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From Night to Light: A Bibliometric Analysis of the Global Research Trajectory of Sleep Disorders in Parkinson's Disease

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Purpose: Sleep disorders are prevalent non-motor symptoms in patients with Parkinson's disease (PD), significantly diminishing the overall quality of life for patients and potentially accelerating the deterioration of motor and cognitive functions, accelerating disease progression. Despite increasing research on sleep disorders in PD, a comprehensive analysis of the knowledge structure and key issues in this field are still lacking. This study aims to identify research hotspots and emerging trends related to sleep disorders in PD through a detailed bibliometric analysis.

Patients and Methods: On October 1, 2024, an extensive search was conducted in the Web of Science Core Collection (WOSCC) database to gather relevant literature on sleep disorders in PD. Bibliometric and knowledge mapping analyses were performed using CiteSpace, VOSviewer, and bibliometrix.

Results: Between January 1, 2004, and October 1, 2024, a total of 3,655 publications on sleep disorders in PD were published by 3,387 institutions across 87 countries. The volume of publications has shown a steady increase, a trend projected to continue. Current research is primarily centered on Neurosciences, Pharmacology, and Clinical Neurology. Emerging trends involve comprehensive evaluations of sleep, early diagnosis and prevention of various sleep disorder subtypes in PD, and advancing research through animal models to develop effective therapies. Emerging keywords include machine learning, sleep quality, biomarkers, covid-19, and mouse model.

Conclusion: This bibliometric analysis sheds light on the global landscape of PD-related sleep disorder research over the past two decades, highlighting key countries, institutions, authors, and journals driving advancements in the field. Moreover, it uncovers pivotal research hotspots and emerging trends, offering valuable insights and guidance for scholars engaged in this area.

Keywords: bibliometric analysis, CiteSpace, Parkinson's disease, REM sleep behavior disorder, restless leg syndrome, sleep disorder

Introduction

Parkinson's disease (PD) ranks as the second most prevalent neurodegenerative condition after Alzheimer's disease, affecting approximately 0.5‰ of the population.[1] Its incidence rises sharply with age, and as global demographics shift towards an aging population, the number of individuals diagnosed with PD continues to surge.[2] In addition to hallmark motor symptoms, non-motor symptoms are highly prevalent in patients with PD, may emerging during the prodromal phase and progressively impacting the entire course of the disease, imposing substantial burdens on patients, caregivers, and society.[3–5] Among these, sleep disorders are particularly common, affecting 60–90% of patients with PD. These disorders not only impair nighttime sleep and reduce daytime quality of life (QoL) for both patients and caregivers, but also accelerate motor and cognitive decline, thereby aggravating disease progression.[6–8] Consequently, a thorough understanding of sleep disorders in PD is vital for enhancing patient outcomes and formulating effective treatments.

Patients with PD frequently experience a range of sleep disorders, including insomnia, sleep-disordered breathing (SDB), excessive daytime sleepiness (EDS), rapid eye movement sleep behavior disorder (RBD), restless legs syndrome (RLS), and

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circadian rhythm disturbances.[9] These conditions exhibit notable individual variability and fluctuate throughout the night.[10] The pathogenesis of sleep disturbances is multifaceted, with PD and sleep disorders exerting reciprocal influences on each other. As circadian rhythms and regular sleep patterns deteriorate, neurodegeneration in patients with PD intensifies.[11] Despite extensive research, mechanisms underlying PD-related sleep disorders remain unclear.[12] These may include neuronal dysfunction, neuroinflammation, glymphatic system impairment, neurotransmitter imbalances, and neurophysiological changes associated with both the dopaminergic and non-dopaminergic systems.[12–15] Studies indicate that diagnosing PD-related sleep disorders presents challenges, with traditional methods relying on questionnaires, video-polysomnography, and consultation with specialized sleep clinicians.[16] Recently, a range of emerging diagnostic tools has advanced the field, including deep learning-based electroencephalographic (EEG) analysis, automated RBD detection systems, and biomarker-driven early diagnostic approaches.[5] Current treatments primarily involve pharmacological and non-pharmacological interventions, while evidence supporting their efficacy remains limited.[17] Thus, understanding the mechanisms and optimizing management strategies for sleep disturbances in PD has become a central focus of contemporary research and clinical practice. In recent years, growing attention has been directed toward the etiology, pathophysiology, clinical presentation, diagnostic criteria, and treatment approaches, contributing to an increasingly intricate body of knowledge.[6] However, a systematic review of the knowledge structure and future development trends within this area remain lacking. Therefore, a bibliometric analysis is crucial to achieving a comprehensive understanding of the current state of research, identifying hotspots, and clarifying future research trajectories in the study of sleep disorders in PD.

Bibliometric analysis is a widely used and robust methodology for exploring and analyzing large datasets of scientific literature.[18] This approach uncovers core concepts, tracks the evolution of research, and identifies underlying relationships within a particular field, offering researchers a holistic perspective on the subject. Additionally, it helps pinpoint research hotspots and emerging trends.[19] In this study, a bibliometric analysis was conducted on publications related to sleep disorders in PD, with a focus on publication volume, citation frequency, and the evolution of key themes. The analysis sheds light on current research trends concerning the mechanisms, diagnostic tools, and treatment strategies for PD-related sleep disorders. It also highlights critical gaps in early disease diagnosis and personalized treatment, particularly regarding the integration of interdisciplinary approaches and the application of emerging technologies. This approach has proven instrumental across various PD-related domains, including biomarkers, accidental falls, depression and anxiety, gut microbiota, and surgical interventions for tremors.[20–24] Despite its widespread application, no bibliometric study has yet been conducted on sleep disorders in PD. Accordingly, this study seeks to identify research hotspots and emerging trends in the study of sleep disorders in PD through systematic bibliometric analysis and knowledge mapping. This will provide researchers a clearer understanding of the field's development while offering theoretical foundations and practical direction for future research.

Materials and Methods

Data Collection

Web of Science is a premier bibliometric database distinguished by its broad disciplinary reach, comprehensive citation indexing, and robust analytical tools. Specifically, the Web of Science Core Collection (WoSCC) database includes high-quality, interdisciplinary journals, and its citation indexing system provides detailed analysis of literature relationships, citation networks, and highly influential publications. These features enable researchers to uncover pivotal research hotspots and emerging trends across various fields. For this bibliometric analysis, we retrieved publications concerning PD and sleep disorders from the WoSCC database. To optimize our search strategy, we complemented the selection of search terms with Medical Subject Headings (MeSH) from PubMed, following a careful review of relevant literature.

On October 1, 2024, we performed a detailed search in the WoSCC using the query: TS = ("sleep disorder*" OR "REM sleep behavior disorder" OR "insomnia" OR "excessive daytime sleepiness" OR "Restless* Leg* Syndrome*") AND TS = (parkinson*). This search yielded 4,629 records, spanning the period from 2004 to 2024. We restricted the document types to Articles and Reviews, excluding retracted publications. After applying these criteria, 3,655 publications were included in the final dataset (Figure 1). The search results were exported in Plain Text File format (Full Record and Cited References) to facilitate data analysis. To ensure the reliability of the dataset, all searches, data extraction, and downloads were conducted on the same day.

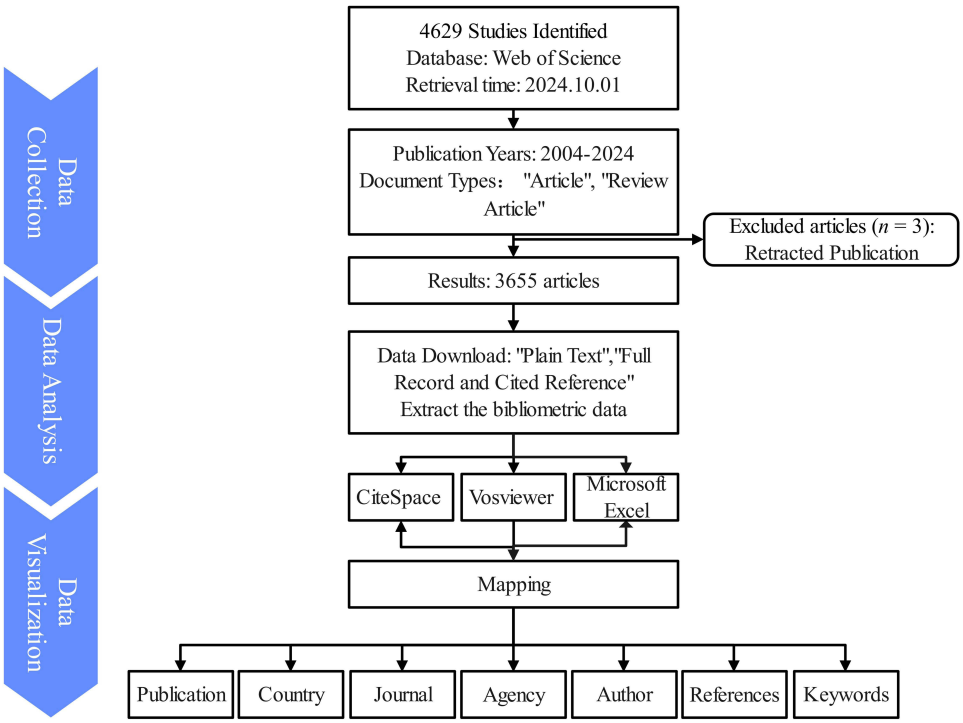

Figure 1 Inclusion and exclusion processes of research on sleep disorders in Parkinson's disease.

These tasks were independently executed by two researchers, with any discrepancies reviewed and resolved through consensus by a third researcher.

Data Analysis

In connection with the the data analysis, CiteSpace 6.3.R1, VOSviewer 1.6.20, Bibliometrix, and Microsoft Excel 2019 were utilized for bibliometric and knowledge mapping analyses. Prior to analysis, data were refined by eliminating duplicate entries in CiteSpace, consolidating synonymous keywords, and discarding irrelevant terms.

VOSviewer

VOSviewer, developed by Nees Jan van Eck and Ludo Waltman at Leiden University, is a widely used free software for bibliometric analysis.[25] It constructs bibliometric networks of keywords, authors, institutions, countries, and journals. The relationships among these elements are visualized through circles and lines of varying size and color, indicating their frequency and interconnections.

CiteSpace

CiteSpace generates key metrics, such as temporal indicators (eg, citation bursts), structural metrics (eg, betweenness centrality), and inter-cluster relationships (eg, cluster dependency).[26] This analysis covered countries, institutions, authors, journals, keywords, and co-cited references.[27] Node size represents the frequency of occurrence, while the thickness of lines signifies the strength of their relationships. Time slicing was set at one year per slice, with the selection criteria were set to g-index with k = 25.

