Mapping the Evolution of Neuroregulation in Autism Spectrum Disorder: A Scientometric Study

Yan Yan, Erlina Abdullah*

School of Applied Science, Lincoln University College, 47301 Selangor, Malaysia

*Corresponding author

Abstract

Introduction: This study investigates the evolving knowledge structure of neuromodulation research in autism spectrum disorder (ASD), aiming to identify core themes, influential works, and collaborative dynamics through integrated bibliometric and content analysis.

Methods: A dataset of 295 ASD-related neuromodulation articles was extracted from Scopus. VOSviewer was employed to conduct co-authorship, co-citation, and keyword co-occurrence analyses.

Results: Publication output has shown sustained growth, peaking after 2020. While the United States leads in productivity and citation influence, emerging contributors such as China and Brazil demonstrate expanding engagement, albeit with relatively lower normalized citation scores. Keyword clustering revealed four converging yet distinct research streams: (1) Neuromodulation Techniques in Autism Spectrum Disorder; (2)Neurodevelopmental Mechanisms and Safety in Brain Stimulation; (3)Clinical Applications and Neuropsychiatric Disorders; (4)Comorbidities and Autonomic Nervous System Modulation. Co-authorship analysis reflects increasingly globalized collaboration, though regional clusters persist. Highly cited works focus on safety, cognitive enhancement, and methodological integration, while high-link-strength papers emphasize empirical validation of neuromodulatory effects in ASD.

Conclusion: The field is maturing toward a multidimensional landscape, balancing clinical translation with mechanistic and methodological depth. Future research may benefit from closer interdisciplinary integration and improved international dissemination, particularly among underrepresented regions and thematic areas.

Keywords

Autism, ASD, Neuromodulation, Brain Stimulation

1. Introduction

Autism spectrum disorder (ASD) is a heterogeneous neurodevelopmental condition marked by deficits in social interaction, communication, and repetitive behaviors [1]. Research over the past two decades has highlighted atypicalities in synaptic plasticity, connectivity, and excitatory-inhibitory balance—particularly in frontotemporal and default mode networks [2-4]. These findings have spurred interest in neuromodulation approaches beyond behavioral and pharmacological treatments. Non-invasive techniques such as transcranial magnetic stimulation, transcranial direct current stimulation, and vagus nerve stimulation show potential to modulate cortical excitability and improve executive, social, and emotional functions [5-7]. Yet questions persist regarding parameters, mechanisms, and long-term efficacy [8-11]. Current research remains fragmented across neuroscience, psychiatry, and engineering, necessitating systematic synthesis. Bibliometric analysis offers a data-driven means to map thematic evolution, cross-disciplinary linkages, and emerging research frontiers in ASD neuromodulation.

2. Methods

In this study, we conducted a comprehensive search of relevant literature in the SCOPUS database up to June 30, 2025, with no restrictions on the start date. We searched for two types of keywords: "autism term "(autism OR "autism spectrum disorder" OR ASD) and" Neuromodulation-related search terms "(to cover the relevant research more comprehensively, the search terms include: "neuromodulation" OR "transcranial magnetic stimulation" OR TMS OR "transcranial direct current stimulation" OR tDCS OR "vagus nerve stimulation" OR VNS OR "deep brain stimulation" OR DBS OR "brain stimulation"), this applies to the title, abstract or keyword section of the paper. This study only includes English papers published in the form of articles and reviews. During this period, 1,485 articles were produced.

Next, we conduct a two-person manual screening of the literature by reading the abstracts to ensure the validity of the included literature. The screening Kappa value was 0.838, indicating high reliability between codes. This measure indicates consistency in the inclusion (1) or exclusion (0) of the items, suggesting a strong consistency between the two filters. A total of 295 articles were included.

This study conducted bibliometric analysis and cluster-based content analysis on the literature related to autism and neuroregulation techniques. In bibliometric analysis, we used the VOSviewer software for quantitative analysis, including keyword co-occurrence and citation coupling. Meanwhile, to supplement the quantitative analysis, we conducted a content analysis on the X clusters discovered in the co-occurrence keyword analysis, thereby conducting a more in-depth exploration and comprehensive understanding of the prominent issues existing in the bibliometric results.

