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ORIGINAL RESEARCH

From Cradle to Early-Life Sleep: A Bibliometric Analysis of Global Research on Neonatal Sleep

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Background: Sleep plays a critical role in neonatal brain maturation and behavioral regulation, and early-life sleep disturbances have been widely studied in relation to neurodevelopmental vulnerability, particularly among preterm and critically ill infants. Although research on neonatal and early developmental sleep has demonstrated steady growth over the past two decades, the global structure of this literature, its evolving research frontiers, and patterns of scholarly collaboration have not been systematically mapped.

Methods: Relevant publications were retrieved from the Web of Science(WOS) Core Collection (2000–2025). Using multiple complementary bibliometric tools, including CiteSpace, VOSviewer, and the bibliometrix R package, we analyzed publication trends, contributing countries and institutions, authorship and co-citation networks, journal distribution, keyword co-occurrence, and emerging thematic clusters.

Results: A total of 530 articles were identified, involving 55 countries and regions, 438 institutions, and 636 authors. The United States contributed 30.75% of all publications and demonstrated the highest citation impact. Véronique Bach was the most productive author, whereas Mark S. Scher was the most frequently co-cited, reflecting sustained methodological influence. Monash University emerged as the leading institution, and *Sleep Medicine* published the highest number of articles. Keyword and temporal analyses revealed an early emphasis on vulnerable neonatal populations and sleep maturation, followed by a progressive shift toward computational analytics, prenatal influences, autonomic regulation, and outcome-oriented research themes.

Conclusion: Neonatal sleep research has evolved from predominantly descriptive studies toward increasingly multidisciplinary and methodologically sophisticated investigations. Bibliometric mapping highlights growing emphasis on advanced analytical approaches, integrative physiological framing, and outcome-oriented perspectives, reflecting shifts in research focus rather than direct mechanistic validation. This structured overview delineates dominant themes, emerging frontiers, and persistent knowledge gaps, and may inform the future development of neonatal sleep research.

Keywords: neonatal sleep, bibliometric analysis, neurodevelopment, autonomic regulation, citespace, VOSviewer

Introduction

Neonates spend most of their time asleep, and during the late fetal and early neonatal stages, sleep is the predominant state of brain activity. It plays a vital role in thermoregulation, energy conservation, and synaptic reorganization, thereby supporting rapid neural maturation and the development of early behavioral regulation.[1,2] Sleep is also essential for brain organization and neurobehavioral development, influencing neural connectivity, sensory processing, and cognitive outcomes throughout infancy and childhood.[3] Spontaneous neural activity during rapid eye movement (REM) sleep, including twitches and other motor events, facilitates the self-organization of central nervous system circuits and the formation of somatotopic maps.[2] Experimental studies have suggested that REM sleep deprivation during critical developmental periods can result in abnormal cortical growth, behavioral disturbances, and long-term neurodevelopmental impairments.[4]

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Neonatal sleep architecture differs markedly from that of older children and adults. It is typically divided into active sleep (AS), quiet sleep (QS), and indeterminate sleep (IS), reflecting the progressive maturation of neural regulation across early development.[5,6] The proportions and cycling of these states change rapidly during early life and serve as sensitive indicators of neurological integrity and developmental health.[7] In neonatal intensive care units (NICUs), sleep-wake cycling is widely regarded as a crucial marker of brain function and developmental prognosis.[8] Accumulating neurophysiological and longitudinal evidence indicates that neonatal sleep development mirrors early brain network maturation. Alterations in sleep organization have been associated with functional connectivity patterns during early life,[9] and systematic evidence further suggests that early sleep trajectories relate to later cognitive, motor, and behavioral development.[10] However, environmental and procedural factors such as excessive light exposure, high noise levels, and frequent handling can disrupt sleep continuity and alter its structure, increasing the risk of neurodevelopmental impairment in preterm and critically ill infants.[11] Therefore, optimizing sleep conditions and minimizing disturbances have become essential components of neuroprotective care in modern neonatology.[12]

In recent years, research on neonatal sleep has expanded substantially across diverse domains including developmental neuroscience, physiology, neuroimaging, and neonatal intensive care. Advances in polysomnography, electroencephalography (EEG), and machine learning-based sleep state classification have generated new insights into neural maturation and sleep physiology.[13,14] Nevertheless, despite this growing body of evidence, the field remains fragmented, with studies differing in methodological approaches, population focus, and clinical outcomes.[15] While existing systematic reviews and meta-analyses have provided valuable insights into specific clinical or physiological questions, they are typically limited to narrowly defined outcomes and therefore do not capture broader patterns of research activity, collaboration, or thematic evolution across the field. The absence of an integrated, field-level overview of how global research on neonatal and early developmental sleep has evolved limits the ability to identify influential contributors, emerging trends, and knowledge gaps.

Bibliometrics provides a systematic approach to evaluating scientific literature through statistical and mathematical analyses, enabling both qualitative and quantitative assessments of research patterns and structures.[16] By examining elements such as countries, institutions, journals, and authorship, bibliometric analysis offers a comprehensive understanding of the development and current status of a scientific domain. This method helps trace the evolution of foundational knowledge and predict future research directions by analyzing citation networks, keyword co-occurrence, and publication trends. Tools such as VOSviewer and CiteSpace facilitate the visualization of intellectual structures and collaboration networks. Bibliometric analysis is particularly useful for identifying influential studies, highlighting emerging research areas, and supporting evidence-based decision-making in research and policy.[17] By systematically identifying dominant themes, emerging trends, and underexplored areas, bibliometric evidence can also inform future research prioritization and support the development of evidence-informed research agendas in neonatal sleep health. Integrating quantitative bibliometric techniques with knowledge mapping, the present study aims to describe publication trends, research hotspots, and collaboration patterns, providing a comprehensive overview of the evolution and future trajectory of this important field of developmental science.

Materials and Methods

Data Sources and Literature Search

In this investigation, the Web of Science (WoS) Core Collection served as the primary data repository, chosen for its rigorous indexing standards and extensive inclusion of premier peer-reviewed journals. WoS is esteemed for its robust citation metrics and prevalent application in bibliometric inquiries.[18] Although alternative databases such as Scopus and Lens provide wider scope, the emphasis here was on high-caliber, impactful scholarship to delineate key contributions in the field. The retrieval protocol incorporated the topic search string: TS = ((“neonate*” OR “newborn*” OR “preterm” OR “premature infant*”) NEAR/3 (“sleep” OR “sleep-wake” OR “sleep cycle” OR “sleep pattern*” OR “sleep architecture” OR “sleep behavior” OR “sleep physiology” OR “sleep disorder*” OR “sleep monitoring”)). Literature selection adhered to three principal criteria: publications addressing neonatal sleep appeared between January 1, 2000, and October 18, 2025; only peer-reviewed original research articles and reviews were incorporated; and all selected works were in English. Exclusion criteria encompassed records unrelated to neonatal sleep, as well as non-empirical formats including letters, news items, editorials, proceedings, brief communications, and conference abstracts. Full-text records were subsequently exported in plain text format.

Conceptual Definition of Neonatal and Early-Life Sleep

In this bibliometric analysis, neonatal sleep refers to sleep-related research focusing on the neonatal period, typically defined as the first 28 days after birth, and includes both full-term and preterm infants. Preterm infants were intentionally included, as sleep organization and maturation in this population constitute a substantial and clinically relevant component of neonatal sleep research. The term early-life sleep was used to capture literature that, while centered on neonatal sleep, also examines prenatal determinants or early developmental consequences beyond the neonatal period, such as subsequent sleep patterns or neurodevelopmental outcomes in infancy or early childhood.

Data Analysis and Visualization

This analysis integrated visual bibliometric techniques through VOSviewer (version 1.6.19), the R-based bibliometrix package (version 4.3.1), and CiteSpace (version 6.2.R4). VOSviewer facilitated the creation and depiction of bibliometric networks, encompassing co-authorship, co-citation, and keyword co-occurrence analyses, thereby enabling detailed scrutiny of structural dynamics and scholarly interrelations to identify salient thematic groupings. The bibliometrix package furnished an array of statistical and graphical functionalities for assessing research output, temporal patterns, and prominent entities such as nations, organizations, and authors, thus permitting quantitative appraisal of productivity and longitudinal shifts from 2000 to 2025. CiteSpace supported the exploration of dynamic trends and conceptual evolutions via co-citation mapping and clustering, aiding in the discernment of emergent domains, landmark publications, and knowledge trajectories. The synergistic deployment of these tools capitalized on their complementary capabilities, yielding a multifaceted, methodologically sound, and interpretable approach to charting the progression of research in neonatal and early-life sleep. Prior to analysis, data cleaning and standardization were performed to improve consistency and accuracy. Synonymous keywords referring to similar neonatal concepts were manually harmonized according to a consistent manual protocol applied across the entire dataset, and author keywords were combined with index keywords for unified analysis. Author names and institutional affiliations were standardized to account for spelling variations and name inconsistencies across records, with disambiguation restricted to clear and recurrent variants to avoid over-merging distinct entities. Detailed procedures and parameter settings are provided in Supplementary Table S1.