Results

Annual Publication and Citation Growth Trend

The annual trend in research output is a key indicator of global academic activity and impact within a specific field. From the WoSCC 3,655 publications related to PD and sleep disorders were included, collectively cited 154,944 times, averaging 42.39 citations per paper, with an H-index of 156. The annual publication and citation trends from 2004 to

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2024 (Figure 2A) illustrate considerable growth in this research domain. In 2021, 297 articles were published, a fourfold increase compared to 2004 (74), with notable peaks in 2010, 2013, and 2021. Citations peaks were observed in 2013, 2017, and 2022. The correlation coefficient for annual publications (R^2 = 0.8061), indicates steady growth, which is projected to continue.

Further insights from the Average Citations Per Year (Figure 2B) reveal influential papers published in 2005, 2008, 2017, and 2019. These years represent the publication dates, with subsequent citations accumulating thereafter. Among these, a standout paper from 2019 by Postuma et al, published in Brain, titled "Risk and predictors of dementia and parkinsonism in idiopathic REM sleep behaviour disorder: a multicentre study", is particularly noteworthy.[28] This article, based on a 12-year follow-up of 1,280 patients across 24 international REM Sleep Behavior Disorder (RBD) study groups, was the first to establish a significantly increased risk of developing PD, Lewy body dementia, and multiple

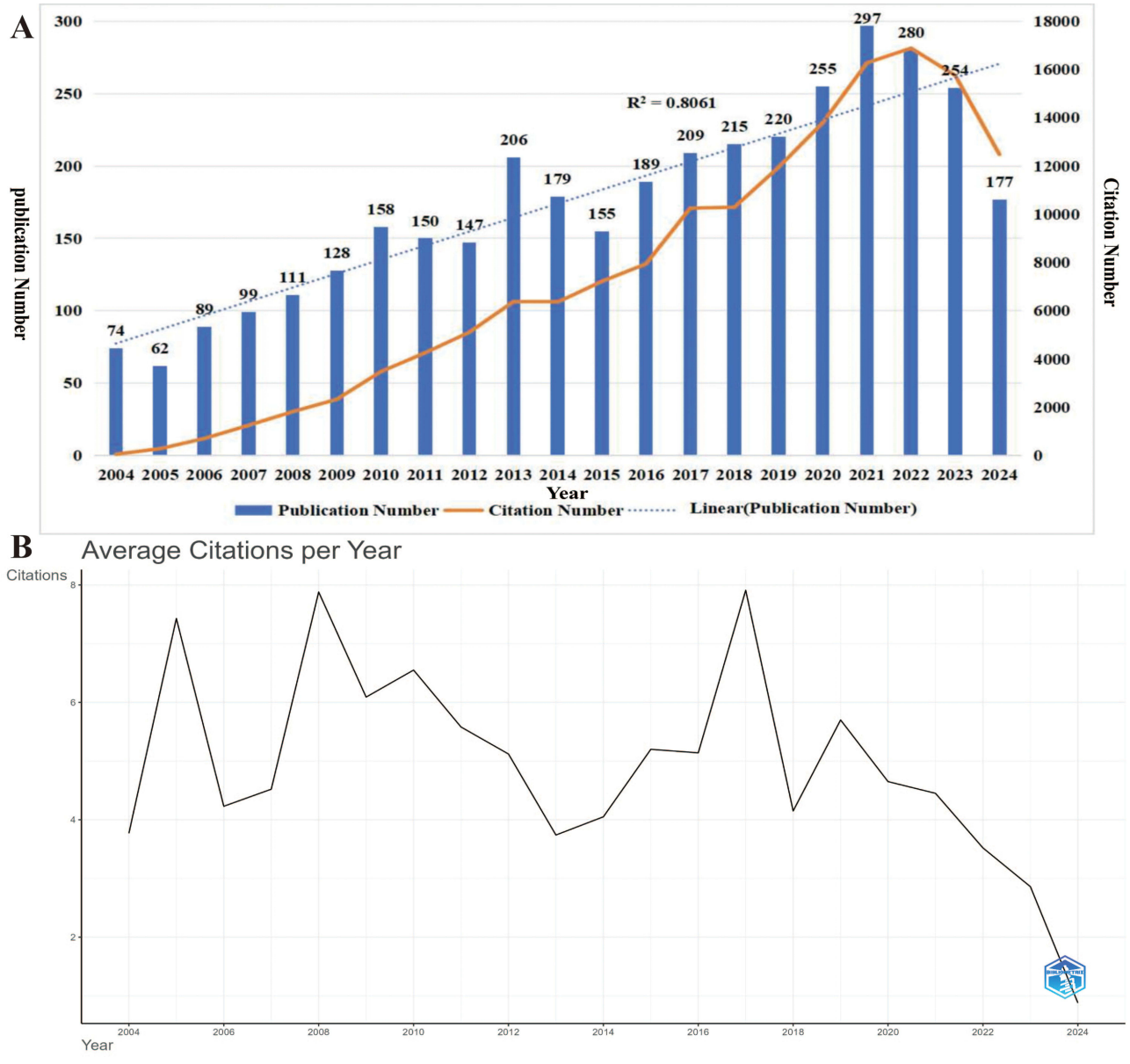


Figure 2 Annual publication and citation growth trend of research on sleep disorders in patients with Parkinson's disease. (**A**) Temporal trends in annual publications and citations related to sleep disorders in Parkinson's disease from 2004 to 2024. The number of publications (bar chart) and citations (solid line) has shown a consistent upward trend, highlighting growing research interest and focus on sleep disorders within the Parkinson's disease population. (**B**) The average citations per year.

system atrophy in patients with idiopathic RBD (iRBD), also identifying early predictors of these neurodegenerative disorders.

Analysis of Countries

Analyzing publications by country provides insights into the most influential nations and highlights the extent of international collaboration. A total of 87 countries contributed to the research. The top 10 countries by publication volume (Supplementary Table S1) were led by the USA (1,010), followed by China (509), and Italy (409). Both the USA and Canada ranked in the top three for citation counts and H-index. The annual publication trends of the top 10 countries (Figure 3A) show that the USA has consistently led in publication volume, while China has experienced rapid growth since 2020.

Betweenness centrality which identifies key hubs connecting different research clusters was measured using CiteSpace (Figure 3B).[29] Purple rings represent centrality scores of ≥0.1. Three countries—USA (0.30), France (0.20), and England (0.17)—exhibited high centrality, underscoring their pivotal roles in the field. Furthermore, citation bursts, which indicate the most active research contributions by a country, were detected using CiteSpace (Figure 3C). China showed the strongest citation burst (32.99), reflecting its increasing prominence and growing research influence.

Collaboration networks among the 35 countries with at least 14 publications were also analyzed (Figure 3D). The USA emerged as a central collaborator, maintaining strong partnerships with multiple countries, particularly with China, demonstrating the depth of their research cooperation.

Analysis of Institutions

Institutional analysis is essential for identifying leading institutions in a specific field, offering insights into potential academic collaborations and exchanges. In this area, 3,387 institutions contributed to research on sleep disorders in PD. The top 10 institutions by publication volume (Supplementary Table S2) and their annual publication trends (Figure 4A and B) show that the University of London (England), McGill University (Canada), and Mayo Clinic (USA) lead in total publications, annual output, and citation impact. Their research focuses on neuroinflammation, synucleinopathy, and sodium oxybate (Figure 4C). Institutions with the strongest citation bursts (Figure 4D) indicate that the University of Cagliari (Italy) and Capital Medical University (China) are currently experiencing significant citation bursts, reflecting their active research engagement and growing influence. The earliest burst was seen at the University of Bergen in 2004, while Dokkyo Medical University had the longest-lasting burst from 2008 to 2015. The University of Copenhagen recorded the strongest burst intensity (9.44).

Collaboration analysis among 32 institutions with over 32 publications (Figure 4E) revealed the strongest partnership between Université de Montréal and McGill University in Canada. In China, Capital Medical University and Shanghai Jiao Tong University demonstrated close collaboration. However, international collaboration in this field remains underdeveloped and represents an area for potential growth.

Analysis of Authors

Author analysis is instrumental in identifying key experts within the field, facilitating future collaborations and academic exchanges. The top 10 authors (Supplementary Table S3) and the timeline of their publications (Figure 5A) reveal that Ronald Postuma and Jean-Francois Gagnon from Canada are prolific contributors with considerable impact and long-standing influence in the field.

The top 10 authors with the strongest citation bursts (Figure 5B) show that Werner Poewe from Austria had both the longest and strongest citation burst (2006–2015, strength: 10.08). Monica Puligheddu and Michela Figorilli from Italy are currently experiencing significant citation bursts, indicating a surge in their research contributions to sleep disorders in PD. For the top 10 cited authors with the strongest citation bursts (Figure 5C), Fereshtehnejad SM from Canada, Michael J. Sateia, Mitchell G. Miglis from the USA, and Zhang Ye from China are currently experiencing strong citation bursts, suggesting their increasing influence within the academic community.