3. Results

This section starts with the bibliographic coupling analysis of keyword co-occurrence analysis and content analysis based on clustering. Then we enter into our bibliographic coupling analysis of influencing factors, including publishing trends, authors, countries, etc. We then developed and interpreted a research conceptual framework drawn from bibliometrics and cluster-based content analysis.

3.1 Keywords Co-Occurrence Analysis and Clustering Based Content Analysis

3.1.1 Publication Trend Analysis

An examination of the annual publication output from 2008 to mid-2025 reveals a clear trajectory of increasing scholarly interest in the intersection of autism spectrum disorder (ASD) and neuromodulation (Figure 1). The field remained nascent between 2008 and 2012, with publication counts fluctuating at low levels (≤4 per year), reflecting an exploratory phase characterized by preliminary inquiries into the neurophysiological underpinnings of ASD and the potential relevance of neuromodulatory interventions.

A notable inflection occurred around 2013, coinciding with emerging clinical studies on transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) in neurodevelopmental disorders. From 2013 to 2018, the annual number of publications grew steadily, with intermittent surges—most prominently in 2015 and 2017—indicating a gradual shift from conceptual exploration to experimental validation.

The field entered a phase of rapid expansion beginning in 2019. This period was marked by a consistent and steep increase in output, culminating in a sharp rise from 23 publications in 2020 to 38 in 2024. This escalation likely reflects not only the increasing clinical uptake of non-invasive brain stimulation (NIBS) techniques in ASD populations but also an epistemic convergence of neuroscience, psychiatry, and cognitive rehabilitation. The elevated volume during 2021-2024 suggests a transition toward domain consolidation, wherein neuromodulation is no longer peripheral but integrated into mainstream autism research.

Although the number of publications recorded in 2025 (n = 29) appears slightly lower than the previous year, it should be emphasized that the data capture only the first half of the year. Assuming a consistent publication rate, the final annual output is projected to align with or exceed 2024 levels. This sustained momentum, even amid global shifts in research funding and clinical priorities, underscores the field's resilience and its increasing translational relevance.

Collectively, the temporal distribution indicates a field that has evolved from marginal inquiry to robust interdisciplinarity. The observed acceleration in scholarly output over the past decade is emblematic of growing confidence in neuromodulation as a viable therapeutic avenue and a fertile site of theoretical innovation in ASD research.