Results

Publication Outputs and Temporal Trends

Figure 1A outlined the methodological workflow for the bibliometric analysis, including the selection criteria applied to records from the WoS Core Collection. An initial retrieval yielded 982 entries, from which 318 were excluded following restriction to the period spanning January 2000 through October 2025. Further refinement to English-language articles and reviews resulted in 530 records for inclusion. As shown in Figure 1B, annual publication volume increased gradually from 9 in 2000 to 28 in 2025, exhibiting a significant positive linear trend (slope = 0.968 publications per year; R^2 = 0.635; $p < 0.001$). The compound annual growth rate across this 25-year span was 4.6%, indicating steady and sustained growth rather than rapid expansion. Output remained modest and relatively stable between 2000 and 2010 (mean < 15 articles per year), rose incrementally from 2011 to 2017, and showed a more pronounced increase after 2018, reaching a maximum of 47 publications in 2022 before stabilizing at elevated levels during 2023–2025. From a bibliometric perspective, these temporal dynamics reflect a gradual broadening of research attention and methodological diversification, rather than abrupt acceleration or paradigm-shifting growth in the field.

Worldwide Research Cooperation and Productivity

Contributions originated from 55 countries, comprising 34 (61.8%) high-income nations, 15 (27.3%) upper-middle-income nations, and 6 (10.9%) lower-middle-income nations. Figure 2A illustrated the international collaboration

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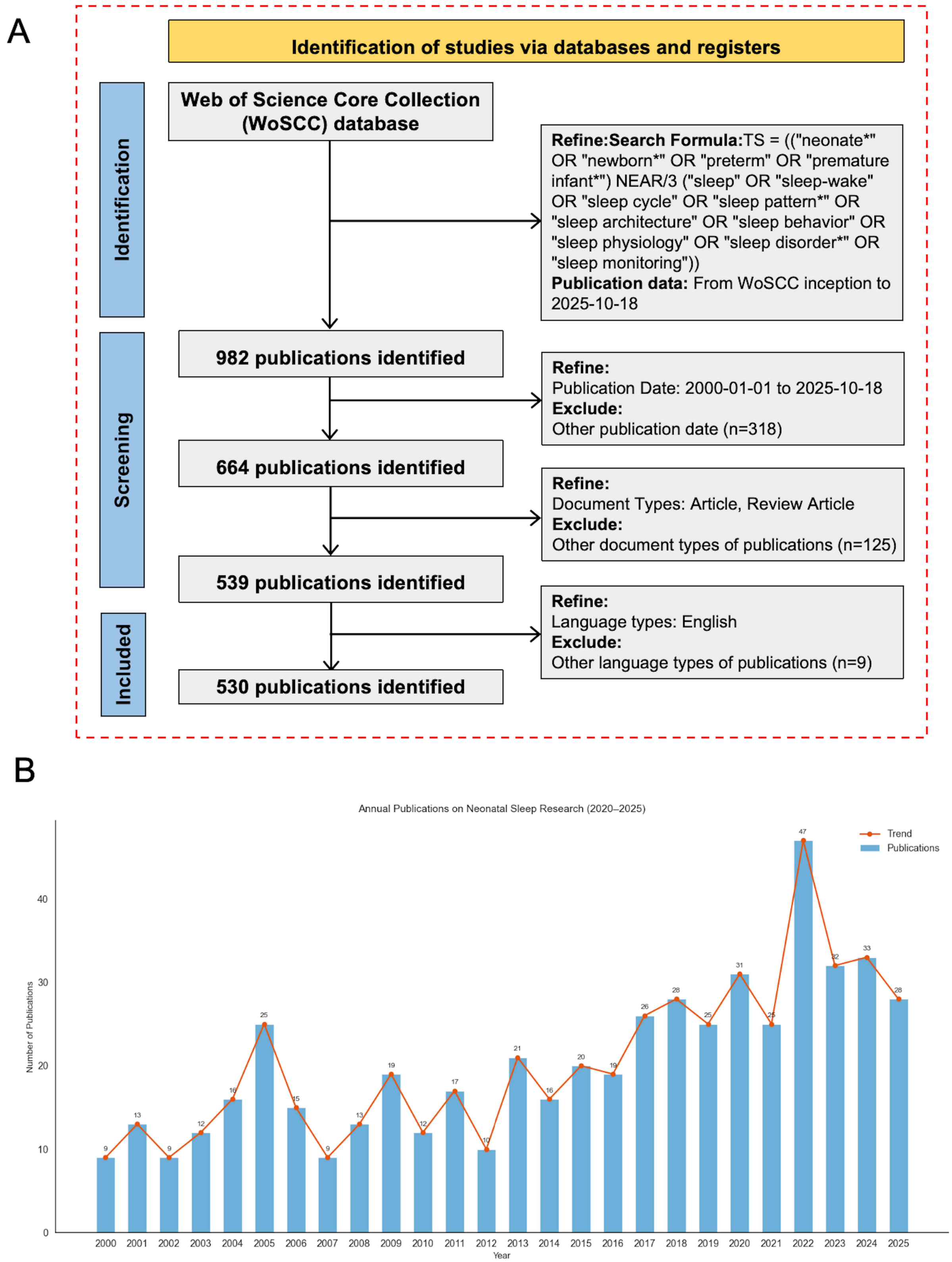

Figure 1 (**A**) Workflow illustrating the process of literature identification and screening in this study. (**B**) Global publication trends in the field of neonatal sleep research.

network, where node size corresponds to publication count and link thickness denotes collaborative intensity. Participating countries clustered into four groups, indicative of varied geographic distributions potentially driven by inter-nation partnerships. The United States (US) led in publication quantity and exhibited extensive global linkages,

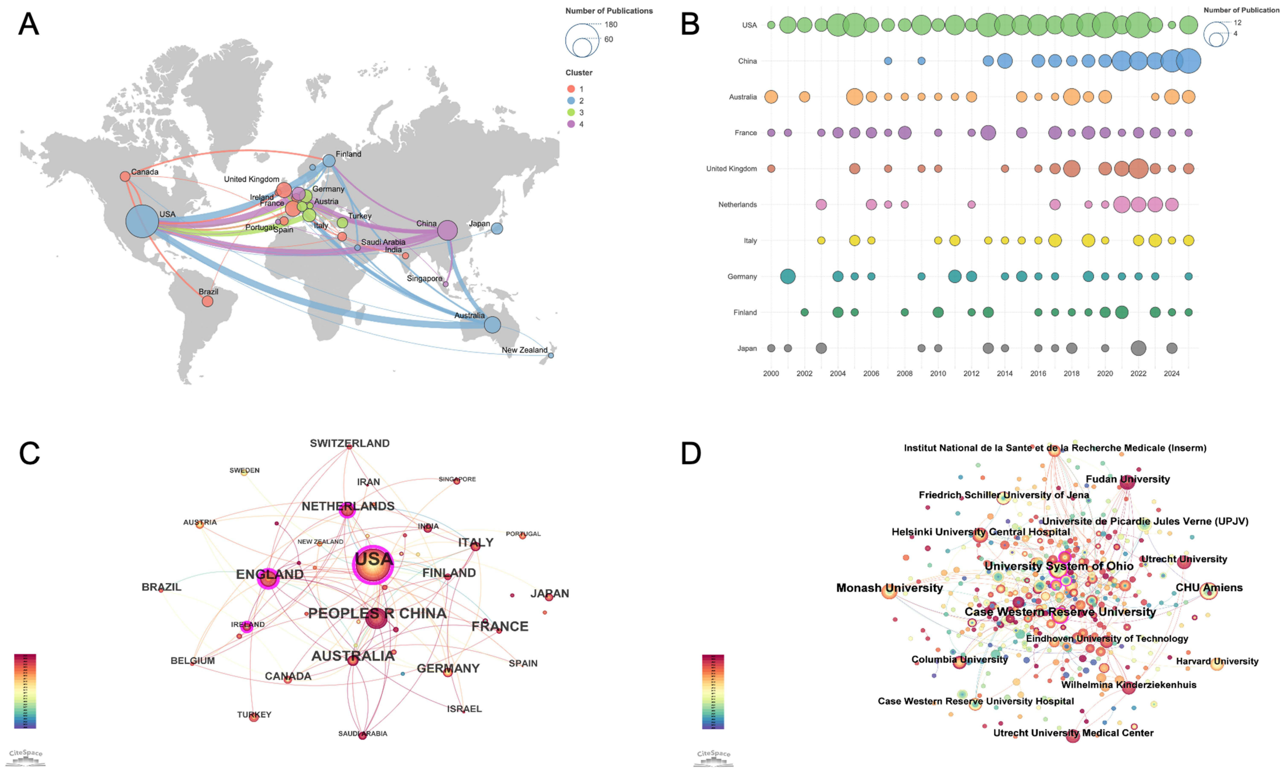

Figure 2 International collaboration patterns in neonatal sleep studies. (**A**) Global map showing collaborative links among countries and regions. (**B**) Publication output trends of the 10 most productive countries. (**C**) Network visualization of international research cooperation. (**D**) Institutional collaboration network in neonatal sleep research.

notably with Finland, China, France, and Australia. China secured the second position in productivity and functioned as a central hub in Asia. European nations, including France, the Netherlands, and the United Kingdom (UK), constituted a tightly interconnected cluster. In aggregate, the network highlights dense cooperation within North America, Europe, Australia, and East Asia, interconnected via transcontinental alliances. Figure 2B depicted annual publication trajectories for the top 10 productive countries over 2000–2025. The US has sustained dominance in neonatal sleep research, with consistent output culminating in a 2022 peak. China has displayed escalating involvement over the last 15 years, overtaking the US in volume during the final three years. European contributors such as France, the UK, and the Netherlands maintained steady engagement, while Italy, Germany, and Finland showed moderate yet persistent activity across the timeframe. Figure 2C presented the country co-occurrence network in neonatal sleep research. The US, bolstered by superior productivity, citation influence, and H-index, assumed a preeminent role, centrally positioned to signify its frequent collaborations and foundational contributions to multinational efforts. China and the Netherlands likewise demonstrated robust co-occurrence connections, emphasizing their substantial participation in worldwide scholarly exchanges.