Collaborative patterns among 139 authors with more than 10 publications were analyzed using VOSviewer (Figure 5D). The authors were grouped into 13 clusters based on collaboration strength and research similarity. The largest cluster (outer red cluster) includes 20 authors, with K.K. Chaudhunk and Chunfeng Liu at the center. The second-largest cluster (green

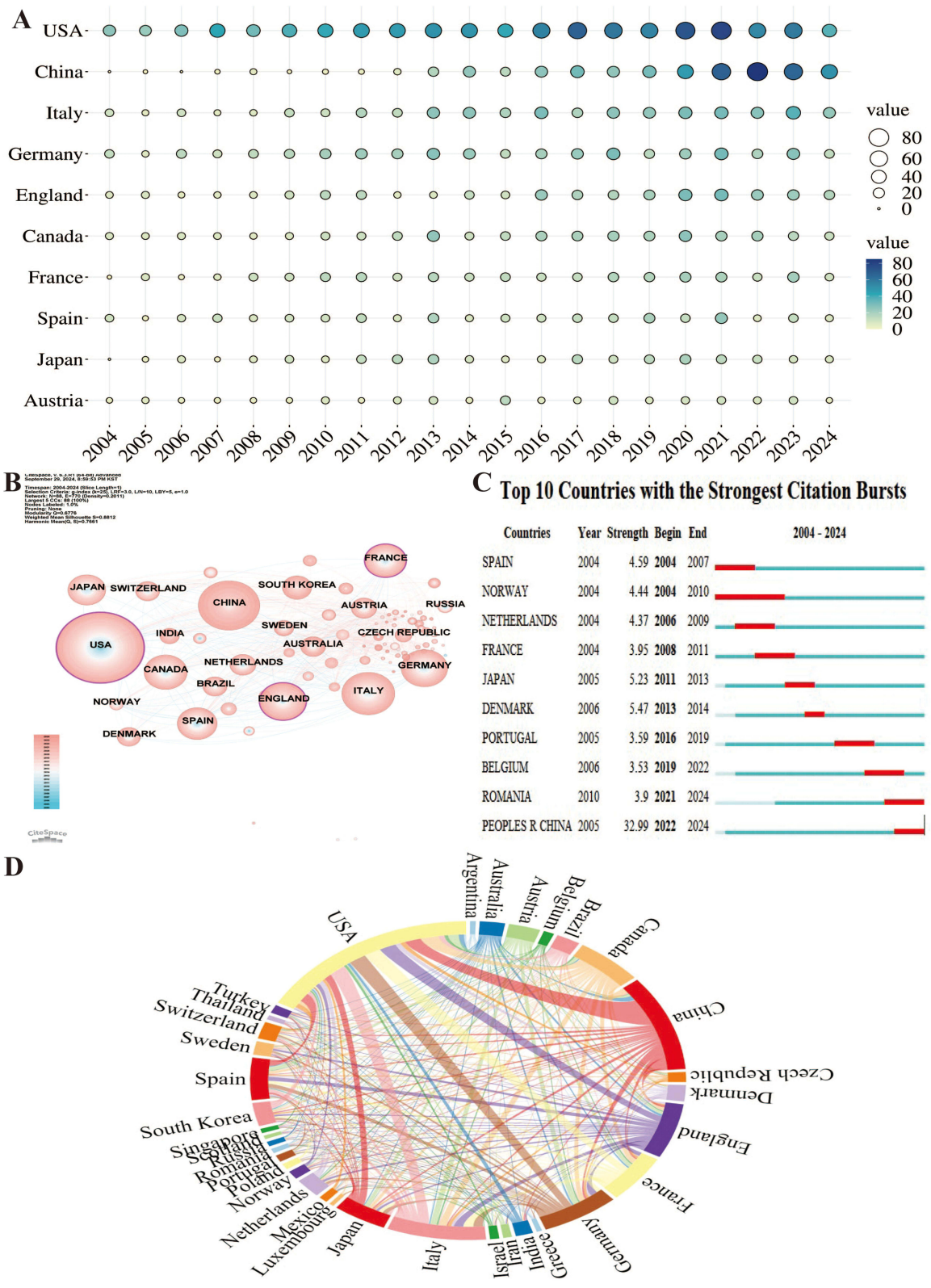


Figure 3 Geospatial analysis of research output on sleep disorders in Parkinson's disease. (**A**) Temporal trends in annual publication output from the top 10 most prolific countries. Node size reflects the annual publication count. (**B**) Co-occurrence network of contributing countries. Node size corresponds to the frequency of co-occurrence, while nodes encircled in purple indicate high centrality (≥ 0.1), signifying influential bridging roles. (**C**) Top 10 countries with strongest citation bursts. (**D**) Collaboration network among countries, where link thickness indicates the strength of collaboration.

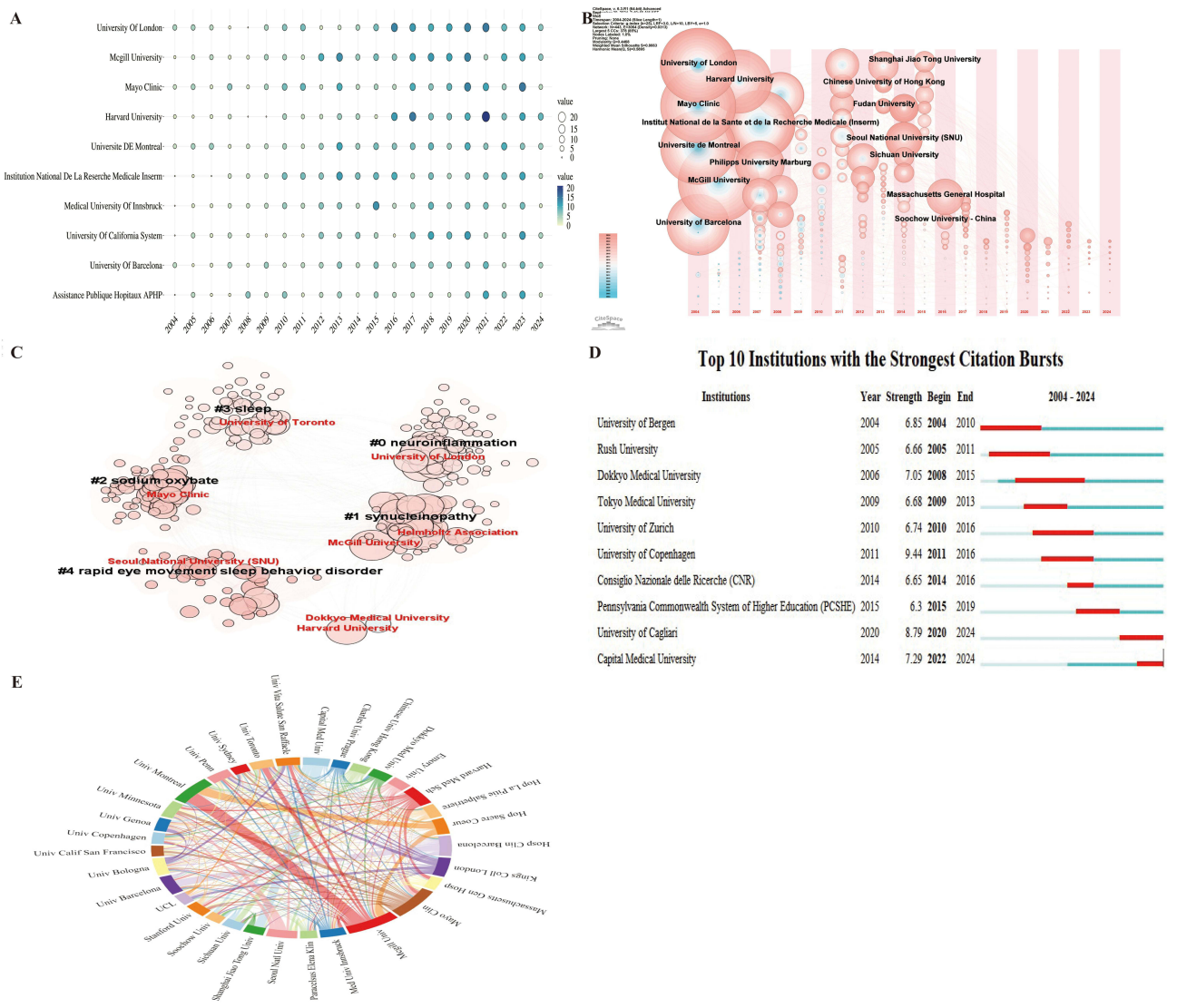
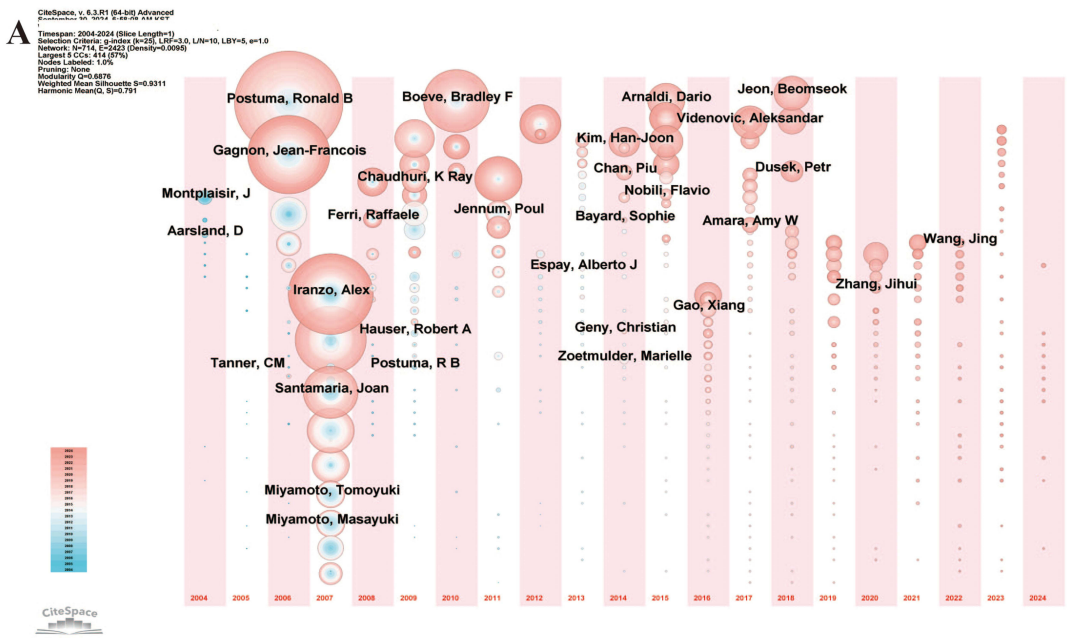


Figure 4 Institutional collaboration network in research on sleep disorders in Parkinson's disease. (**A**) Temporal trends in annual publication output from the top 10 most prolific institutions, with node size reflecting the annual publication count. (**B**) Co-occurrence network showing the timezone of contributing institutions. The horizontal axis represents the year of the institution's first published article, with node size indicating the number of articles published. Blue nodes signify earlier publications, while pink nodes indicate more recent ones. Overlapping colors reflect multiple publications within a given year, with a higher count forming rings, symbolizing continuous and extensive publication activity over time. (**C**) Research focus of the top three influential countries. (**D**) Top 10 institutions with the strongest citation bursts, highlighting periods of notable academic impact. (**E**) Co-occurrence network of contributing institutions, where node colors represent different collaborative clusters. Node size reflects total publication output, and the thickness of links indicates the strength of collaborations between institutions.

cluster) contains 18 authors, centered around Claudia Trenkwalder and Aleksandar Videnovic. The third-largest cluster (blue cluster) is composed of 17 authors, with Dario Arnaldi and Luigi Ferini-Strambi serving as central figures.