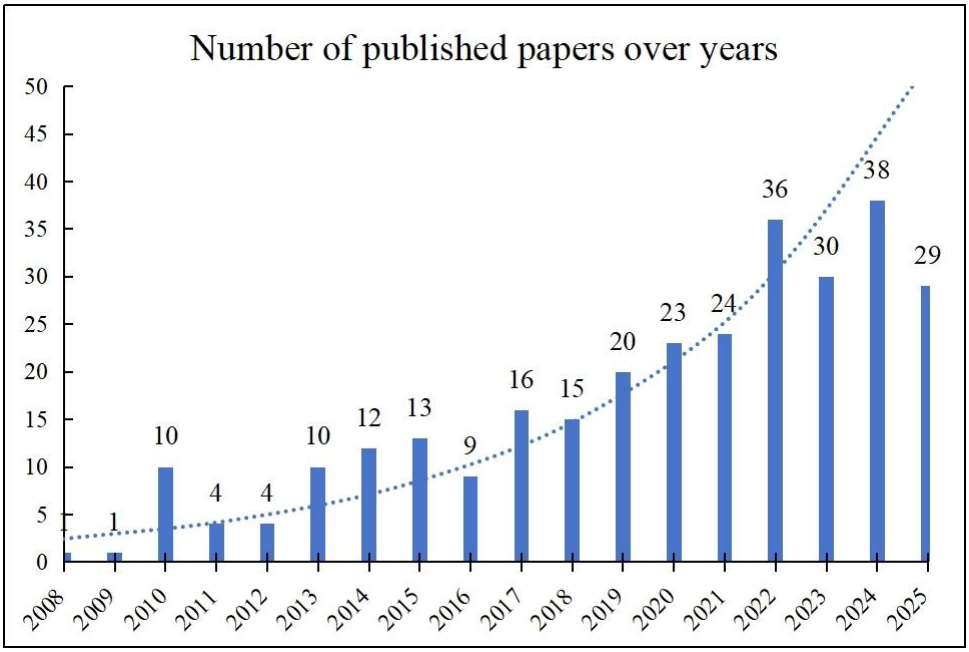

Figure 1. Number of published papers over years

3.1.2 Author Distribution Characteristics

The co-authorship analysis of researchers with more than three publications reveals a field characterized by fragmented yet thematically structured collaboration (Figure 2). Rather than forming a single cohesive network, authors are distributed across distinct clusters that mirror the segmentation of the field into methodological subdomains—such as transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), neuroimaging biomarkers, and clinical intervention trials in autism spectrum disorder (ASD). These subfields function as relatively self-contained collaborative ecosystems, with limited cross-cluster integration, suggesting that interdisciplinary convergence, though present, remains underdeveloped.

Authors such as Wu Chen-Te, Ni Hsing-Chang, and Lin Hsiang-Yuan exhibit strong intra-cluster link strengths, indicating sustained collaborations often anchored in institutional or national research programs, especially within East Asia. Conversely, networks centered around researchers like Croarkin Paul E. and Daskalakis Zafiris J. reflect North American clinical neuroscience collaborations with relatively broader international reach. Notably, authors affiliated with neuromodulation-focused groups (e.g., using rTMS/tDCS for ASD) show high normalized citation scores, suggesting that clinical translational studies are currently at the forefront of impact within this field.

The collaborative patterns reveal a field in which topical cohesion drives author connectivity more strongly than institutional alignment. While global collaboration exists, particularly between North America and East Asia, the overall structure suggests that deeper integration across neurotechnological and behavioral research fronts could enhance knowledge transfer. These findings highlight a research landscape defined by parallel innovation tracks with emerging, yet underexploited, opportunities for cross-pollination.