A total of 438 institutions engaged in neonatal sleep investigations. Figure 2D portrayed the institutional co-occurrence network, elucidating primary collaborative frameworks among entities in this domain. Prominent institutions with robust linkages encompassed Case Western Reserve University, the University System of Ohio, and Monash University. Additional key participants included Fudan University, Helsinki University Central Hospital, and Eindhoven University of Technology, signifying concentrated expertise in major hubs across North America, Europe, and Asia, and underscoring the expansion of international cooperation in neonatal sleep studies. Tables 1 and 2 encapsulated the top ten most productive countries and institutions. The US emerged as the foremost producer and influencer, accounting for 163 publications (30.75% of total) with the greatest network centrality (0.53), indicative of its central function in global partnerships. US-based works garnered 5408 citations, yielding a citation-per-publication ratio of 33.18, the highest worldwide and reflective of exceptional scholarly caliber. China (51 publications, centrality 0.06)

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Table 1 Top 10 Countries with the Highest Research Output on Neonatal Sleep

Rank	Country	Count	Centrality	Citation	Citation per Publication
1	United States	163 (30.75%)	0.53	5408	33.18
2	China	51 (9.62%)	0.06	583	11.43
3	Australia	41 (7.74%)	0.06	900	21.95
4	France	37 (6.98%)	0.01	702	18.97
5	United Kingdom	35 (6.60%)	0.36	771	22.03
6	Netherlands	27 (5.09%)	0.16	662	24.52
7	Italy	26 (4.91%)	0.04	424	16.31
8	Germany	25 (4.72%)	0.02	408	16.32
9	Finland	23 (4.34%)	0.08	731	31.78
10	Japan	20 (3.77%)	0.00	200	10.00

Notes: a Count represented the number of publications, with percentages indicating the proportion of total publications; b Centrality referred to betweenness centrality derived from the collaboration network. It indicated how strongly a country connected other countries, reflecting its influence within international research collaborations; c Citation showed the total number of citations received by publications from each country; d Citation per publication gave the average number of citations per article.

Table 2 Top 10 Research Institutions Contributing to Studies on Neonatal Sleep

Rank	Institution	Country	Count	Citations	Average Citation
1	Monash University	Australia	23 (4.34%)	557	24.22
2	Case Western Reserve University	United States	20 (3.77%)	931	46.55
3	University of Helsinki	Finland	15 (2.83%)	652	43.47
4	Fudan University	China	13 (2.45%)	102	7.85
5	University Medical Center Utrecht	Netherlands	12 (2.26%)	141	11.75
6	University of Jena	Germany	11 (2.08%)	166	15.09
7	University of North Carolina System	United States	9 (1.70%)	274	30.44
8	The University of Sydney	Australia	9 (1.70%)	148	16.44
9	Columbia University	United States	9 (1.70%)	207	23.00
10	Stanford University	United States	9 (1.70%)	313	34.78

Notes: a Count represented the number of publications, with percentages indicating the proportion of total publications; b Citation showed the total number of citations received by publications from each institution; c Average citation gave the mean number of citations per publication.

and Australia (41 publications, centrality 0.06) ranked among top performers, evidencing vigorous recent output and integration into international networks. The leading ten institutions generated 24.53% of the corpus, highlighting the critical influence of select academic entities. Monash University (Australia) topped the list with 23 papers (4.34%) and 557 citations (24.22 per paper). Case Western Reserve University (US) issued 20 papers but amassed the most citations (931, 46.55 per paper), trailed by the University of Helsinki (Finland, 15 papers, 652 citations, 43.47 per paper). Other notable entities comprised Fudan University (China, 13 papers), University Medical Center Utrecht (Netherlands, 12), and University of Jena (Germany, 11). The US featured three institutions in this cohort, collectively demonstrating elevated productivity and impact. Collectively, these organizations form a geographically varied and profoundly impactful assembly within the discipline.

Author Impact and Collaborative Networks

Between 2000 and 2025, a total of 636 authors contributed to neonatal sleep research, with 759 authors being co-cited in the field. Figure 3A illustrated the co-authorship network of prominent researchers. Veronique Bach emerged as the most central figure, exhibiting the highest co-authorship frequency. Jeroen Dudink also showed extensive collaborative activity, while Rosemary S.C. Horne and Wei Chen maintained stable connections with other active investigators. Collectively, these authors occupy the core of the collaborative network, highlighting their influential roles in advancing neonatal sleep research. Figure 3B visualized the author co-citation network generated using CiteSpace. Mark S. Scher

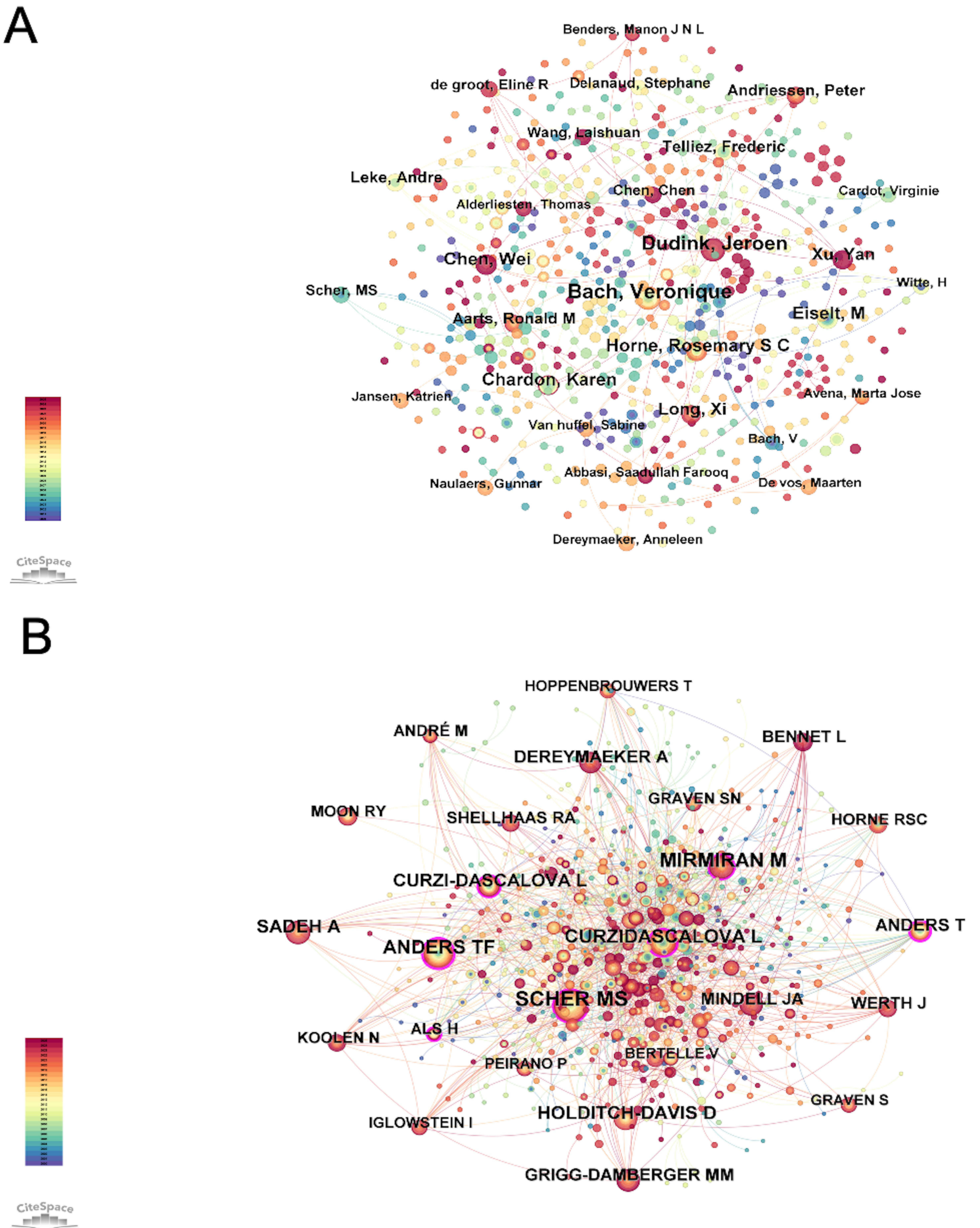

Figure 3 Visualization of authorship and co-citation patterns in neonatal sleep research. (**A**) Network map of contributing authors. (**B**) Co-citation visualization highlighting frequently cited researchers in the field.