Analysis of Journals

Journal analysis provides critical insights into the most active and influential journals in the field of sleep disorders in PD, helping researchers identify appropriate venues for manuscript submissions and stay informed on emerging trends. The top 10 journals by publication volume, as listed in Supplementary Table S4, represent 34.40% of the total 3,655 publications in this domain. According to Bradford's Law of core sources (Figure 6A), Movement Disorders, Parkinsonism & Related Disorders, Sleep Medicine, Neurology, Sleep, Journal of Neurology, Frontiers in Neurology, Journal of Parkinson's Disease, and Journal of the Neurological Sciences are the most influential journals in this field.



B **Top 10 Authors with the Strongest Citation Bursts**

Authors	Year	Strength	Begin	End	2004 - 2024
Montplaisir, J	2004	6.96	2004	2009	
Poewe, Werner	2006	10.08	2006	2015	
Miyamoto, Tomoyuki	2007	7.33	2007	2013	
Miyamoto, Masayuki	2007	7.33	2007	2013	
Hirata, Koichi	2007	7.08	2007	2013	
Frauscher, Birgit	2009	8.46	2009	2015	
Inoue, Yuichi	2009	7.79	2009	2014	
Jennum, Poul	2011	6.03	2011	2014	
Puligheddu, Monica	2020	7.45	2020	2024	
Figorilli, Michela	2018	6.48	2020	2024	

C **Top 10 Cited Authors with the Strongest Citation Bursts**

Cited Authors	Year	Strength	Begin	End	2004 - 2024
FRUCHT S	2004	37.37	2004	2009	
RYE DB	2004	28.96	2004	2010	
COMELLA CL	2004	27.92	2004	2012	
ONDO WG	2004	27.49	2004	2011	
EISENSEHR I	2004	27.11	2004	2013	
FERESHTEHNEJAD SM	2016	29.24	2018	2024	
SATEIA MJ	2018	33.26	2020	2024	
ZHANG Y	2021	34.61	2021	2024	
STEFANI A	2017	30.86	2021	2024	
MIGLIS MG	2022	30.94	2022	2024	

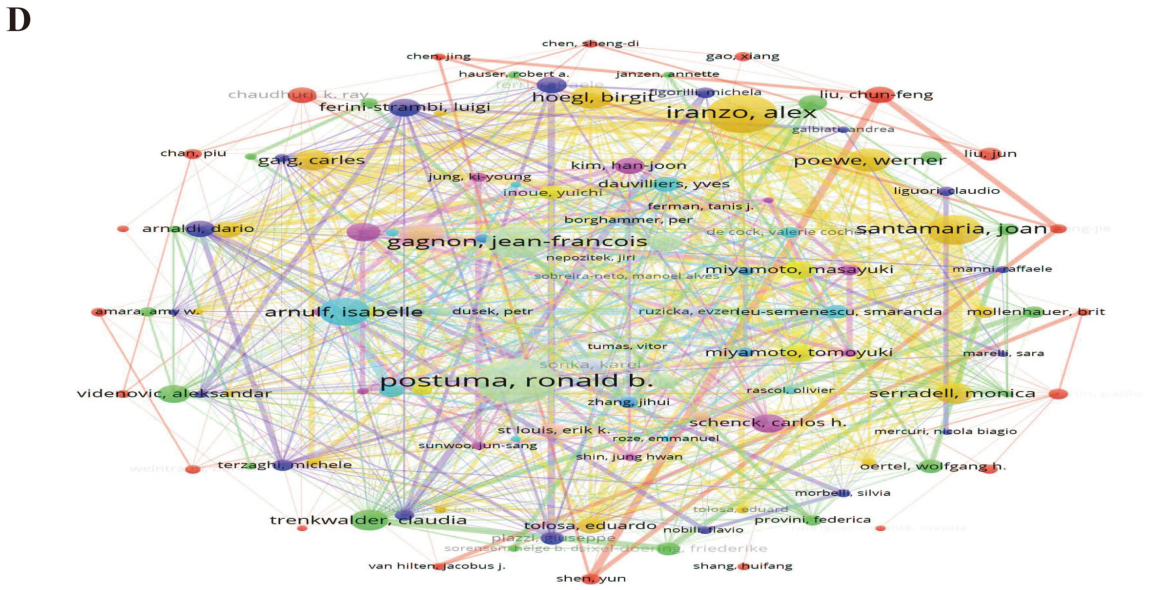


Figure 5 Author collaboration network in research on sleep disorders in Parkinson's disease. (**A**) Co-occurrence network of contributing authors presented in a timezone view. (**B**) Top 10 authors with the strongest citation bursts, highlighting periods of intense academic influence. (**C**) Top 10 cited authors with the strongest citation bursts, showcasing their significant impact over time. (**D**) Co-authorship network of contributing authors in sleep disorder research on Parkinson's disease. Nodes are colored by cluster membership to reflect collaborative patterns, with node size corresponding to the frequency of co-authorship and links indicating co-authored publications between authors.

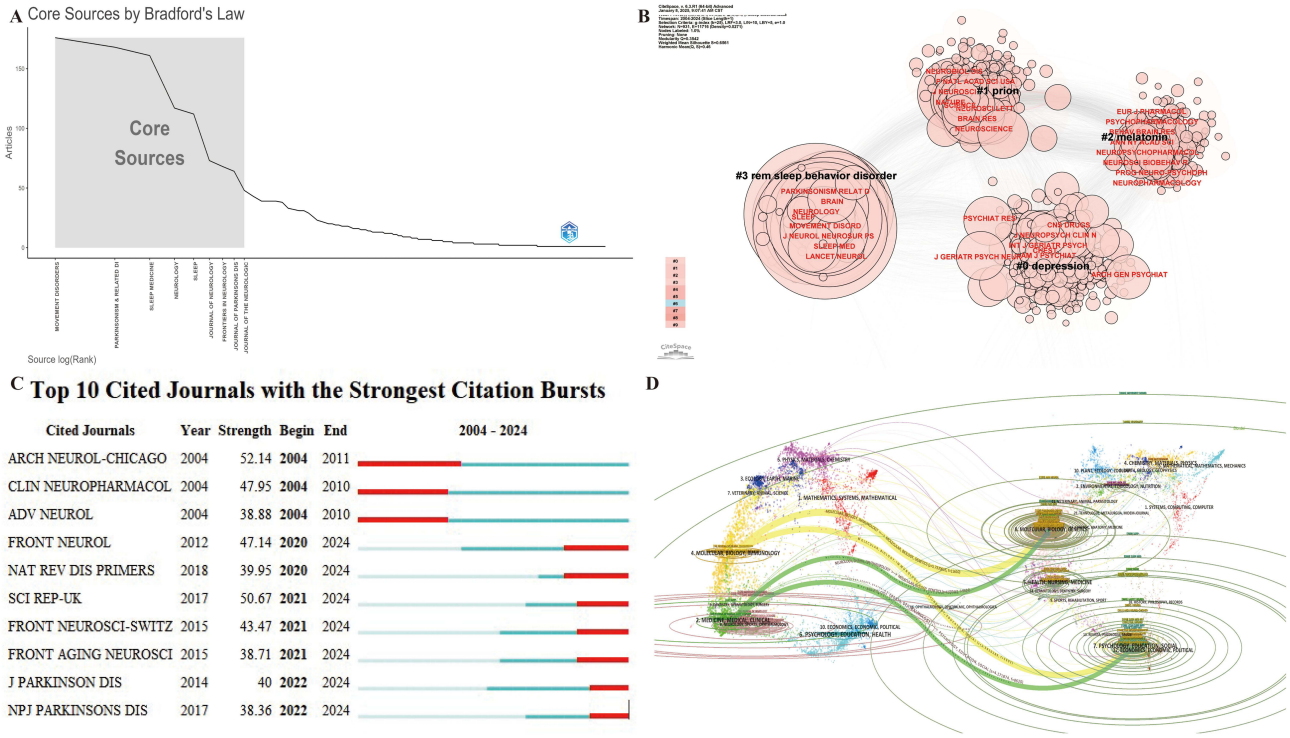


Figure 6 Academic journals related to sleep disorders in Parkinson's disease. (**A**) Bradford's Law according to the academic journals. (**B**) The primary focus of the top three journals. (**C**) Top 10 cited journals with strongest citation bursts. (**D**) Dual-map overlay of the citation landscape in sleep disorders research within Parkinson's disease. On the left, clusters represent citing journal groups, while on the right, clusters represent the most frequently cited journals. Colored lines connecting the two maps illustrate the citation relationships between citing and cited journal clusters.

Notably, five of these journals are ranked in JCR Q1 and four in JCR Q2, indicating that much of the work published in this area is of high quality. The primary focus of the top three journals is on REM sleep behavior disorder (Figure 6B).