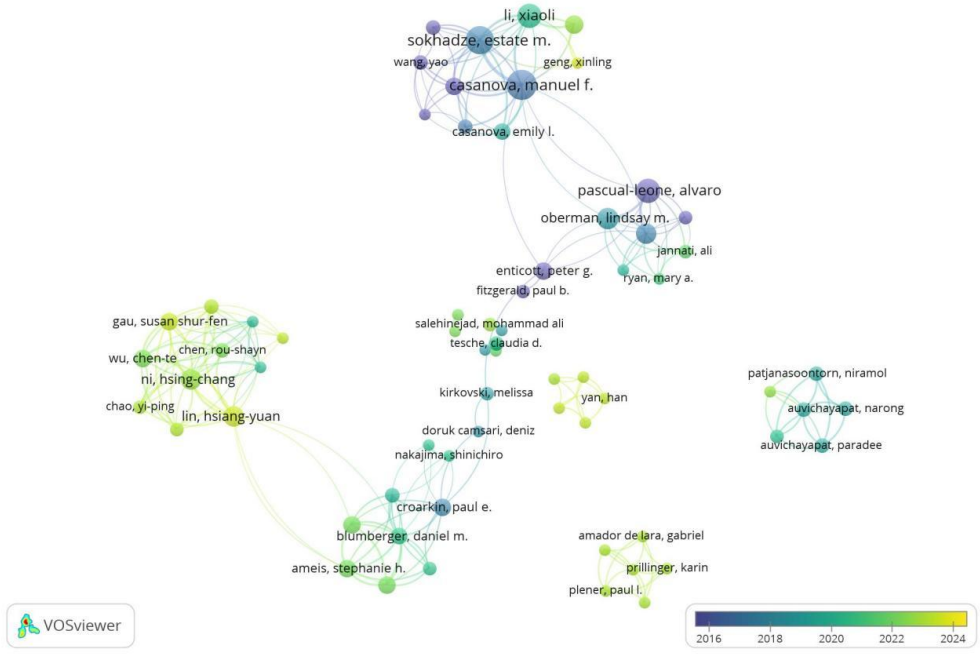

Figure 2. The Overlay Visualization of Co-authorship Authors

3.1.3 Study the Distribution Characteristics of Countries and Regions

The country-level co-authorship analysis reveals a progressively globalized and regionally concentrated research landscape in neuromodulation for autism spectrum disorder (ASD) (Figure 3). The United States stands as the predominant contributor, with 120 publications and an overwhelming citation count of 4,292, reflecting its sustained leadership and pivotal role in both foundational and clinical studies. Its average publication year of 2018.8 indicates consistent scholarly activity, while a normalized citation score of 1.34 underscores its enduring academic influence.

European nations such as Germany (38 publications, 986 citations, normalized citation 1.43), Italy (29 publications, 608 citations, normalized citation 1.38), and Spain (32 publications, 595 citations, normalized citation 2.09) exhibit not only substantial productivity but also high impact, with Spain notably leading in normalized citation metrics, signaling influential and widely recognized recent research outputs. Switzerland and the Netherlands also display high average citation rates per publication, highlighting their focus on high-impact collaborative work.

Asian countries, particularly China (51 publications, 753 citations, normalized citation 0.92), China Taiwan (21 publications, 132 citations), and South Korea (3 publications, 122 citations, normalized citation 1.26), have increased their research presence significantly. However, China's relatively lower normalized citation score and average citations compared to Western counterparts suggest challenges in global visibility or integration.

Countries such as Canada (53 publications, 681 citations, normalized citation 1.28), Brazil (29 publications, 326 citations, normalized citation 1.29), and Australia (22 publications, 745 citations, normalized citation 1.01) maintain balanced profiles combining moderate-to-high output and citation impact, reflecting their active engagement within international collaborative networks. Collectively, these patterns demonstrate a maturing, transnational research field with robust regional hubs and expanding cross-border collaborations advancing ASD neuromodulation studies.

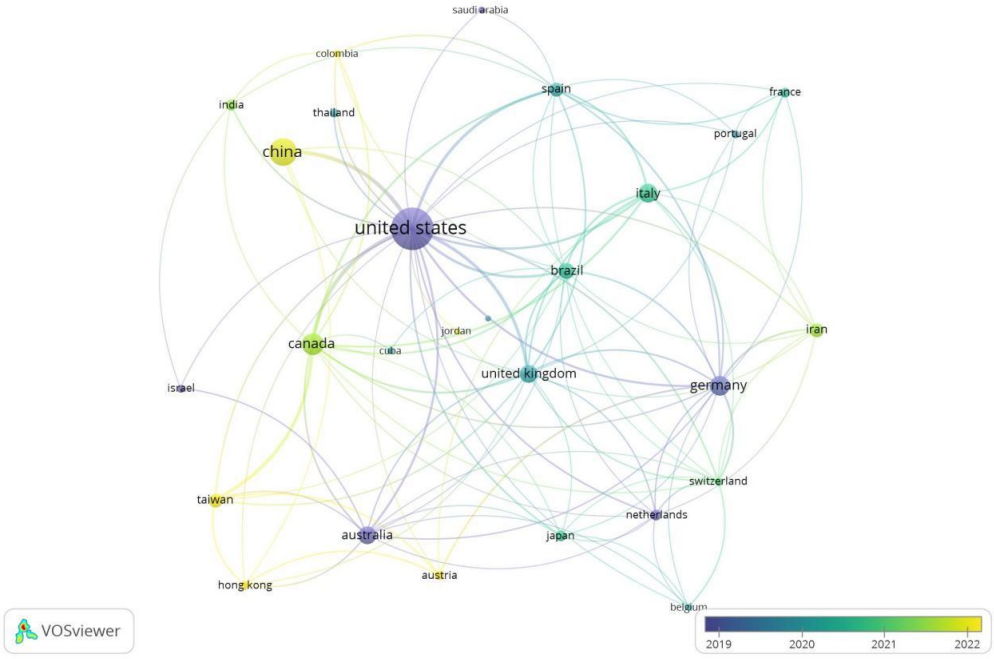

Figure 3. The Overlay Visualization of Co-authorship Countries

3.2 Thematic Analysis

Through VOSviewer, 617 author keywords were excavated and keywords with a frequency of not less than 3 times were included. In order to improve the clarity of clustering and highlight the main research topics, the Minimum cluster size was set to 5. A total of 79 keywords were included, forming 4 clusters, with a total link strength of 1102. This relatively high total link strength indicates strong semantic associations and frequent co-mentions among the keywords, reflecting well-established thematic connections within the research field (Figure 4).