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and Lilia Curzi-Dascalova occupied the most prominent positions, reflecting their sustained and influential contributions to neonatal sleep research. Majid Mirmiran and Thomas F. Anders also appeared as highly co-cited authors, indicating wide recognition across the literature. Additionally, Diane Holditch-Davis and Avi Sadeh demonstrated frequent co-citation links, highlighting their continued relevance in shaping the field. Table 3 listed the ten most prolific and frequently co-cited authors in the neonatal sleep research. Together, they contributed 121 publications (22.83% of total) and accumulated over 1,090 citations, indicating a concentrated core of influential researchers. Veronique Bach led with 16 papers (3.02%), followed by André Léké (14, 2.64%) and Jeroen Dudink (13, 2.45%). These leading authors are primarily from France, the Netherlands, Australia, and China, with France contributing the largest share. In the co-citation network, Mark S. Scher (260 citations) and Lilia Curzi-Dascalova (153 citations) were most frequently cited, reflecting their lasting impact. These findings highlight that a small group of highly productive authors drives a substantial portion of the research output and scholarly influence.

Prominent Journals and Citation Patterns

Figure 4A displayed the journal co-citation network in the field of neonatal sleep. *Pediatrics* emerged as the most frequently co-cited journal, occupying a central position within the network. Other journals with high co-citation frequencies included *Sleep, Pediatric Research, Early Human Development, Journal of Pediatrics*, and *Clinical Neurophysiology*. Additional journals such as *Acta Paediatrica, Sleep Medicine, Sleep Medicine Reviews*, and *PLOS ONE* further reflected the field's focus on pediatrics and neonatal sleep science. The dual-map overlay generated by CiteSpace depicted the disciplinary structure and citation pathways in neonatal sleep research. As illustrated in Figure 4B, citation trajectories extend from citing journals on the left to cited journals on the right. Two principal citation routes were observed. Studies published in medical, clinical, and neurological journals primarily referenced works in molecular biology, health sciences, and psychology, whereas publications from psychology, education, and economics journals mainly cited research in health, nursing, and behavioral sciences. This cross-disciplinary citation pattern underscores the dynamic exchange of knowledge between biomedical and psychosocial domains, emphasizing the integrative and multidisciplinary nature of neonatal sleep research. Tables 4 and 5 presented the top 10 most productive journals and co-cited journals in the field of neonatal sleep research. *Sleep Medicine* published the largest number of articles (22, 4.15%), followed by *Sleep* (19, 3.58%) and *Clinical Neurophysiology* (16, 3.02%). Among these, *Pediatrics* had the highest impact factor (IF=6.4) and, along with the others, was classified within Q1 or Q2 quartiles. Co-citation frequency serves as an indicator of a journal's scientific influence. *Pediatrics* was the most frequently co-cited journal (1,039 times), followed by *Sleep* (861) and *Clinical Neurophysiology (including Electroencephalography and Clinical Neurophysiology)* (594). Notably, *Sleep Medicine Reviews* was cited 278 times and held the highest IF (9.7) among the top 10 co-cited journals. All journals in the co-citation list were also within Q1 or Q2 categories, reflecting their strong academic influence in the field.

Table 3 Top 10 Productive and Co-Cited Authors in Neonatal Sleep Research

Rank	Authors	Count	Country	Co-Cited Authors	Citations	Country
1	Bach, Veronique	16(3.02%)	France	Scher, Mark S.	260	United States
2	Léké, André	14(2.64%)	France	Curzi-Dascalova, Lilia	153	France
3	Dudink, Jeroen	13(2.45%)	Netherlands	Mirmiran, Majid	147	United States
4	Horne, Rosemary S.C.	13(2.45%)	Australia	Sadeh, Avi	105	Israel
5	Telliez, Frédéric	13(2.45%)	France	Holditch-Davis, Diane	90	United States
6	Witte, Hanno	11(2.08%)	Germany	Anders, Thomas F.	86	United States
7	Chardon, Karen	11(2.08%)	France	Feldman, Ruth	67	Israel
8	Long, Xi	10(1.89%)	Netherlands	Horne, Rosemary S.C.	66	Australia
9	Chen, Wei	10(1.89%)	China	Moon, Rachel Y	65	United States
10	Delanaud, Stephane	10(1.89%)	France	Mindell, Jodi A.	58	United States

Notes: a Count represented the number of publications by each author, with percentages indicating the proportion of total publications; b Co-cited authors referred to the most frequently co-cited authors alongside the listed author; c Citation showed the total number of citations received by the author's publications.

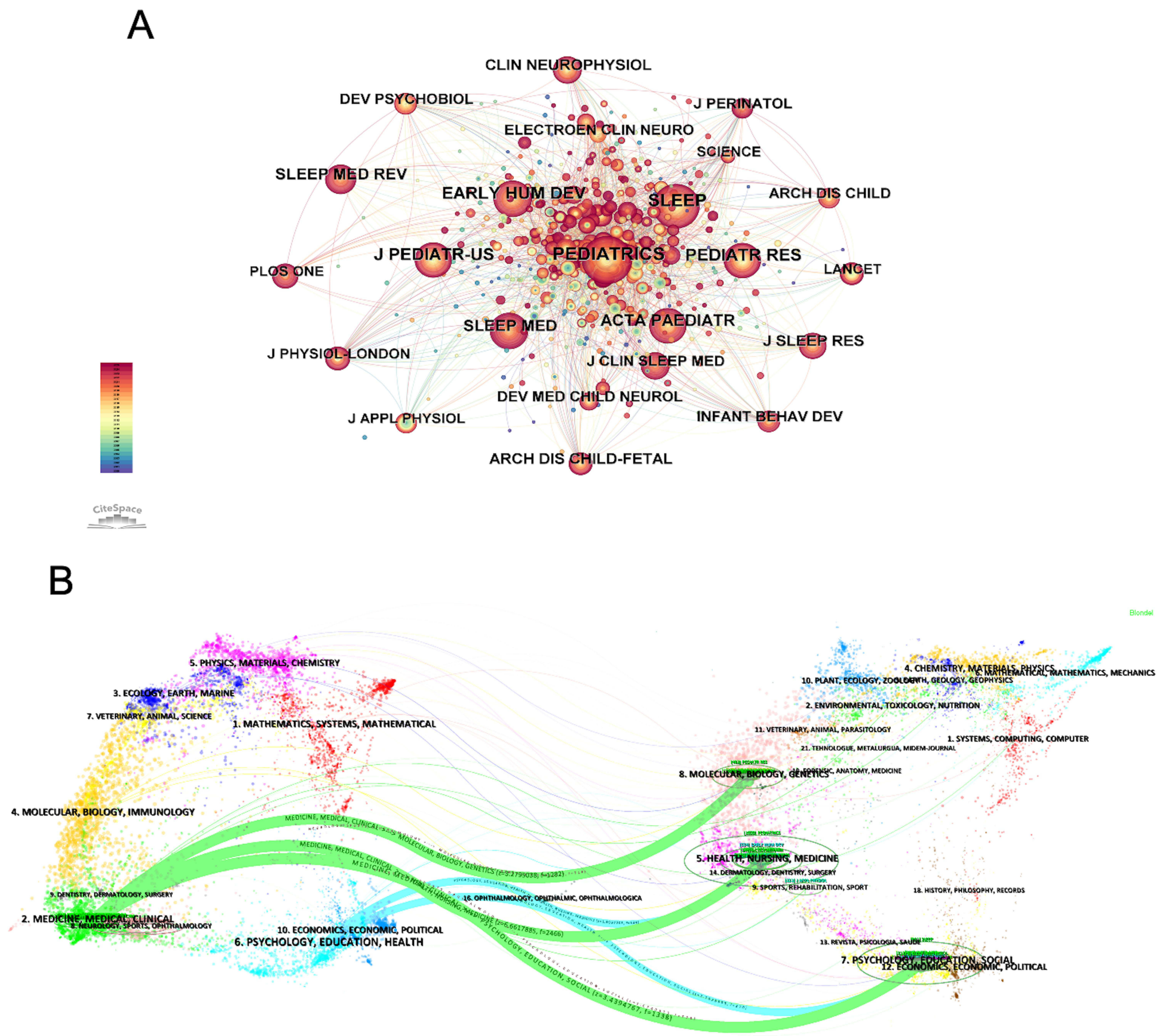

Figure 4 Journal co-citation landscape in neonatal sleep studies. (**A**) Network map of journal co-citation relationships. (**B**) Dual-map overlay showing disciplinary intersections among journals publishing neonatal sleep research.

Key References and Foundational Works

Reference co-citation analysis, a key function of CiteSpace, is frequently applied to uncover major research themes within a given field. Figure 5A displayed the resulting co-citation network of references. Each node represents a highly cited reference, with node size corresponding to its co-citation frequency. Key publications such as Grigg-Damberger MM (2016), Stangenes KM (2017), Werth J (2017) were positioned centrally, followed by Dereymaeker A(2017) and Levy J (2017), reflecting their foundational roles in shaping the discourse on neonatal sleep. The reference co-citation clustering map (Figure 5B) identified ten clusters representing major research themes in neonatal sleep. Cluster #0 (“neonatal”) was the largest and most central, focusing on neonatal sleep physiology and developmental patterns. Clusters #1 (“pediatrics”) and #2 (“neonatal intensive care unit”) emphasized clinical monitoring and interventions in hospitalized infants. Clusters #3 (“sleep position”) and #4 (“preterm”) addressed risk factors and sleep-related complications such as sudden infant death syndrome (SIDS) and preterm sleep maturation. Clusters #5 (“lighting”) and #6 (“sleep disorder”) explored environmental and behavioral determinants of sleep. Clusters #7 (“infant”), #8 (“endophenotypes”),

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Table 4 Top 10 Academic Journals Publishing Research on Neonatal Sleep

Rank	Journal	Count	IF	JCR
1	Sleep Medicine	22 (4.15%)	3.4	Q2
2	Sleep	19 (3.58%)	4.9	Q1
3	Clinical Neurophysiology	16 (3.02%)	3.6	Q1
4	Pediatric Research	16 (3.02%)	3.1	Q1
5	Journal of Sleep Research	16 (3.02%)	3.9	Q1
6	Early Human Development	14 (2.64%)	2.0	Q2
7	Acta Paediatrica	13 (2.45%)	2.1	Q2
8	Journal of Clinical Sleep Medicine	12 (2.26%)	2.9	Q2
9	Journal of Pediatrics	10 (1.89%)	3.5	Q1
10	Pediatrics	9 (1.70%)	6.4	Q1

Notes: a Count represented the number of publications in each journal, with percentages indicating the proportion of total publications.
Abbreviations: IF, Impact Factor; JCR, Journal Citation Reports.