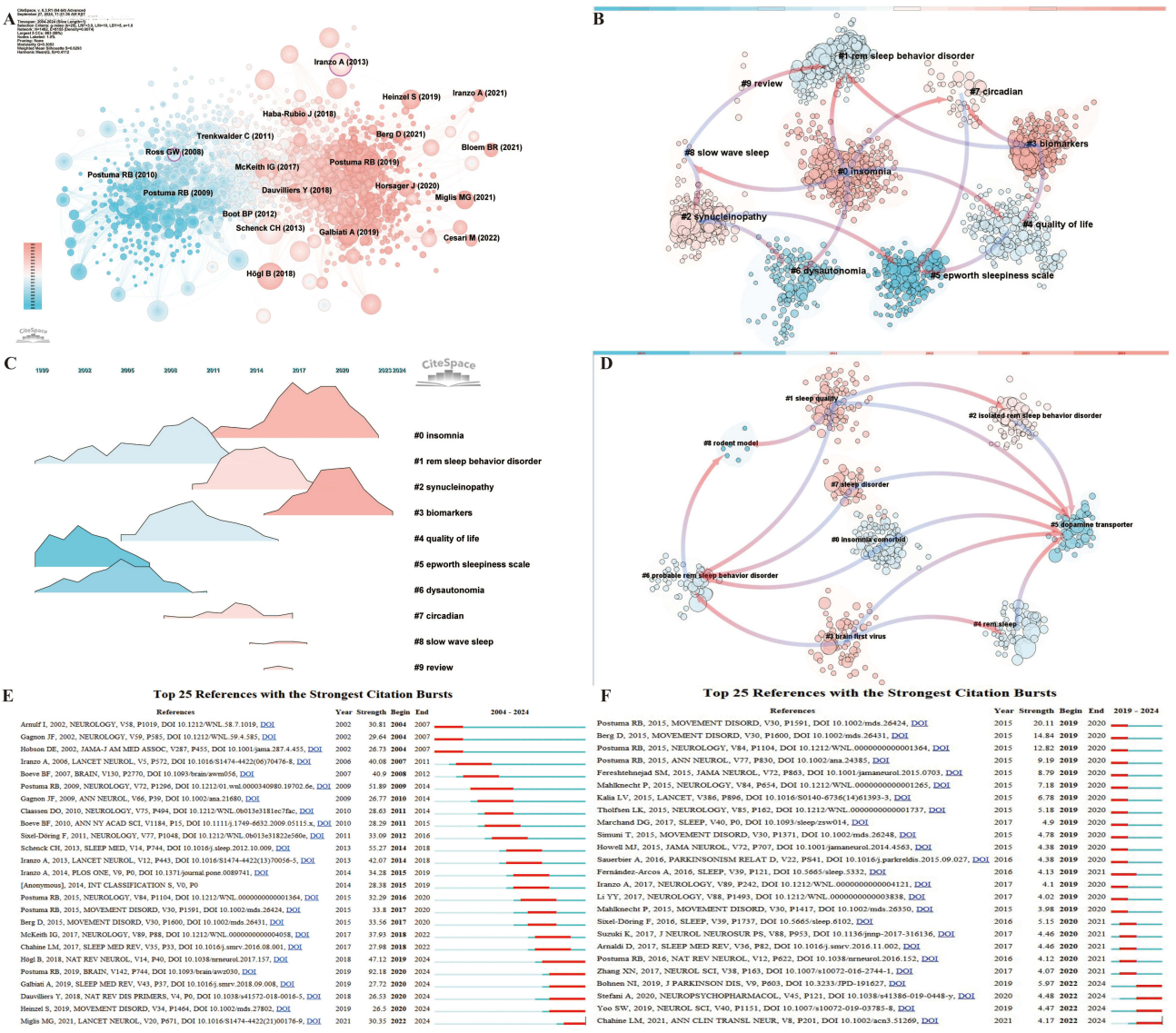
The Top 10 Cited Journals with the Strongest Citation Bursts (Figure 6C) show that seven journals are currently experiencing citation bursts, signaling their pivotal role in disseminating influential research on sleep disorders in PD. These journals include NPJ Parkinson's Disease Nature, Frontiers in Neurology, Journal of Parkinson's Disease, Frontiers in Aging Neuroscience, Frontiers in Neuroscience, Scientific Reports, and Nature Reviews Disease Primers. Their ongoing citation bursts suggest they have published significant work in recent years that continues to shape the field.

The dual-map overlay of journals (Figure 6D) offers a visual representation of citation dynamics. On the left, citing journal categories encompass molecular biology immunology, medicine medical clinical, neurology sports ophthalmology, while on the right, cited journal categories include molecular biology genetics, psychology education and social sciences. The four thickest citation trajectories illustrate a transition in research focus from molecular biology genetics, psychology education and social towards molecular biology immunology, medicine medical clinical, and neurology sports ophthalmology disciplines, reflecting the interdisciplinary evolution of research on sleep disorders in PD.

Analysis of Reference

The analysis of references provides valuable insights into the core studies and key knowledge hubs within a field, shedding light on academic trends and influential works.[21] Among the top 10 most-cited papers (Supplementary Table S5),[30–39] 7 are reviews, and 3 are original research articles. The top three papers, each cited over 3,000 times, address critical topics such as sleep disorders in PD, disease progression, neurodegenerative changes, pharmacological treatments, and economic burdens. A recurring theme in these papers is the discussion of RBD as a prodromal marker of PD.

Betweenness centrality analysis using CiteSpace (Figure 7A) identified two articles with high centrality (≥ 0.1). One particularly significant study, "Neurodegenerative disease status and post-mortem pathology in idiopathic rapid-eye-movement sleep behavior disorder: an observational cohort study" by Iranzo et al, published in Lancet Neurology



E

Top 25 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2004 - 2024
Armulf I, 2002, NEUROLOGY, V58, P1019, DOI 10.1212/WNL.58.7.1019, DOI	2002	30.81	2004	2007	
Gagnon JF, 2002, NEUROLOGY, V59, P585, DOI 10.1212/WNL.59.4.585, DOI	2002	29.64	2004	2007	
Hobson DE, 2002, JAMA-J AM MED ASSOC, V287, P455, DOI 10.1001/jama.287.4.455, DOI	2002	26.73	2004	2007	
Iranzo A, 2006, LANCET NEUROL, V5, P572, DOI 10.1016/S1474-4422(06)70476-8, DOI	2006	40.08	2007	2011	
Boeve BF, 2007, BRAIN, V130, P2770, DOI 10.1093/brain/awm056, DOI	2007	40.9	2008	2012	
Postuma RB, 2009, NEUROLOGY, V72, P1296, DOI 10.1212/01.wnl.0000340980.19702.6e, DOI	2009	51.89	2009	2014	
Gagnon JF, 2009, ANN NEUROL, V66, P39, DOI 10.1002/ana.21680, DOI	2009	26.77	2010	2014	
Claassen DO, 2010, NEUROLOGY, V75, P494, DOI 10.1212/WNL.0b013e3181ec7fac, DOI	2010	28.63	2011	2014	
Boeve BF, 2010, ANN NY ACAD SCI, V1184, P15, DOI 10.1111/j.1749-6632.2009.05115.x, DOI	2010	28.29	2011	2015	
Sixel-Döring F, 2011, NEUROLOGY, V77, P1048, DOI 10.1212/WNL.0b013e31822e560e, DOI	2011	33.09	2012	2016	
Schenck CH, 2013, SLEEP MED, V14, P744, DOI 10.1016/j.sleep.2012.10.009, DOI	2013	55.27	2014	2018	
Iranzo A, 2013, LANCET NEUROL, V12, P443, DOI 10.1016/S1474-4422(13)70056-5, DOI	2013	42.07	2014	2018	
Iranzo A, 2014, PLOS ONE, V9, P0, DOI 10.1371/journal.pone.0089741, DOI	2014	34.28	2015	2019	
[Anonymous], 2014, INT CLASSIFICATION S, V0, P0	2014	28.38	2015	2019	
Postuma RB, 2015, NEUROLOGY, V84, P1104, DOI 10.1212/WNL.0000000000001364, DOI	2015	32.29	2016	2020	
Postuma RB, 2015, MOVEMENT DISORD, V30, P1591, DOI 10.1002/mds.26424, DOI	2015	33.8	2017	2020	
Berg D, 2015, MOVEMENT DISORD, V30, P1600, DOI 10.1002/mds.26431, DOI	2015	33.56	2017	2020	
McKeith IG, 2017, NEUROLOGY, V89, P88, DOI 10.1212/WNL.0000000000004058, DOI	2017	37.93	2018	2022	
Chahine LM, 2017, SLEEP MED REV, V35, P33, DOI 10.1016/j.smrv.2016.08.001, DOI	2017	27.98	2018	2022	
Högl B, 2018, NAT REV NEUROL, V14, P40, DOI 10.1038/nrneurol.2017.157, DOI	2018	47.12	2019	2024	
Postuma RB, 2019, BRAIN, V142, P744, DOI 10.1093/brain/awz030, DOI	2019	92.18	2020	2024	
Galbiati A, 2019, SLEEP MED REV, V43, P37, DOI 10.1016/j.smrv.2018.09.008, DOI	2019	27.72	2020	2024	
Dauvilliers Y, 2018, NAT REV DIS PRIMERS, V4, P0, DOI 10.1038/s41572-018-0016-5, DOI	2018	26.53	2020	2024	
Heinzel S, 2019, MOVEMENT DISORD, V34, P1464, DOI 10.1002/mds.27802, DOI	2019	26.5	2020	2024	
Miglis MG, 2021, LANCET NEUROL, V20, P671, DOI 10.1016/S1474-4422(21)00176-9, DOI	2021	30.35	2022	2024	

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Top 25 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2019 - 2024
Postuma RB, 2015, MOVEMENT DISORD, V30, P1591, DOI 10.1002/mds.26424, DOI	2015	20.11	2019	2020	
Berg D, 2015, MOVEMENT DISORD, V30, P1600, DOI 10.1002/mds.26431, DOI	2015	14.84	2019	2020	
Postuma RB, 2015, NEUROLOGY, V84, P1104, DOI 10.1212/WNL.0000000000001364, DOI	2015	12.82	2019	2020	
Postuma RB, 2015, ANN NEUROL, V77, P830, DOI 10.1002/ana.24385, DOI	2015	9.19	2019	2020	
Fereshtehnejad SM, 2015, JAMA NEUROL, V72, P863, DOI 10.1001/jamaneurol.2015.0703, DOI	2015	8.79	2019	2020	
Mahlknecht P, 2015, NEUROLOGY, V84, P654, DOI 10.1212/WNL.0000000000001265, DOI	2015	7.18	2019	2020	
Kalia LV, 2015, LANCET, V386, P896, DOI 10.1016/S0140-6736(14)61393-3, DOI	2015	6.78	2019	2020	
Tholfsen LK, 2015, NEUROLOGY, V85, P162, DOI 10.1212/WNL.0000000000001737, DOI	2015	5.18	2019	2020	
Marchand DG, 2017, SLEEP, V40, P0, DOI 10.1093/sleep/zsw014, DOI	2017	4.9	2019	2020	
Simuni T, 2015, MOVEMENT DISORD, V30, P1371, DOI 10.1002/mds.26248, DOI	2015	4.78	2019	2020	
Howell MJ, 2015, JAMA NEUROL, V72, P707, DOI 10.1001/jamaneurol.2014.4563, DOI	2015	4.38	2019	2020	
Sauerbier A, 2016, PARKINSONISM RELAT D, V22, PS41, DOI 10.1016/j.parkreldis.2015.09.027, DOI	2016	4.38	2019	2020	
Fernández-Arcos A, 2016, SLEEP, V39, P121, DOI 10.5665/sleep.5332, DOI	2016	4.13	2019	2021	
Iranzo A, 2017, NEUROLOGY, V89, P242, DOI 10.1212/WNL.0000000000004121, DOI	2017	4.1	2019	2020	
Li YY, 2017, NEUROLOGY, V88, P1493, DOI 10.1212/WNL.0000000000003838, DOI	2017	4.02	2019	2020	
Mahlknecht P, 2015, MOVEMENT DISORD, V30, P1417, DOI 10.1002/mds.26350, DOI	2015	3.98	2019	2020	
Sixel-Döring F, 2016, SLEEP, V39, P1737, DOI 10.5665/sleep.6102, DOI	2016	5.15	2020	2021	
Suzuki K, 2017, J NEUROL NEUROSUR PS, V88, P953, DOI 10.1136/jnnp-2017-316136, DOI	2017	4.46	2020	2021	
Arnaldi D, 2017, SLEEP MED REV, V36, P82, DOI 10.1016/j.smrv.2016.11.002, DOI	2017	4.46	2020	2021	
Postuma RB, 2016, NAT REV NEUROL, V12, P622, DOI 10.1038/nrneurol.2016.152, DOI	2016	4.12	2020	2021	
Zhang XN, 2017, NEUROL SCI, V38, P163, DOI 10.1007/s10072-016-2744-1, DOI	2017	4.07	2020	2021	
Bohnen NI, 2019, J PARKINSON DIS, V9, P603, DOI 10.3233/JPD-191627, DOI	2019	5.97	2022	2024	
Stefani A, 2020, NEUROPSYCHOPHARMACOL, V45, P121, DOI 10.1038/s41386-019-0448-y, DOI	2020	4.48	2022	2024	
Yoo SW, 2019, NEUROL SCI, V40, P1151, DOI 10.1007/s10072-019-03785-8, DOI	2019	4.47	2022	2024	
Chahine LM, 2021, ANN CLIN TRANSL NEUR, V8, P201, DOI 10.1002/acn3.51269, DOI	2021	4.17	2022	2024	