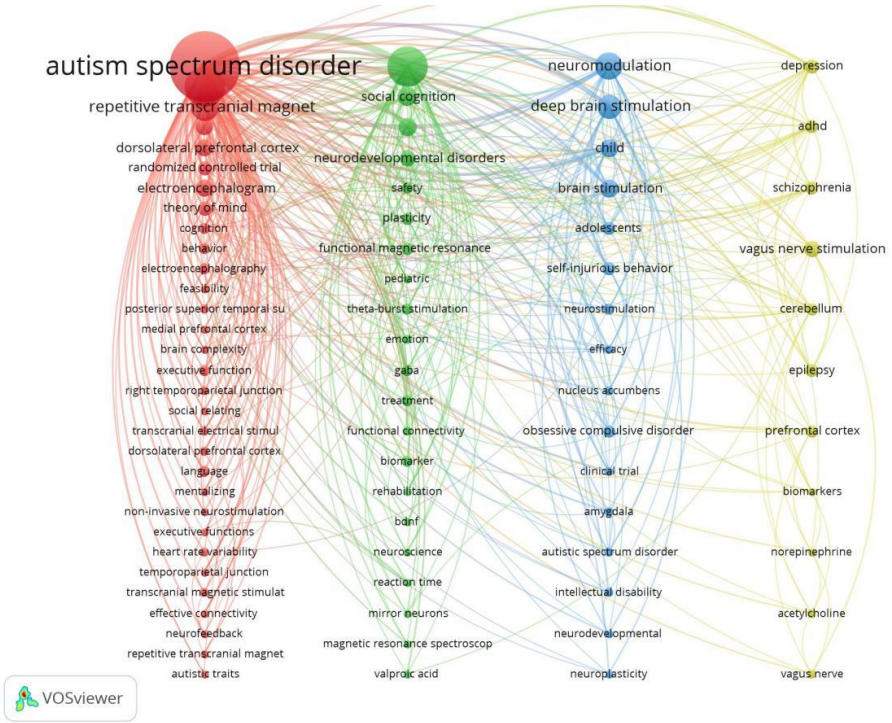

Figure 4. The Network Visualization of Co-occurrence-Author keywords

3.2.1 Keywords Frequency Analysis

The most frequently used keyword was “autism spectrum disorder” (n=200), indicating its central role across studies. Core stimulation modalities such as “transcranial direct current stimulation” (n=66), “transcranial magnetic stimulation” (n=66), and “repetitive transcranial magnetic stimulation” (n=33) also featured prominently, reflecting the sustained research interest in non-invasive neuromodulation techniques for ASD.

Notably, terms like “neuromodulation” (n=30), “deep brain stimulation” (n=24), and “noninvasive brain stimulation” (n=14) underscore the growing diversity of intervention strategies. Emerging neuroscience-related terms such as “functional connectivity”, “GABA”, and “plasticity” suggest increasing attention to neural mechanisms underlying treatment response. Keywords including “depression”, “ADHD”, and “schizophrenia” indicate cross-diagnostic exploration, while “vagus nerve stimulation” and “heart rate variability” reflect a rising focus on autonomic regulation in ASD.

Overall, the distribution and frequency of keywords highlight a field that is not only focused on clinical application, but also increasingly concerned with mechanistic understanding and comorbidity, indicating maturation and diversification of research themes within ASD neuromodulation studies.