Table 5 Top 10 Journals Most Frequently Co-Cited in Neonatal Sleep Studies

Rank	Co-Cited Journal	Citations	IF	JCR
1	Pediatrics	1039	6.4	Q1
2	Sleep	861	4.9	Q1
3	Clinical Neurophysiology (including Electroencephalography and Clinical Neurophysiology)	594	3.6	Q1
4	Early Human Development	554	2.0	Q2
5	Pediatric Research	483	3.1	Q2
6	Journal of Pediatrics	370	3.5	Q1
7	Acta Paediatrica	346	2.1	Q2
8	Sleep Medicine	328	3.4	Q2
9	Sleep Medicine Reviews	278	9.7	Q1
10	Journal of Applied Physiology	251	3.3	Q2

Notes: a Citations indicated the total number of times each journal was co-cited in the dataset.
Abbreviations: IF, Impact Factor; JCR, Journal Citation Reports.

and #9 ("phase analysis") reflected emerging interests in neurophysiological mechanisms and quantitative sleep analysis, indicating a shift toward mechanistic and data-driven research.

Citation burst analysis identified the 15 references with the most significant citation surges, as illustrated in Figure 5C, reflecting influential publications that gained rapid scholarly attention during specific time periods. The strongest burst was observed for Grigg-Damberger MM et al (2016) (strength = 9.07), followed by Bennet L et al (2018) and Dereymaeker A et al (2017), which emphasized the clinical significance of neonatal sleep-wake cycling as a biomarker of neurological maturation and brain function. More recent bursts from Knoop MS et al (2021), Uchitel J et al (2022), and Bourel-Ponchel E et al (2021) highlighted the growing research focus on automated sleep state detection, advanced neurophysiological monitoring, and the integration of machine learning techniques in neonatal sleep analysis. Table 6 summarized the top 10 co-cited references on neonatal sleep. The article entitled 'Development of fetal and neonatal sleep and circadian rhythms' in *Sleep Medicine Reviews* (IF =9.7) was the most co-cited reference and Majid Mirmiran served as the lead author of the publication.

Keyword Co-Occurrence and Research Hotspots

Analyzing keywords provides an effective approach to delineate the thematic structure and evolutionary trajectory of research within a specific field. As shown in Figure 6A, the keyword co-occurrence network of neonatal sleep research revealed the conceptual core and emerging directions of the discipline. Frequently occurring terms such as "preterm infants," "premature infants," "patterns," "infants," and "children" reflected the predominant clinical and developmental

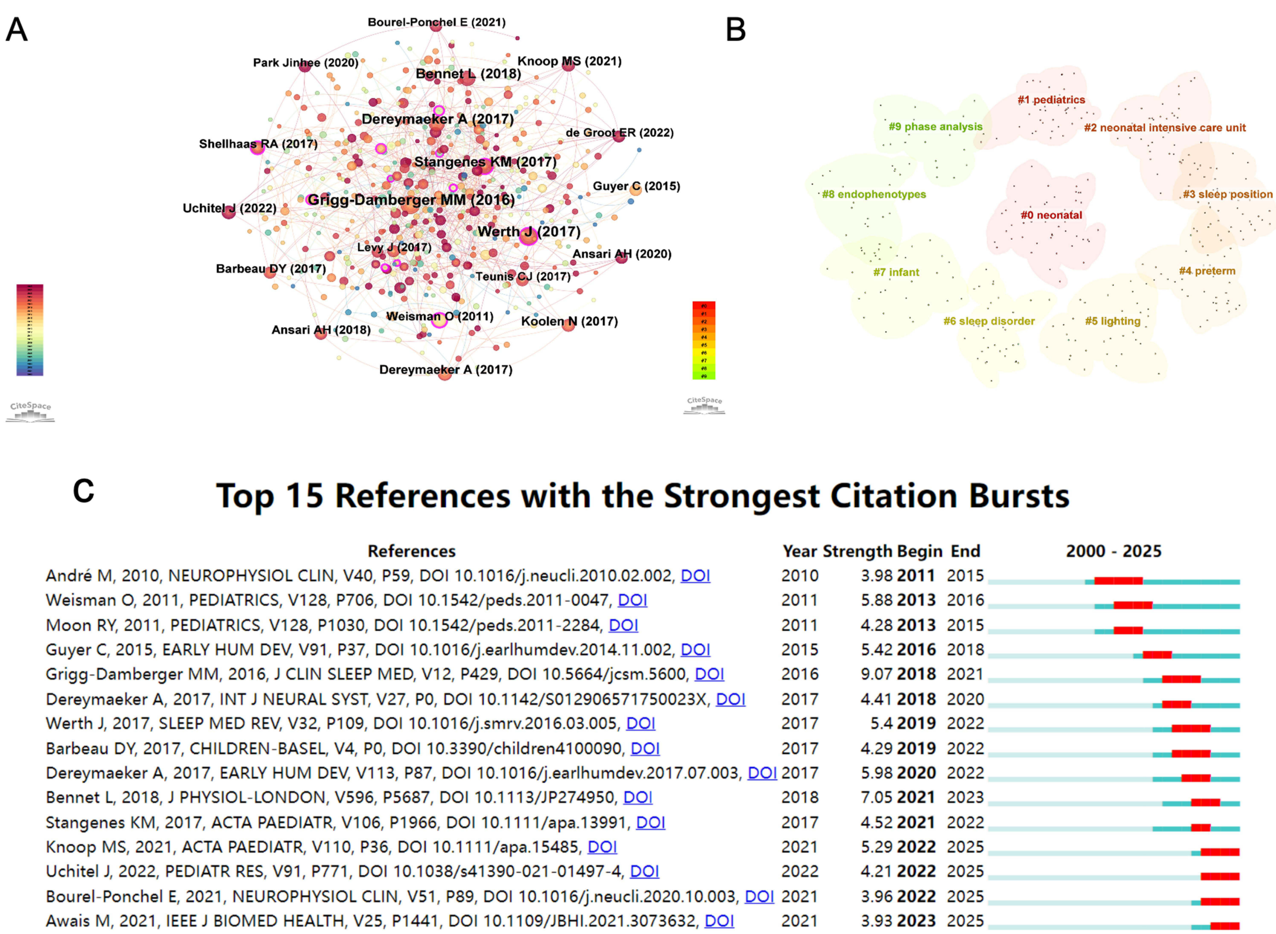

Figure 5 Co-cited reference mapping in neonatal sleep research. (**A**) Network of co-cited literature in the field. (**B**) Cluster visualization of reference groups. (**C**) Top 15 co-cited articles displaying the strongest citation bursts.

focus on vulnerable neonatal populations and sleep maturation processes. Meanwhile, keywords like "states," "behavior," and "EEG" indicated a strong research emphasis on the physiological characterization of sleep-wake states and the application of neurophysiological tools to quantify brain activity.

Table 6 Top 10 Most Highly Co-Cited References in Neonatal Sleep Literature

Rank	Co-Cited Reference	Citations
1	Mirmiran M, 2003, sleep med rev,v7, p321[19]	48
2	Holditch-Davis D, 2004, early hum dev, v80, p43[20]	41
3	Anders T, 1971, manual standardized, v0, p0[21]	40
4	Grigg-damberger MM, 2016, j clin sleep med,v12,p429[1]	35
5	Roffwarg HP,1966, science, v152, p604[22]	31
6	Prechtl HFR,1974,brain res,v76,p185[23]	31
7	Curzi-Dascalova L,1993, pediatr res,v34,p624[24]	30
8	Graven S,2006,clin perinatol,v33,p693[25]	30
9	Curzi-Dascalova L,1996,manual methods recor,v0,p0[26]	30
10	André M,2010,neurophysiol clin,v40,p59[27]	29

Notes: a Co-cited reference referred to a publication cited together with others in the neonatal sleep literature, reflecting its influence on the field; b Citations indicated the total number of times each reference was co-cited in the dataset.