Figure 7 Reference analysis in sleep disorders research in Parkinson's disease. (**A**) Co-citation network visualization, where node size represents citation frequency. Nodes encircled in purple indicate high centrality (≥ 0.1), highlighting pivotal works that connect different research clusters. The transition from pink to blue in node color reflects the temporal distribution of publications, with pink denoting more recent works. (**B**) Reference clustering based on semantic similarity, with pink arrows illustrating the primary flow of citations within each cluster. (**C**) Landscape map of reference clusters, providing a visual representation of the research landscape. (**D**) Clustering of references from 2019 to 2024, focusing on semantic similarity to identify emerging trends. (**E**) Top 25 references with the strongest citation bursts from 2004 to 2024. Red bars signify periods of heightened citation activity, spotlighting publications that received intense scholarly focus during specific intervals. (**F**) Top 25 references with the strongest citation bursts from 2019 to 2024, underscoring recent influential works.

(centrality 0.12), has drawn substantial attention.[40] This work underscores iRBD as a key early indicator of neurodegenerative diseases, particularly Lewy body diseases. It emphasizes the importance of long-term follow-up and early intervention for patients with iRBD to potentially slow the progression of neurodegeneration.

Clustering analysis of references was also conducted using CiteSpace (Figure 7B and C). The co-citation cluster analysis spanning 2004 to 2024 (Figure 7B) revealed two dominant research trends in the study of sleep disorders associated with PD. The first trend shows that cluster #1 (REM sleep behavior disorder) evolved into clusters #0 (insomnia), #8 (slow-wave sleep), and #3 (biomarkers). The second trend demonstrates that cluster #5 (Epworth Sleepiness Scale) evolved into clusters #2 (synucleinopathy), #4 (quality of life), and #7 (circadian rhythm), which further evolved into clusters #8 (slow-wave sleep), #3 (biomarkers), and #0 (insomnia). Figure 7C highlights the temporal progression of these clusters, with clusters #0 (insomnia) and #3 (biomarkers) emerging as current research hotspots and trends. In addition, co-citation analysis from 2019 to 2024

(Figure 7D) identified cluster #1 (sleep quality), cluster #3 (brain-first virus hypothesis), and cluster #7 (sleep disorders) as prominent research areas currently.

An analysis of the top 25 references with the strongest citation bursts from 2004 to 2024 (Figure 7E) revealed two papers with the longest burst duration of 5 years, from 2009 to 2014 and from 2019 to 2024. The paper with the strongest ongoing citation burst (92.18) is "Risk and predictors of dementia and parkinsonism in idiopathic REM sleep behavior disorder: a multicentre study" by Postuma et al (2019), published in Brain.[28] Currently, six papers are experiencing ongoing citation bursts,[16,41–45] underscoring the strong link between RBD and PD, particularly the role of RBD as a prodromal symptom and an early diagnostic marker. Further analysis of the top 25 references with the strongest citation bursts from 2019 to 2024 (Figure 7F) indicates that four papers are currently experiencing bursts,[16,46–48] focusing primarily on sleep disorders as prodromal symptoms of PD, factors affecting quality of life, and potential predictors of disease progression.

Analysis of Hotspots and Frontiers

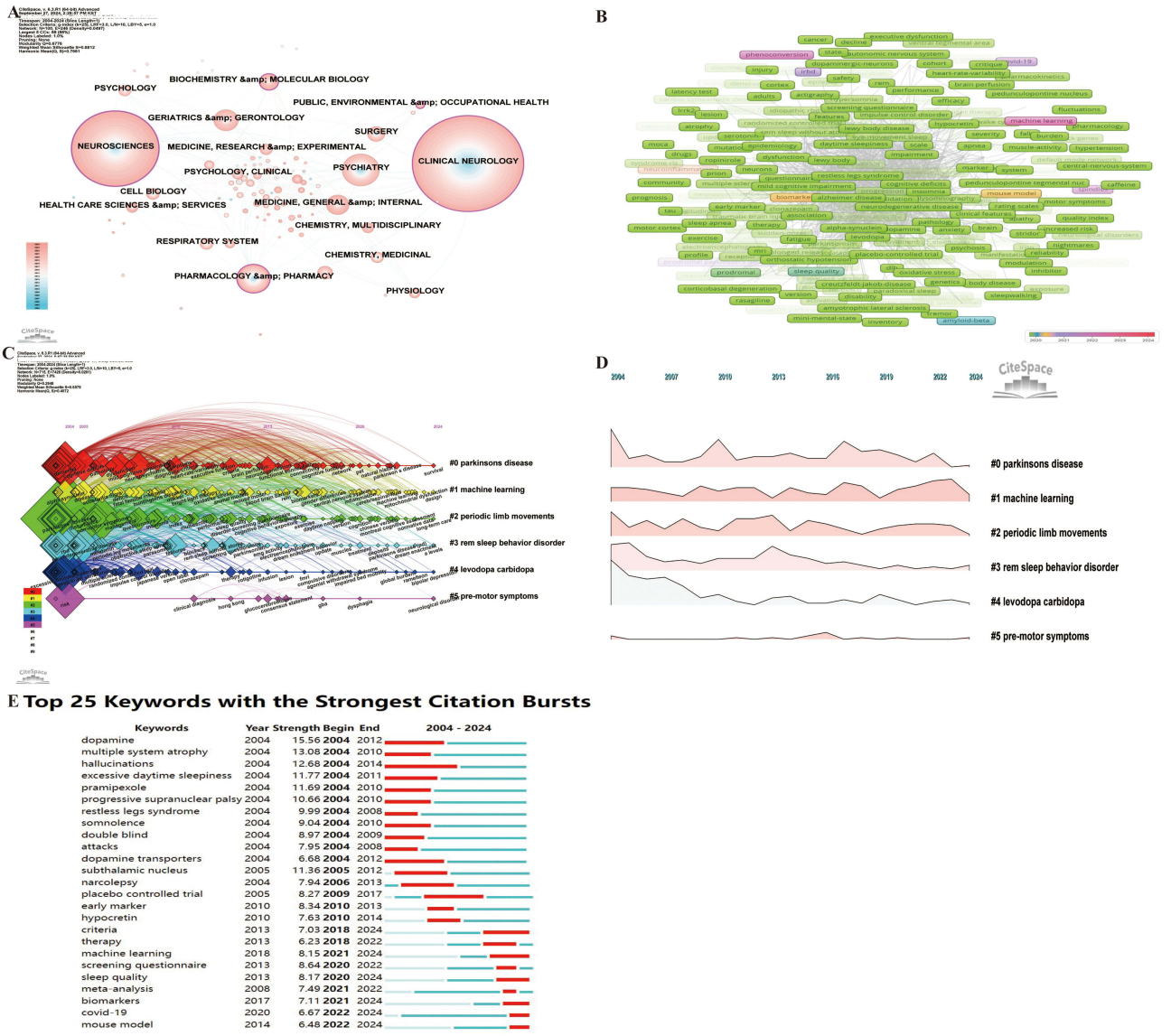
Keyword analysis is a powerful bibliometric tool for tracking the developmental trends and research hotspots in a field. Using CiteSpace for disciplinary analysis (Figure 8A), five categories with high centrality were identified in the study of sleep disorders in PD: Neurosciences (0.38), Pharmacology & Pharmacy (0.20), Clinical Neurology (0.19), Biochemistry & Molecular Biology (0.15), and Public Environmental & Occupational Health (0.11). These disciplines play a pivotal role in driving research advancements in this area.

Keyword frequency analysis conducted with VOSviewer highlighted key terms beyond fundamental concepts like "Parkinson disease", "sleep disorders", "REM sleep behavior disorder", "insomnia", and "excessive daytime sleepiness." The top 10 most frequent keywords were: quality of life (385), diagnosis (378), risk (354), depression (329), Alzheimer disease (315), prevalence (219), alpha-synuclein (215), scale (210), dopamine (206), and validation (193). These keywords suggest three central research focuses: the impact of sleep disorders on the quality of life in patients with PD (quality of life, depression, prevalence), the pathological mechanisms underlying these disorders (Alzheimer disease, alpha-synuclein, dopamine), and the effectiveness of diagnostic and therapeutic strategies (diagnosis, risk, scale, validation).

VOSviewer further examined 421 keywords with a frequency of $\geq$ 10 (Figure 8B), assessing the average appearance year (AAY) of emerging terms from 2020 to 2024. Green-colored keywords appeared predominantly before 2020, while purple and red ones represent more recent trends. Noteworthy emerging topics include machine learning, Covid-19, sleep quality, duration, phenoconversion, spindle, iRBD, biomarkers, connectivity, neuroinflammation, pathogenesis, sex, and gender differences, signaling their growing relevance in the field.

Timeline and landscape analyses of keyword clusters using CiteSpace (Figure 8C and D) revealed that all six clusters remain active. According to Figure 8C, cluster #2 (periodic limb movements) was the earliest to be cited, with initial keywords such as "disturbance" and "non-motor symptoms" evolving into recent terms like "long-term care", "normative data", and "Montreal Cognitive Assessment." The largest cluster, cluster #0 (Parkinson disease), features "survival" as its most recent keyword, while cluster #1 (machine learning) highlights emerging terms like "design" and "mitochondrial dysfunction." Figure 8D illustrates the rapid rise of cluster #1 (machine learning) since 2018, with cluster #0 (Parkinson disease) peaking in 2022 and cluster #2 (periodic limb movements) showing steady growth over the years. These results highlight current research hotspots and emerging trends in the field.