3.2.2 Average Year of Keyword Co-Occurrence

Analysis of the average publication year of author keywords provides insight into the temporal dynamics of research focus in neuromodulation and ASD. Foundational terms such as “autism spectrum disorder” (2020.06), “transcranial magnetic stimulation” (2019.62), and “transcranial direct current stimulation” (2020.36) show sustained interest over recent years, reflecting the consolidation of core methods and disease contexts.

More recent entries, including “randomized controlled trial” (2022.67), “neurostimulation” (2022.4), “efficacy” (2023.0), and “biomarkers” (2023.33), signal a growing emphasis on clinical translation, standardized trial design, and objective outcome metrics. Notably, the emergence of “functional connectivity” (2020.75) and “nucleus accumbens” (2021.0) suggests an increasing interest in circuit-level mechanisms and target-specific stimulation.

In contrast, earlier average years are observed in “neurofeedback” (2016.0), “mirror neurons” (2017.0), and “mentalizing” (2015.3), implying that some cognitive neuroscience themes may have peaked in attention and are now less central to current studies.

Overall, the temporal profile indicates a field that has gradually shifted from exploratory cognitive frameworks toward mechanistic neuroscience and rigorous clinical validation, aligning with broader trends in precision neuropsychiatry.

3.3 Content Analysis Based on Keyword Clustering

The co-occurrence analysis of author keywords revealed four main thematic clusters representing the core research focuses within this field (Table 1).

Table 1. Keywords Content Analysis Based on Clustering

Cluster	Topics	Keywords
1	Neuromodulation Techniques in Autism Spectrum Disorder	autism spectrum disorder, transcranial direct current stimulation, repetitive transcranial magnetic stimulation, theta burst stimulation, dorsolateral prefrontal cortex, electroencephalogram, randomized controlled trial, theory of mind, behavior, cognition, electroencephalography, executive function, language, dorsolateral prefrontal cortex (dlpfc), heart rate variability, posterior superior temporal sulcus, right temporoparietal junction, transcranial electrical stimulation, transcranial magnetic stimulation (tms), autistic traits, brain complexity, effective connectivity, empathy, executive functions, feasibility, medial prefrontal cortex, mentalizing, neurofeedback, non-invasive neurostimulation, repetitive transcranial magnetic stimulation (rtms), social relating, temporoparietal junction
2	Neurodevelopmental Mechanisms and Safety in Brain Stimulation	transcranial magnetic stimulation, social cognition, noninvasive brain stimulation, neurodevelopmental disorders, plasticity, functional magnetic resonance imaging, biomarker, gaba, safety, theta-burst stimulation, treatment, emotion, functional connectivity, rehabilitation, bdnf, magnetic resonance spectroscopy, mirror neurons, neuroscience, pediatric, reaction time, valproic acid
3	Clinical Applications and Neuropsychiatric Disorders	neuromodulation, deep brain stimulation, brain stimulation, child, depression, adhd, adolescents, schizophrenia, self-injurious behavior, obsessive compulsive disorder, neurostimulation, amygdala, autistic spectrum disorder, clinical trial, efficacy, neuroplasticity, nucleus accumbens, anxiety, neurodevelopmental
4	Comorbidities and Autonomic Nervous System Modulation	vagus nerve stimulation, epilepsy, cerebellum, prefrontal cortex, intellectual disability, acetylcholine, vagus nerve, aggression, biomarkers, norepinephrine

Cluster 1: Neuromodulation Techniques in Autism Spectrum Disorder. This cluster centers on the application of non-invasive brain stimulation methods, such as transcranial direct current stimulation (tDCS) and repetitive

transcranial magnetic stimulation (rTMS), targeting autism spectrum disorder (ASD). Key terms reflects research on modulating social cognition and executive function deficits. The average publication year around 2020 indicates recent growth, while moderate citation impact suggests ongoing efforts to validate clinical efficacy and underlying mechanisms.

Cluster 2: Neurodevelopmental Mechanisms and Safety in Brain Stimulation. Focused on understanding neural plasticity and safety issues, this cluster highlights "neurodevelopmental disorders," "functional connectivity," and "noninvasive brain stimulation." The relatively high average citations emphasize influential work elucidating brain network dynamics and methodological rigor in applying neuromodulation, especially in pediatric and rehabilitative contexts.