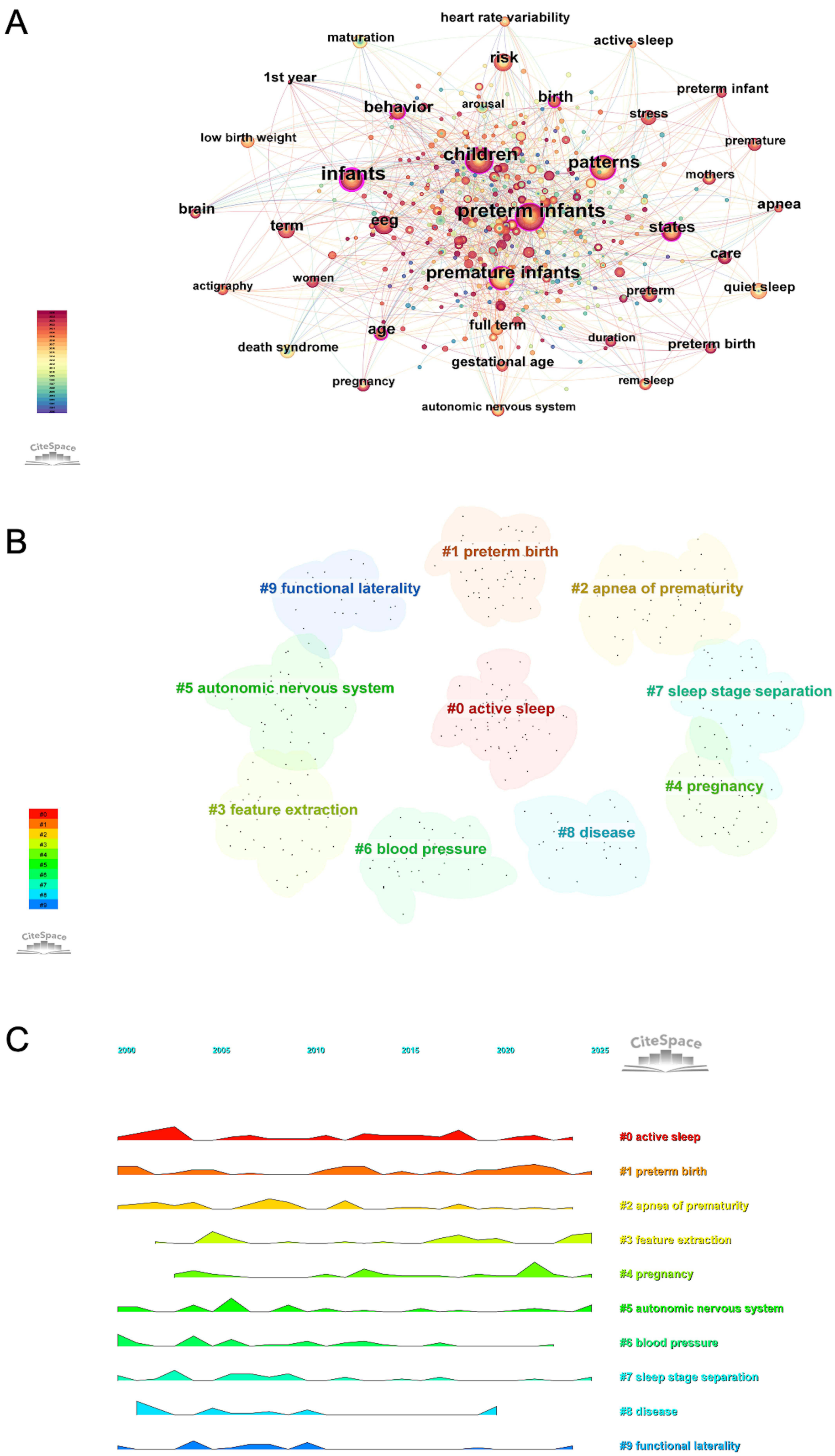

Figure 6 Keyword mapping in neonatal sleep studies. (**A**) Visualization of keyword co-occurrence networks. (**B**) Clustered distribution of related keyword groups. (**C**) Thematic structure and conceptual landscape of research keywords.

As illustrated in Figure 6B, the keyword clustering analysis identified ten major clusters that together depict the structural composition and thematic evolution of neonatal sleep research. Cluster #0 ("active sleep") and #7 ("sleep stage separation") captured the physiological and methodological core, focusing on sleep state characterization, maturation of sleep-wake cycles, and automated state recognition using neurophysiological signals. Cluster #1("preterm birth"), #2 ("apnea of prematurity"), and #8 ("disease") highlighted clinical concerns, emphasizing sleep disturbances and cardiorespiratory instability in high-risk neonates. Cluster #3 ("feature extraction") highlighted the integration of advanced computational and signal-processing techniques to enhance the precision of neonatal sleep assessment. Cluster #4 ("pregnancy") extended the scope of investigation toward prenatal factors influencing postnatal sleep organization, suggesting a growing recognition of the fetal origins of sleep regulation. Cluster #5 ("autonomic nervous system") and #6 ("blood pressure") indicated increasing attention to the physiological coupling between sleep states, cardiovascular regulation, and autonomic maturation, offering new insights into neurodevelopmental homeostasis. Finally, Cluster #9 ("functional laterality") indicated emerging interest in hemispheric asymmetry and early brain specialization. The keyword burst map (Figure 6C) revealed temporal shifts in research focus within neonatal sleep studies. Early investigations were primarily concentrated on clusters #0, #1, and #2, reflecting foundational work on sleep states, preterm birth, and apnea of prematurity. In contrast, more recent studies have shifted toward clusters #3, #4, #5, and #7, highlighting emerging interests in computational analysis, prenatal influences, autonomic regulation, and sleep stage characterization. Notably, cluster #8, which addressed disease-related aspects, has declined markedly since 2020, suggesting a gradual transition in the field's priorities.

Figure 7A presented the timeline of keyword clusters, illustrating the temporal evolution of research themes in neonatal sleep. Cluster #1 ("preterm birth") and Cluster #3 ("feature extraction") have remained consistently prominent, reflecting their foundational role in both clinical and methodological aspects of the field. In contrast, clusters such as #4 ("pregnancy"), #5 ("autonomic nervous system"), and #7 ("sleep stage separation") have gained increasing attention in recent years, highlighting a shift toward prenatal influences, autonomic regulation, and detailed characterization of sleep architecture. Meanwhile, Cluster #8 ("disease") exhibited declining activity after 2020, suggesting a waning focus on this area. Overall, the timeline underscores the dynamic nature of neonatal sleep research, with emerging themes complementing long-standing core topics. The timezone visualization (Figure 7B) provided a detailed perspective on the temporal evolution of research priorities in neonatal sleep. Early studies primarily focused on fundamental developmental issues and exposure pathways, with keywords such as "preterm infants," "infants," and "behavior" dominating the early landscape. Around 2005, attention expanded to include topics such as "patterns," "care," "pregnancy," and "states," reflecting growing interest in clinical management and physiological characterization of sleep. In more recent years, research emphasis has shifted toward methodological refinement and outcome assessment, as indicated by the emergence of keywords like "sleep quality," "pain," and "validation," highlighting a trend toward improving measurement accuracy and linking sleep with broader health outcomes. Figure 8 presented the 15 keywords with the most significant citation bursts, with red bars indicating periods of intensified academic focus. Early bursts, such as "infant death syndrome," reflected initial research attention on neonatal mortality and its association with sleep-related risk factors. In contrast, more recent bursts, including "pain," "sleep quality," and "cognitive development," highlighted a shift toward exploring the broader functional outcomes of neonatal sleep, emphasizing both clinical assessment and neurodevelopmental implications.

Discussion

Global Overview of Research Activity

Research on neonatal sleep has experienced steady growth over the past 25 years. Before 2010, publication output remained relatively stable, followed by gradual increases, with modest surges after 2018 and around 2022. These trends appear to reflect the broader adoption of advanced neurophysiological monitoring, computational approaches, and data-driven methodologies rather than a single triggering discovery.[28] Contributions from 55 countries demonstrate a highly uneven global distribution. The United States leads with 30.75% of total publications and the highest citation impact, reflecting sustained funding, extensive collaborative networks, and long-standing expertise in neonatal neuroscience.[29,30]