Another significant metric in keyword analysis is burst detection, which helps identify sudden increases in the frequency of keywords, signaling emerging research trends. Using CiteSpace, several keyword bursts were detected (Figure 8E). The longest-lasting burst was for "hallucinations" (2004–2014), while "dopamine" exhibited the strongest burst (15.56). Currently, keywords like criteria, machine learning, sleep quality, biomarkers, Covid-19, and mouse model are experiencing bursts, underscoring their prominence in recent research. These keywords highlight critical areas of focus: the diagnosis and early prevention of sleep disorders in PD (criteria, biomarkers, machine learning), treatment strategies (sleep quality, mouse model), and the impact of Covid-19 on sleep disorders. As highlighted in the study by Miglis et al, biomarkers have the potential to predict the risk of PD development in patients with iRBD.[42] Hunt, Jeremy et al discussed the current status and potential of various genetic and neurotoxin-induced PD mouse models in advancing research on sleep disorders related with PD.[49] Additionally, the research by Taquet, Maxime et al indicated that COVID-19 may exacerbate



E Top 25 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2004 - 2024
dopamine	2004	15.56	2004	2012	
multiple system atrophy	2004	13.08	2004	2010	
hallucinations	2004	12.68	2004	2014	
excessive daytime sleepiness	2004	11.77	2004	2011	
pramipexole	2004	11.69	2004	2010	
progressive supranuclear palsy	2004	10.66	2004	2010	
restless legs syndrome	2004	9.99	2004	2008	
somnolence	2004	9.04	2004	2010	
double blind	2004	8.97	2004	2009	
attacks	2004	7.95	2004	2008	
dopamine transporters	2004	6.68	2004	2012	
subthalamic nucleus	2005	11.36	2005	2012	
narcolepsy	2004	7.94	2006	2013	
placebo controlled trial	2005	8.27	2009	2017	
early marker	2010	8.34	2010	2013	
hypocretin	2010	7.63	2010	2014	
criteria	2013	7.03	2018	2024	
therapy	2013	6.23	2018	2022	
machine learning	2018	8.15	2021	2024	
screening questionnaire	2013	8.64	2020	2022	
sleep quality	2013	8.17	2020	2024	
meta-analysis	2008	7.49	2021	2022	
biomarkers	2017	7.11	2021	2024	
covid-19	2020	6.67	2022	2024	
mouse model	2014	6.48	2022	2024	

Figure 8 Analytical overview of research domains and key terms in the study of sleep disorders in Parkinson's disease. (**A**) Co-occurrence network of research fields and disciplines, where node size reflects citation frequency. Purple nodes represent high centrality (≥ 0.1), indicating influential works that connect multiple research clusters. (**B**) Co-occurrence network of prominent keywords from 2020 to 2024, illustrating key terms driving recent research. (**C**) Timeline map of keyword clusters, showing the evolution of research topics over time. (**D**) Landscape map of keyword clusters, providing a visual depiction of the relationships and structures within research topics. (**E**) Top 25 keywords with the strongest citation bursts, with red bars representing periods of significantly increased citation activity, highlighting emerging trends that garnered considerable academic attention.

sleep disturbances in patients with PD.[31] This aligns with the findings from keyword co-occurrence (Figure 8B) and timeline analysis (Figure 8C), reinforcing their status as key research trends.

The evolution of research within this field can also be traced through the top 25 keywords with the strongest citation bursts. In earlier years, keywords such as dopamine, multiple system atrophy, hallucinations, excessive daytime sleepiness, pramipexole, progressive supranuclear palsy, restless legs syndrome, somnolence, and double-blind were prominent. This phase primarily focused on the major symptoms of sleep disorders in PD, comorbidities, and initial treatment approaches, particularly those involving dopamine dysregulation and excessive daytime sleepiness. As the field progressed, keywords like attacks, dopamine transporters, subthalamic nucleus, narcolepsy, placebo-controlled trial, early marker, and hypocretin gained prominence. During this period, research deepened its investigation into the neurological mechanisms behind sleep disorders in PD, particularly examining dopamine transporters, the subthalamic nucleus, and early biomarkers. In more recent years, keywords such as criteria, therapy, neurodegeneration, screening questionnaire,

sleep quality, meta-analysis, biomarkers, melatonin, mouse model, and neurodegeneration have become central to the research focus. Current studies emphasize establishing diagnostic criteria, developing new therapeutic approaches, understanding neurodegenerative changes, and utilizing screening questionnaires and biomarkers to comprehensively assess sleep quality. Animal models are increasingly used for in-depth exploration of these disorders. These findings align with the co-citation cluster analysis (Figure 7B–D), reflecting a growing understanding of sleep disorders in PD and the continuous refinement of research methodologies.

Discussion

General Analysis

In recent years, the rising prevalence of PD, largely driven by global population aging, has attracted considerable attention. Sleep disorders, one of the most common non-motor symptoms of PD, significantly impact patients' quality of life. Our study analyzed 3,655 articles from the WOSCC database over the past 20 years, focusing on sleep disorders in PD. The number of publications in this area has grown rapidly between 2004 and 2024 ($R^2 = 0.8061$), reflecting increasing interest from the research community, a trend likely to persist. The USA, England, and France have led the field, owing to their robust research funding, leading academic institutions, interdisciplinary collaborations, abundant clinical resources, and advantages in international cooperation. Meanwhile, China has seen a notable rise in research output and influence, especially since 2020. This surge correlates with China's aging population, the increasing number of patients with PD, and heightened attention from Chinese researchers who are addressing this pressing issue.

Institutional analysis highlights the University of London (UK), McGill University (Canada), and the Mayo Clinic (USA) as the most influential contributors. Meanwhile, the University of Cagliari (Italy) and Capital Medical University (China) have shown significant recent research activity, though international collaboration remains an area for improvement. Key authors in the field include Ronald Postuma and Jean-Francois Gagnon from Canada, and Werner Poewe from Austria. High-impact journals include Movement Disorders, Parkinsonism Related Disorders, Sleep Medicine, Neurology, Sleep, Journal of Neurology, Frontiers in Neurology, Journal of Parkinson's Disease, and Journal of the Neurological Sciences. Researchers should focus on these institutions, authors, and journals to stay informed of emerging trends and foster collaboration.

A dual-map overlay of journals indicates a shift in research toward molecular biology, genetics, and psychosocial education. Reference analysis, a critical tool for identifying core studies and knowledge hubs, helps guide future research directions.[21] A key reference in this area is Alex Iranzo's 2013 study, "Neurodegenerative disease status and post-mortem pathology in idiopathic rapid-eye-movement sleep behavior disorder: an observational cohort study",[40] published in Lancet Neurology. This paper, with the highest betweenness centrality (0.12), identifies iRBD as a key early marker for neurodegenerative diseases, particularly Lewy body diseases. The study emphasizes the importance of long-term follow-up and early intervention to potentially slow disease progression in patients with iRBD.

Reference clustering analysis reveals the evolving focus of research over time. In the past five years, prominent research hotspots include cluster #0 (insomnia comorbidity), cluster #1 (sleep quality), cluster #3 (brain-first virus hypothesis), and cluster #7 (sleep disorders). Analysis of the top 25 references with the strongest citation bursts from 2019 to 2024 (Figure 7F) indicates that current research continues to focus on sleep disorders as prodromal symptoms of PD, their impact on quality of life, and their role as potential markers of disease progression.

Analysis of Hotspots and Frontiers

Bibliometric analysis is instrumental in uncovering research hotspots and tracking developmental trends within a given field.[50] Keywords encapsulate the core themes of articles, making keyword analysis a vital tool for identifying trends and focal areas in specific research domains.[18,43] An examination of the Top 25 keywords with the strongest citation bursts (Figure 8E) reveals that early investigations into sleep disorders in PD predominantly focused on core symptoms and initial treatment strategies, such as dopamine, hallucinations, excessive daytime sleepiness, restless legs syndrome, and

somnolence. As research evolved, attention shifted towards understanding the mechanisms behind these disorders, particularly the roles of dopamine transporters and the subthalamic nucleus. From 2010 onward, the emphasis gradually moved to identifying early biomarkers, with more recent studies, particularly since 2018, focusing on refining diagnostic criteria for various subtypes of sleep disorders. In the past three years, keywords such as "machine learning", "sleep quality", "biomarkers", "Covid-19", and "mouse model" have gained prominence, reflecting emerging research directions. Keyword analysis by discipline (Figure 8A) highlights that current research is concentrated in Neurosciences, Pharmacology & Pharmacy, Clinical Neurology, Biochemistry & Molecular Biology, and Public, Environmental & Occupational Health. This distribution illustrates the interdisciplinary nature of sleep disorder studies in PD. It indicates that the research extends beyond a single domain and spans multiple disciplines, each contributing a unique perspective. The interdisciplinary approach highlights the necessity of a comprehensive approach in managing PD-related sleep disorders, one that integrates insights from neuroscience, pharmacology, and public health to optimize treatment strategies and enhance patient outcomes.

The Relationship Between Covid-19 Survivors and Sleep Disorders in Parkinson's Disease

The Covid-19 pandemic, which emerged in late 2019, has had a profound impact on global public health and individual well-being. Increasing evidence suggests that Covid-19 not only affects the respiratory system but also causes long-term damage to the central nervous system, manifesting in symptoms such as sleep disorders, anxiety, and depression.[51,52] Our findings reveal that "Covid-19" remains one of the most frequently cited keywords in recent years (Figure 8E) and continues to be a burst keyword in the co-occurrence analysis for 2020–2024 (Figure 8B). In the keyword clustering timeline, the largest cluster, #0 (Parkinson's disease), includes recent terms like "survival", further indicating its prominence as a research hotspot (Figure 8C and D). Additionally, co-citation clustering analysis shows that cluster #3 (brain-first virus) is the most recent, highlighting its importance as a current focus of research (Figure 7D).