Cluster 3: Clinical Applications and Neuropsychiatric Disorders. This theme covers deep brain stimulation (DBS) and its use in treating neuropsychiatric conditions such as obsessive-compulsive disorder and depression. Keywords like "clinical trial," "amygdala," and "nucleus accumbens" indicate translational studies integrating anatomical targets and efficacy evaluations. Inclusion of developmental terms ("child," "adolescents") shows an interest in age-specific treatment effects, with generally high citation scores reflecting the clinical relevance.

Cluster 4: Comorbidities and Autonomic Nervous System Modulation. The fourth cluster relates to comorbid psychiatric conditions including ADHD, schizophrenia, and their modulation via autonomic interventions like "vagus nerve stimulation." High citation metrics for terms such as "ADHD" highlight growing attention to multidisciplinary approaches addressing both central and peripheral nervous system contributions to neurodevelopmental and psychiatric disorders.

Together, these four clusters map a comprehensive research landscape integrating neuromodulation methods, neural mechanism studies, clinical translation, and autonomic modulation, illustrating an active, multidisciplinary field advancing neurodevelopmental disorder therapeutics.

3.4 Knowledge Base of the Research Field

A co-citation analysis was conducted on all 295 publications, identifying 95 references with over five co-citations, yielding a total link strength of 1450. Among the cited references, 54 articles were cited more than 50 times, and only 11 exceeded 100 citations (Figure 5). To better understand the knowledge base of this field, we analyzed one paper with the highest citation frequency and one paper with the highest total link strength (TLS).

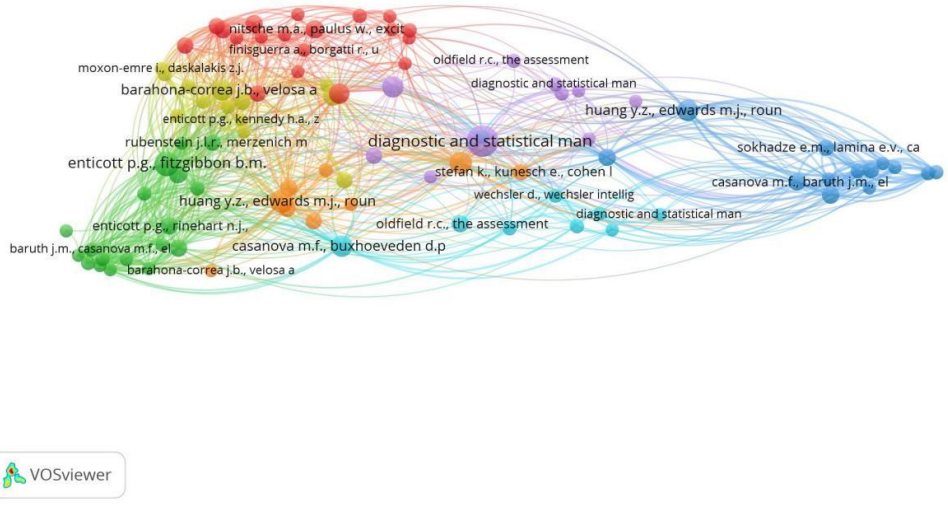

Figure 5. The Network Visualization of citation Cited References

3.4.1 Highly Cited Literature

The paper "Safety of noninvasive brain stimulation in children and adolescents" ranks first in citation frequency, authored by Bikson et al. and published in Brain Stimulation in 2015 [12]. This review systematically synthesizes clinical and experimental evidence regarding the tolerability of tDCS and rTMS in pediatric populations. Minor and transient adverse effects, such as scalp irritation and fatigue, are reported, with no serious complications identified. Notably, the authors underscore neurodevelopmental sensitivity as a crucial consideration, advocating for age-specific

protocols. The review emphasizes the necessity of standardized stimulation parameters and long-term surveillance to ensure safety. This seminal work has established ethical and methodological baselines for subsequent pediatric neuromodulation research and remains a reference point for clinical trial frameworks involving youth with neurodevelopmental vulnerabilities.