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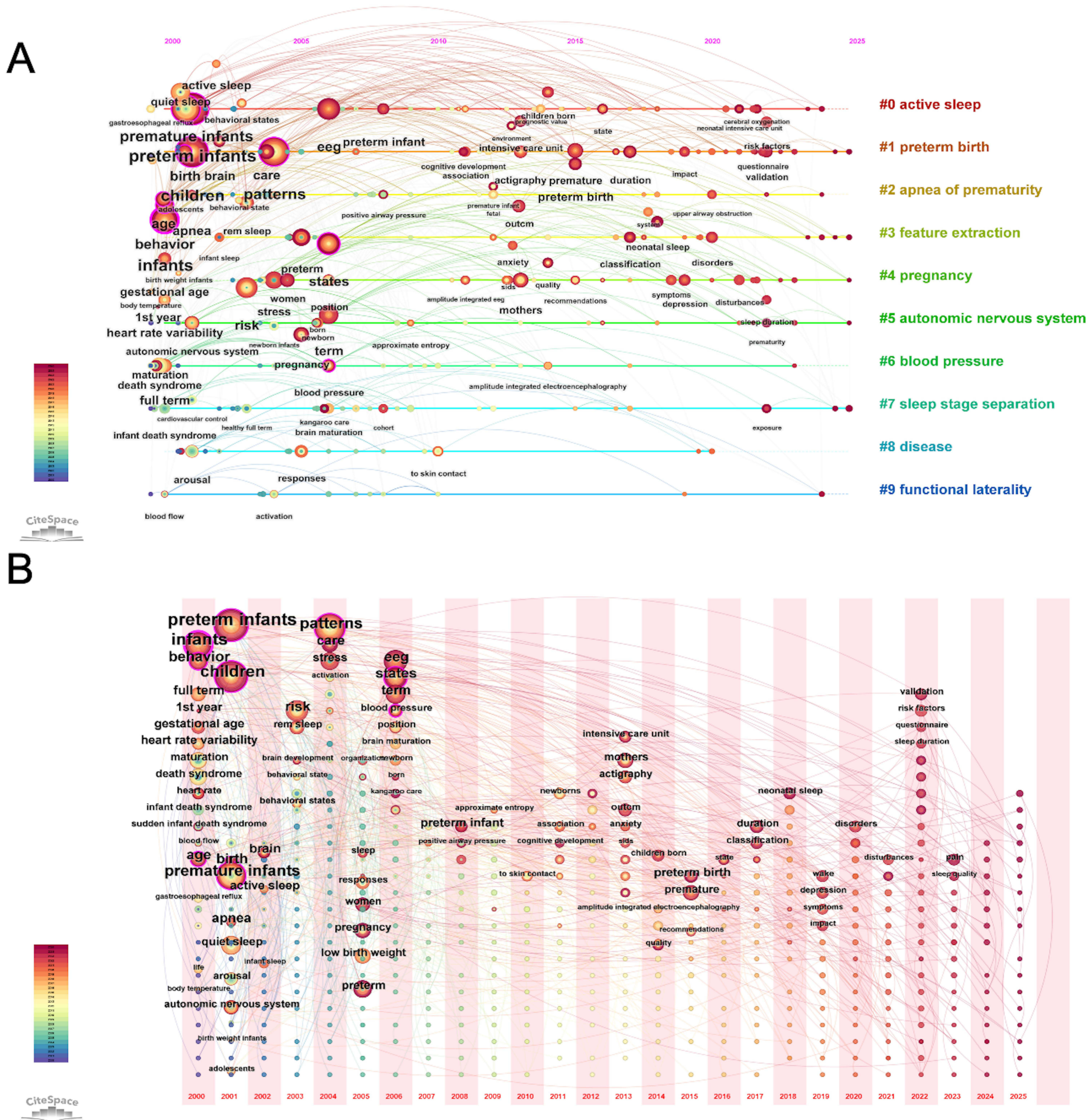

Figure 7 Temporal evolution of keywords in neonatal sleep research. (**A**) Timeline view of keyword clusters associated with the topic. (**B**) Chronological mapping illustrating the emergence and progression of research themes.

China has markedly increased its publication volume over the past decade; however, citation metrics suggest that its international influence is still emerging.[31] European countries, particularly France and the Netherlands, maintain stable output and dense collaboration networks, consistent with established consortia such as the European Neonatal Brain Club.[32]

At the institutional level, Monash University, Case Western Reserve University, and the University of Helsinki have emerged as key hubs. Monash University, through The Ritchie Centre's neonatal neurodevelopment program, has produced 14 peer-reviewed publications addressing neonatal brain injury and strategies to improve outcomes in high-risk infants.[33] Case Western Reserve University, in collaboration with UH Rainbow Babies and Children's Hospital, has

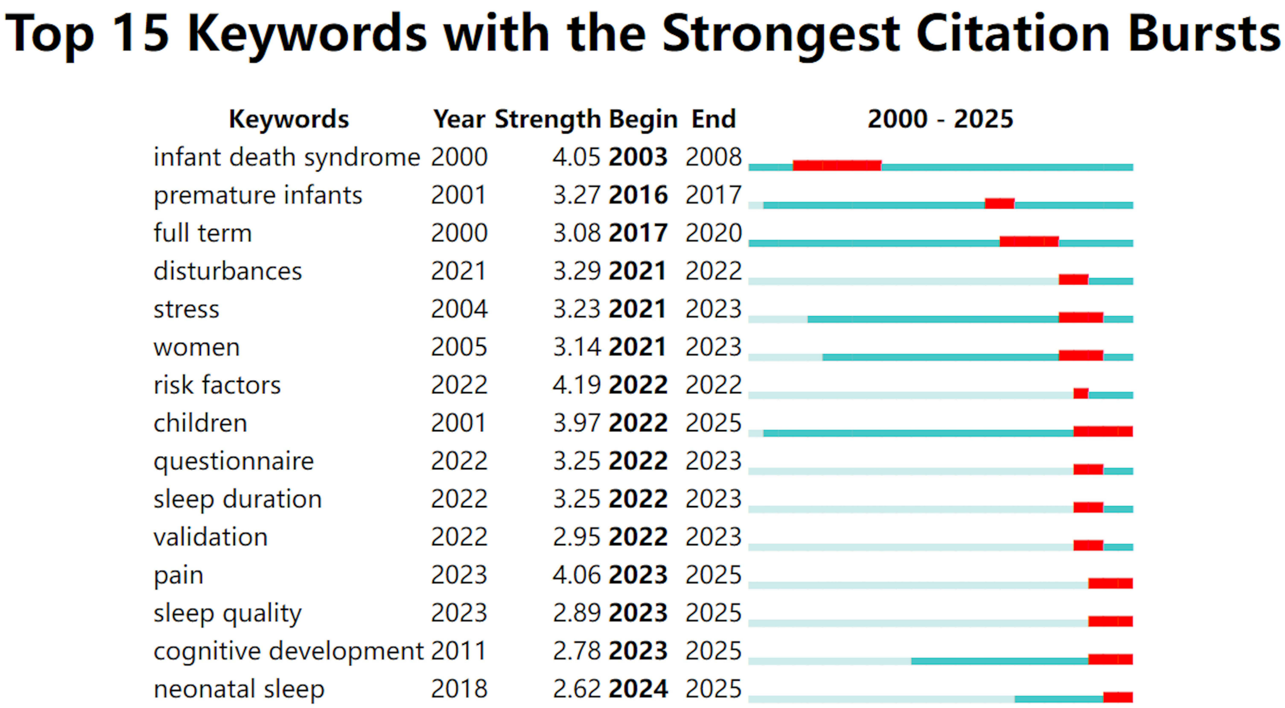

Figure 8 Top 15 keywords demonstrating the most intense citation bursts. Blue segments indicate periods of lower citation frequency, while red segments represent intervals of increased scholarly focus.

advanced translational neonatal research supported by the US National Institutes of Health.[34] These institutions'prominence reflects methodological leadership and network centrality rather than direct evidence of superior clinical outcomes. Contributions from low- and middle-income regions remain limited, highlighting persistent disparities in research infrastructure and funding. Expanding international collaboration, promoting capacity-building initiatives, and establishing open-access data platforms could help reduce these gaps and foster a more inclusive and globally balanced research landscape.

Influential Contributors and Citation Patterns

Bibliometric analysis indicates that neonatal sleep research is concentrated among a small cohort of highly cited investigators. Leading authors such as Véronique Bach, André Léké, and Jeroen Dudink occupy central positions in co-authorship and co-citation networks, shaping methodological standards and research agendas. Bach's publications are frequently cited in studies examining sleep-wake organization and autonomic regulation in preterm infants.[35] Léké's work informs early sleep initiation and physiological regulation,[36] whereas Dudink's contributions focus on associations between early neural activity patterns and subsequent developmental outcomes.[37]

Foundational methodological work by Mark S. Scher and Lilia Curzi-Dascalova, including EEG-based sleep scoring systems, continues to underpin contemporary practice and standardization efforts.[26,38] Rosemary S.C. Horne has contributed extensively to frameworks of arousal regulation.[39] At the journal level, research is concentrated within specialized outlets such as Sleep Medicine, Sleep, and Clinical Neurophysiology, while co-citation patterns highlight Pediatrics, Sleep, and Clinical Neurophysiology as key platforms for methodological consolidation. Collectively, these patterns emphasize that progress in neonatal sleep research has been driven primarily by cumulative methodological refinement, network centrality, and consensus building, rather than direct mechanistic validation, aligning with bibliometric evidence on publication trends, citation patterns, and keyword co-occurrence.[19–21,26,27]

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Emerging Hotspots and Research Frontiers

Bibliometric analysis of neonatal sleep research reveals three interrelated but conceptually distinct hotspots, reflecting the field's evolution from descriptive characterization toward quantitative, integrative, and outcome-oriented investigation. Hotspots capture collective patterns of publication activity, keyword usage, and citation concentration. Analyses of co-occurrence networks, clustering, and temporal bursts suggest a layered evolution in which new research themes build upon established methodological foundations.