Studies suggest that patients with PD who contract Covid-19 face higher hospitalization and mortality rates compared to the general population, with late-stage or long-term PD individuals experiencing mortality rates as high as 28.6%.[53,54] Among survivors, Covid-19 exacerbates both motor and non-motor symptoms, including pain, anxiety, cognitive impairment, fatigue, and sleep disorders, significantly lowering quality of life. Up to one-third of patients with PD require adjustments to their treatment regimens as a result.[55] Reports also show that during and after the pandemic, the prevalence of anxiety among patients with PD increased from 14% to 66.5%, and those reporting sleep disturbances rose from 35.4% to 68.9%.[56,57]

This exacerbation may be linked to the neuroinflammation and oxidative stress inherent to PD.[1,2] Covid-19 infection triggers systemic and neurological inflammation, with the SARS-CoV-2 virus inducing cytokine storms and activating neuroinflammatory pathways, thereby worsening PD symptoms.[58] Furthermore, the virus binds to ACE2 receptors, which are highly expressed in dopaminergic neurons, potentially aggravating PD symptoms and increasing the demand for dopamine replacement therapy, which in turn may exacerbate sleep disorders.[59,60] Additionally, Covid-19-related anxiety, post-traumatic stress symptoms (PTSS), or post-traumatic stress disorder (PTSD) could further impair sleep, significantly diminishing the quality of life for patients with PD.[61]

While this phenomenon has garnered considerable academic attention, specific interventions remain unclear. Some studies propose that cannabidiol (CBD) might help alleviate sleep disturbances and anxiety symptoms related to Covid-19, though more comprehensive research is needed.

In summary, a complex relationship likely exists between Covid-19 and sleep disorders in PD. Future research should focus on the long-term effects of Covid-19 on sleep disorders in PD, investigating mechanisms such as neuroinflammation, psychological stress, and sleep quality decline. Additionally, identifying effective strategies for managing post-Covid-19 symptoms and improving sleep quality in patients with PD could enhance their overall quality of life and clinical outcomes.

The Bidirectional Relationship Between Sleep Quality and Parkinson's Disease

In recent years, sleep disorders have gained prominence as a key focus in the study of non-motor symptoms of PD. Research suggests that RBD may serve as an early predictor of PD, potentially manifesting years before motor

symptoms, underscoring the need for close monitoring of individuals with this sleep disorder.[62,63] Furthermore, the relationship between sleep disorders and PD is intricate and bidirectional: PD disrupts sleep-wake regulation, resulting in insomnia and excessive daytime sleepiness, while sleep disorders exacerbate motor dysfunction, impair daily functioning, diminish quality of life, and may accelerate cognitive decline, thereby contributing to disease progression and increasing the burden on caregivers.[64–67] Consequently, the effective management of sleep disturbances in patients with PD is critical.

Our findings highlight that "sleep quality" "biomarkers" and "mouse model" remains a highly cited and relevant keyword (Figure 8E). The keyword timeline indicates that cluster #2 (non-motor symptoms) was one of the earliest frequently cited clusters, and its latest keyword, "montreal cognitive assessment", reflects its ongoing significance (Figure 8C). In the co-occurrence analysis from 2020 to 2024, "sleep quality" and "duration" have emerged as keywords with strong bursts, emphasizing their current importance (Figure 8B). Co-citation analysis from 2019 to 2024 identifies cluster #1 (sleep quality) as the most recent (Figure 7D), indicating that sleep quality is a major research focus and trend.

Sleep quality and duration are critical components of sleep disorders in PD.[68] Current assessment methods for sleep disturbances in PD include both subjective and objective measures. Subjective tools such as the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Scale (ESS), and REM Sleep Behavior Disorder Screening Questionnaire (RBDSQ) assess overall sleep quality, daytime sleepiness, and RBD, respectively. Objective assessments include polysomnography (PSG), the gold standard for diagnosing sleep disorders, along with actigraphy, polygraphy, and electroencephalography (EEG).

Animal models have proven invaluable in elucidating the pathophysiological mechanisms underlying sleep disorders in PD. Mouse models, in particular, are able to simulate PD-related sleep disorders to some extent, offering new insights into the nature of these disorders.[69–71] These models are widely used to study sleep abnormalities, circadian rhythm disruptions, and RBD.[72,73] This makes them crucial for testing new therapeutic approaches before clinical application. However, existing models still have limitations in fully reproducing the sleep phenotypes seen in human PD patients.

Interventions for PD-related sleep disorders range from medications—such as modafinil, melatonin, clonazepam, and sodium oxybate—to non-pharmacological treatments, including light therapy, acupuncture, music therapy, complementary and alternative therapies, exercise, and cognitive-behavioral therapy.[74–82] Lifestyle modifications like sleep hygiene education and structured sleep schedules are also recommended.[81,83,84] Additionally, emerging treatments such as deep brain stimulation (DBS), transcranial magnetic stimulation (TMS), and optogenetic therapies show promise in addressing sleep disturbances in PD.[85]

However, the complexity and variability of sleep disorders among patients with PD necessitate tailored intervention strategies, as no single approach effectively addresses all types of sleep disturbances. Future research should focus on specific sleep issues, disease progression, and individual patient factors. A multidisciplinary approach, involving neurologists, sleep specialists, and psychologists, is crucial for understanding the bidirectional relationship between sleep disorders and PD. Such collaboration will facilitate early diagnosis and identification while exploring the long-term efficacy and safety of various interventions. This could pave the way for more precise diagnostic tools and innovative therapeutic targets, ultimately improving patient outcomes and quality of life.

Application of Machine Learning in Sleep Disorders Within PD

With technological advancements, machine learning (ML) has become increasingly prominent in the medical field, enabling the analysis of complex datasets to uncover patterns and trends that enhance diagnostic accuracy and offer innovative approaches to managing sleep disorders in PD.[86–90] Our findings highlight "machine learning" as an emerging keyword (Figure 8E), with co-occurrence analysis from 2020 to 2024 identifying it as a burst keyword (Figure 8B). The keyword cluster timeline shows that Cluster #1 (machine learning) has remained highly active and experienced significant growth in recent years, indicating its importance as a current research hotspot (Figure 8C and D).

ML has played a crucial role in the early detection of sleep disorders and the prediction of disease progression, particularly in the identification of insomnia, RBD, and EDS. Traditional methods, which rely on manual scoring by experts, are both time-consuming and subjective. For example, Deng et al applied a Cox proportional hazards regression model and XGBoost ML on data from 995 patients with PD without excessive daytime sleepiness (EDS) across multiple

centers in China, achieving an accuracy of 71.86% in predicting EDS.[91] This model facilitates early identification and intervention, significantly reducing the time required for diagnosis.

ML algorithms have demonstrated significant potential in the early detection of RBD, a key prodromal symptom of PD, as well as in predicting disease progression. Using electroencephalogram (EEG) data, ML models have detected the transition from iRBD to PD with 90.1% accuracy.[92] Arnaldi et al applied ML to analyze clinical data and presynaptic dopaminergic imaging from the international RBD study group, achieving 77% sensitivity and 85% specificity in distinguishing synucleinopathy-related RBD from non-phenotypically transformed RBD. Moreover, their approach demonstrated 85% sensitivity and 86% specificity in differentiating PD converters from dementia with Lewy bodies (DLB).[93] Similarly, Li et al used ML to detect and monitor PD and iRBD at early stages, attaining an accuracy of 96.9%, providing a promising set of biomarkers for identifying prodromal iRBD and PD individuals.[94] Walter et al leveraged brainstem tractography combined with ML to identify PD subtypes associated with varying severities of REM sleep behavior disorder.[95]

In addition to early detection, ML has demonstrated significant potential in predicting sleep quality and enabling personalized management strategies. Wu et al developed a gradient-boosted tree model using data from wearable devices, patient-reported outcomes, and clinical assessments to predict the PSQI, achieving an impressive R^2 value of 0.83.[96] ML algorithms can also facilitate the creation of personalized sleep management strategies, including intelligent sleep monitoring systems. By analyzing data from smartwatch sensors, researchers were able to measure sleep quality through questionnaires and physiological metrics, identifying the impact of clonazepam on reducing abnormal REM sleep behavior in patients with PD.[97] Rechichi et al employed wearable inertial measurement units (IMUs) to collect sleep data from patients with PD, achieving a 96.2% accuracy rate in detecting sleep patterns and evaluating sleep quality.[98] These results illustrate the effectiveness of wearable devices in monitoring nocturnal motor symptoms in PD and open up new possibilities for personalized sleep analysis and intervention.

ML holds substantial promise in diagnosing, predicting, and managing sleep disorders in PD by extracting critical insights from complex sleep data, enhancing diagnostic precision, and enabling personalized treatment approaches. However, several challenges must be addressed to successfully translate ML technologies into clinical practice, including improving data quality, enhancing model interpretability, and overcoming implementation barriers.[99] Future research should prioritize refining ML model transparency, standardizing data collection protocols, ensuring ethical considerations, and conducting rigorous clinical validations to promote the application of ML in this field. With interdisciplinary collaboration and continuous innovation, ML is well-positioned to revolutionize the management of sleep disorders in PD, ultimately leading to better patient outcomes.

Limitations

Several limitations in this study should be acknowledged. First, since the WoS database is open-access, our analysis does not include newly published papers after the search date, thereby reflecting only the current research landscape. Second, due to the time required for citations to accumulate, recently published high-quality studies may take years to achieve significant citation counts. This lag effect could result in an underestimation of the impact of emerging research, limiting the ability to capture the latest research hotspots and developments in real time. Third, the data used in this study were exclusively sourced from the WOSCC, which may lead to incomplete coverage of publications. However, according to Bradford's Law, journals indexed in the WoS Science Citation Index Expanded (SCI-E) are considered to be among the most prestigious due to the rigorous selection process.[100] As such, the publications indexed in WoS are broadly representative of the field. Future research could incorporate additional databases to provide a more comprehensive exploration of the domain.

Conclusion

In summary, this study utilized bibliometric methods to examine the literature on sleep disorders in PD published over the past two decades, identifying key countries, institutions, authors, and journals that have shaped the field. The analysis also uncovered research hotspots and emerging trends in PD-related sleep disorder studies. Interest in this area has grown significantly and is expected to continue expanding in the coming years. The USA, England, and France have remained

leaders in the field, while China has seen a substantial rise in research activity and influence in recent years. Notably, the University of London (England), McGill University (Canada), and Mayo Clinic (USA) have emerged as the most influential institutions. Additionally, journals such as Movement Disorders, Parkinsonism & Related Disorders, and Sleep Medicine are among the most impactful in this area.

Current research is primarily centered on neuroscience, pharmacology and pharmacy, clinical neurology, biochemistry and molecular biology, and public environmental and occupational health. Emerging trends include comprehensive assessments of sleep, the early diagnosis and prevention of various subtypes of sleep disorders in PD, and advanced animal model research aimed at developing effective treatments. This study provides an objective analysis of sleep disorder research in PD, offering valuable insights and guidance for scholars pursuing future research in this rapidly evolving field.

Data Sharing Statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

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Disclosure

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