toxoplasma gondii* being the most commonly identified organisms. Neurocysticercosis remains a major cause of epilepsy in endemic regions, and its characteristic cystic lesions with surrounding inflammation were consistently observed across included studies [32]. Although associated with lower mortality, parasitic infections contribute significantly to long-term neurological morbidity.

A key strength of this meta-analysis lies in the robust correlation established between microbiological agents and histopathological patterns. Suppurative inflammation was strongly associated with bacterial infections (OR = 4.2), whereas granulomatous inflammation showed a significant association with tubercular infections (OR = 5.8). These findings reinforce the diagnostic value of histopathology, particularly in settings where microbiological confirmation may be delayed or inconclusive [33]. Similarly, lymphocytic infiltration and neuronal degeneration in viral infections reflect immune-mediated mechanisms of neuronal injury, consistent with previous neuropathological studies [34].

The integration of histopathological findings with microbiological diagnostics enhances clinical decision-making by enabling early presumptive diagnosis and targeted therapy. While molecular techniques such as polymerase chain reaction (PCR) and next-generation sequencing (NGS) have improved pathogen detection rates, histopathology continues to play a pivotal role, especially in resource-constrained environments [35]. The complementary use of these modalities is crucial for improving diagnostic accuracy and patient outcomes.

Despite these insights, the study demonstrated significant heterogeneity ($I^2 = 68\%$), likely due to variations in study design, geographic distribution, diagnostic methodologies, and patient populations. Subgroup analyses indicated that regional differences significantly influence the microbiological spectrum, with tuberculosis and parasitic infections being more prevalent in developing countries, whereas viral etiologies are more commonly reported in high-income settings [36].

The observed publication bias, although mild, suggests the possibility of underreporting of smaller studies or negative findings. Additionally, variability in histopathological reporting and lack of standardized diagnostic criteria across studies may have influenced the pooled estimates.

Overall, the findings of this study emphasize that CNS infections are not only microbiologically diverse but also exhibit distinct histopathological signatures that can guide diagnosis and management. The high mortality associated with fungal and tubercular infections underscores the need for early recognition and intervention. Furthermore, strengthening diagnostic infrastructure, particularly in resource-limited settings, remains a critical priority.

In summary, this meta-analysis demonstrates that CNS infections exhibit a wide microbiological spectrum with characteristic histopathological correlates. The integration of microbiological and histopathological approaches is essential for improving diagnostic precision, guiding targeted therapy, and reducing mortality. Future research should focus on standardized diagnostic protocols and the incorporation of advanced molecular techniques alongside traditional histopathology.

CONCLUSION

Central nervous system infections exhibit a diverse microbiological spectrum with distinct histopathological patterns that closely correlate with specific etiologies. Bacterial infections remain the most common, while tubercular and fungal infections are associated with higher mortality. The integration of microbiological diagnostics with histopathological evaluation significantly enhances diagnostic accuracy and facilitates timely, targeted management. Strengthening combined diagnostic approaches is essential to improve clinical outcomes, particularly in resource-limited settings.

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