Hotspot 1: Automated Neurophysiological Monitoring and Data-Driven Sleep Analytics

Automated neurophysiological monitoring and computational analysis represent the most rapidly consolidating hotspot in neonatal sleep research. Frequent co-occurrence of keywords such as EEG, feature extraction, sleep stage separation, and validation indicates sustained focus on standardized, reproducible analytic approaches. This trend primarily reflects methodological maturation rather than shifts in biological theory. Recent studies emphasize algorithm-based sleep staging, machine learning-assisted EEG analysis, and multimodal signal integration, with convolutional neural networks increasingly applied to neonatal sleep classification, particularly in preterm populations.[15] Dense citation clusters suggest convergence around shared methodological challenges, including reproducibility, scalability, and inter-rater variability.[3,40,41]

Within this literature, automated EEG analysis is commonly used to characterize developmental patterns of neural organization and is discussed in the context of processes such as synaptogenesis and myelination, reflecting interpretive frameworks rather than direct mechanistic validation.[6,42] Similarly, studies integrating EEG with near-infrared spectroscopy or electrocardiography frequently report temporal co-occurrence of sleep-state transitions with changes in cerebral oxygenation or heart-rate variability, supporting integrated physiological narratives without establishing causal coupling.[43,44] Multimodal approaches incorporating EEG, electrocardiography, respiration, or cerebral oximetry highlight the growing interest in comprehensive NICU monitoring systems.[45] Persistent gaps include limited cross-cohort validation and underrepresentation of low-resource settings, underscoring the need to enhance generalizability and translational applicability.

Hotspot 2: Autonomic Regulation, Prenatal Context, and Systemic Framing

The second hotspot reflects increasing emphasis on autonomic regulation within prenatal and systemic contexts. Keywords such as heart rate variability, blood pressure, pregnancy, and physiological regulation indicate a conceptual shift toward integrated, systems-level perspectives. Clustering of sleep-related terms with autonomic and cardiovascular markers suggests that neonatal sleep is increasingly examined within broader physiological frameworks. Neonatal sleep architecture is frequently interpreted as emerging from interactions among prenatal influences, autonomic regulation, and cardiovascular dynamics.[46–48]

Experimental and animal studies indicate that atypical autonomic tone during sensitive developmental windows may influence neural activity patterns and functional organization.[49] Clinical interventions designed to promote physiological stability, including skin-to-skin contact, circadian light regulation, and minimization of noxious stimuli, appear to support both sleep organization and autonomic balance.[50] Bibliometric evidence alone cannot determine whether autonomic changes drive sleep alterations, co-occur with parallel developmental processes, or merely coexist in clinical contexts. Prenatal-related keywords underscore growing interest in fetal and perinatal contributions to postnatal sleep, with maternal stressors reported to affect infant parasympathetic regulation during sleep.[51] Conceptual parallels drawn from broader sleep research offer contextual framing without implying population-specific causal inference.[52] Methodological mapping highlights a growing emphasis on longitudinal, integrative, and multimodal approaches while revealing a scarcity of mechanistic experimental studies, illustrating persistent gaps between descriptive integration and causal understanding.[53]

Hotspot 3: Sleep Architecture, Connectivity Metrics, and Developmental Outcomes

The third hotspot focuses on sleep architecture, connectivity-related metrics, and neurodevelopmental outcomes. Keywords such as functional laterality, connectivity, sleep quality, cognition, and development reflect growing interest in the potential long-term relevance of neonatal sleep patterns. Bibliometric evidence indicates expansion of outcome-oriented research rather than the establishment of validated predictive biomarkers. Highly cited studies report associations between early sleep organization and subsequent neurodevelopment using EEG or neuroimaging.[54–57] Quantitative EEG and sleep metrics are increasingly examined for their associations with early cognitive and motor trajectories. Coherent active-sleep bursts and structured sleep–wake cycling are interpreted as reflecting maturation of corticocortical and thalamocortical circuits.[56] Fragmented or irregular sleep patterns have been associated with delayed myelination, reduced network efficiency, and suboptimal developmental performance.[57] Experimental and translational research suggests that sleep-dependent oscillations may facilitate synaptic pruning, memory consolidation, and long-range connectivity, whereas disruptions may reflect atypical interneuron maturation or glial dysfunction.[56,58] Neuroimaging studies using diffusion and resting-state functional MRI indicate that more organized active sleep corresponds with stronger white-matter integrity and more coherent functional networks.[55]

Integration of EEG-derived connectivity metrics with autonomic and neuroimaging data underscores the potential for multimodal, longitudinal, and computationally informed analyses, although these associations remain largely correlative rather than mechanistic. Machine learning-derived sleep metrics have shown preliminary promise in identifying patterns associated with white-matter maturation.[59] Methodological priorities include cross-cohort comparisons, harmonization of analytic pipelines, and multi-center collaboration to enhance reproducibility, consistency, and interpretability.[60] Remaining gaps include longitudinal follow-up beyond early childhood, integration with functional and behavioral outcomes, and validation across diverse populations. These areas highlight opportunities to develop robust, evidence-informed risk-stratification frameworks.

Synthesis and Implications for Future Research

Collectively, the three hotspots illustrate the field's evolution from descriptive characterization toward standardized analytics, integrative physiological framing, and outcome-oriented investigation. Bibliometric evidence delineates where scholarly attention has concentrated but does not provide direct support for causal mechanisms or clinical efficacy. Structural gaps, including limited cross-cohort validation, predominance of associative studies, and uneven global representation, constrain translational interpretation. Addressing these gaps through longitudinal designs, harmonized pipelines, and careful distinction between research trends and biological inference will be critical for advancing the field. Bibliometric synthesis provides a structured framework to contextualize progress, identify knowledge gaps, and guide future research priorities without overextending conclusions beyond what the data support.

Clinical and Translational Implications

Understanding neonatal sleep carries direct translational significance. Automated neurophysiological monitoring, multimodal assessment, and neuroimaging provide continuous, objective measures of neural maturation and may facilitate earlier identification of infants at risk for cognitive or behavioral impairments. In NICU settings, real-time monitoring of sleep organization and autonomic function supports individualized care, optimization of environmental stimuli, and evaluation of interventions including caffeine administration, non-invasive ventilation, and skin-to-skin care. Machine learning-driven sleep staging exemplifies a shift toward automated, reproducible assessment, providing actionable insights to guide NICU protocols and early neurodevelopmental monitoring. Integration of sleep physiology with autonomic and metabolic indices allows observation of coordinated developmental processes, bridging basic neuroscience and bedside application. Trends highlighted in this bibliometric analysis, particularly prenatal influences and computational analytics, indicate that future neonatal care may increasingly employ individualized, data-informed strategies, promoting early detection, targeted interventions, and improved long-term developmental outcomes.

Strengths and Limitations

This work presented the first thorough and systematic bibliometric investigation of research on neonatal sleep, providing a clear and objective overview that can guide clinicians and researchers in this field. A combination of bibliometric tools was employed to examine major research themes from multiple analytical perspectives. However, several limitations should be recognized. First, the literature search was completed on October 18, 2025, and publications released thereafter were not included. Second, to ensure consistency of citation information and comparability of bibliometric indicators, the

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analysis was restricted to peer-reviewed articles and reviews indexed in the WoS Core Collection. As a result, other publication types, such as books, clinical trial reports, and meta-analyses, were not captured, despite their potential relevance to clinical practice. Reliance on a single database may also have influenced the representativeness of the dataset. In particular, some clinically oriented and translational neonatal sleep studies may be underrepresented, as such work is often indexed preferentially in biomedical databases such as PubMed/MEDLINE rather than the WoS. In addition, limiting the analysis to English-language publications may have led to the omission of relevant research from non-English-speaking regions with active neonatal research programs. These database- and language-related constraints should be considered when interpreting the observed publication trends, collaboration patterns, and geographic distributions.

Conclusions

This study provided a comprehensive overview of global research on neonatal sleep, revealing sustained growth associated with technological advances and increasing interdisciplinary collaboration. Bibliometric analysis identifies several prominent research frontiers, including automated neurophysiological monitoring, autonomic and cardiovascular perspectives on sleep regulation, and the use of sleep-related metrics in relation to brain connectivity. Together, these patterns indicate a shift from predominantly descriptive research toward more quantitative, integrative, and outcome-oriented approaches. Across this literature, neonatal sleep is increasingly viewed as a sensitive indicator of early brain organization and systemic physiological regulation during a critical developmental period. Although current evidence remains largely associative, emerging analytical and multimodal frameworks lay an important foundation for future work aimed at improving early neurodevelopmental monitoring and risk stratification. From a bibliometric perspective, these findings underscore both the growing translational potential of neonatal sleep research and the continued need for rigorous mechanistic validation and clinical evaluation.

Data Sharing Statement

All data used in this study were retrieved from the WoS Core Collection, which is an openly accessible academic database. The bibliometric analysis examined publications concerning neonatal sleep that were published between January 1, 2000, and October 18, 2025. The datasets compiled and analyzed in this research can be obtained from the corresponding author upon reasonable request. Further details or Supplementary Materials supporting the study's conclusions are also available from the corresponding author upon request.

Ethics Approval and Consent to Participate

This study did not generate or collect any new data from human or animal participants. All information used in the bibliometric analysis was obtained directly from the WoS Core Collection, which means that formal ethical approval and informed consent were not necessary. The work complies with the ethical standards and regulations applicable to research based on publicly accessible datasets. If subsequent studies expand on these results and include direct involvement of human or animal subjects, the corresponding ethical reviews and approvals should be secured in advance.

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Author Contributions

Jiahui He: Conceptualization; Methodology; Data curation; Formal analysis; Visualization; Writing-original draft; Project administration. Lingling Xiao: Methodology; Software; Validation; Investigation; Writing-review & editing. Xueqin You: Data curation; Resources; Investigation; Writing-review & editing. Yuxin Liu: Visualization; Validation; Writing-review

& editing. Lili Song: Conceptualization; Supervision; Writing-review & editing. Feng Jiang: Conceptualization; Supervision; Writing-review & editing. All authors gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare no competing interests.

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