3.4.2 High Link Strength Literature

The article "A double-blind, randomized trial of deep Repetitive Transcranial Magnetic Stimulation (rTMS) for autism spectrum disorder" ranks first in link strength, authored by Oberman et al. and published in Brain Stimulation in 2014 [13]. This seminal trial employed a randomized, double-blind, sham-controlled design targeting the bilateral dorsomedial prefrontal cortex with high-frequency deep rTMS. The intervention yielded significant amelioration in core ASD symptoms—particularly social interaction and stereotyped behaviors—with minimal adverse effects. Notably, it established the initial safety and feasibility of deep rTMS for ASD, positioning neural network modulation as a viable therapeutic avenue. The study has since become a cornerstone reference in protocol development and translational neuromodulation research, evidencing the clinical relevance of targeting executive and social cognitive circuits in autism.

4. Discussion

This study aimed to identify and systematically characterize the evolving landscape of research on neuromodulation in autism spectrum disorder (ASD) by employing bibliometric methods combined with cluster-based content analysis. Our findings reveal a dynamic and multidisciplinary field that has progressively transitioned from exploratory neurophysiological investigations to more focused clinical applications and mechanistic studies [14,15]. The integration of keyword co-occurrence patterns and publication metadata underscores the maturation of the domain, highlighting key thematic concentrations such as noninvasive brain stimulation techniques, neurodevelopmental mechanisms, clinical efficacy trials, and autonomic nervous system modulation [16-19]. These insights provide a robust intellectual framework to inform future research trajectories, emphasizing the need for methodological rigor, translational relevance, and interdisciplinary collaboration.

The overall publication trends and author collaboration networks reflect a geographically and institutionally diverse yet thematically segmented research community. Leading contributions predominantly emerge from the United States and parts of Europe, with East Asian countries such as China and Taiwan rapidly increasing output but exhibiting relatively lower citation impact, suggesting potential gaps in global integration and visibility. Notably, scholars cluster around distinct methodological approaches, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), often within regionally concentrated research groups [20,21]. This fragmentation, while fostering deep expertise, may limit cross-pollination of ideas across subdomains. The relatively recent surge in publications since 2019 aligns with broader trends in precision neuropsychiatry and reflects growing confidence in neuromodulation as a therapeutic avenue for ASD. Future efforts should prioritize fostering interdisciplinary networks and enhancing international collaborations to bridge these divides and amplify collective scientific impact.

A dominant thematic focus emerges around the application of noninvasive brain stimulation modalities—chiefly tDCS and repetitive TMS—to modulate social cognition and executive function deficits characteristic of ASD. Keywords related to the dorsolateral prefrontal cortex, theory of mind, and executive functions highlight the targeting of neural circuits underlying social and cognitive impairments [22-24]. While these investigations demonstrate promising preliminary efficacy and neurophysiological engagement, the moderate citation impact and relatively recent average publication year indicate an ongoing validation process. Clinical heterogeneity and variability in stimulation parameters pose significant challenges to generalizability [25]. Thus, future research must aim to standardize protocols and incorporate larger, more diverse cohorts to substantiate clinical benefits and facilitate personalized intervention frameworks.

Closely linked to clinical applications is a substantial research corpus elucidating neurodevelopmental mechanisms and safety profiles associated with brain stimulation in pediatric populations. The prominence of keywords such as neuroplasticity, functional connectivity, and biomarker signals an increasing emphasis on understanding the neural substrates mediating treatment effects and adverse event risks [24,26,27]. Given the heightened sensitivity of the developing brain, rigorous longitudinal safety assessments remain imperative [28]. The high citation influence of these studies attests to their foundational role in informing ethical guidelines and clinical trial design. Integrating multimodal neuroimaging and electrophysiological biomarkers with comprehensive safety monitoring will be critical for optimizing neuromodulation parameters and tailoring interventions to individual neurodevelopmental trajectories.

Translational clinical studies exploring deep brain stimulation and related interventions further expand the therapeutic horizon by targeting neuropsychiatric comorbidities frequently observed in ASD, including obsessive-compulsive disorder and depression [29,30]. The involvement of subcortical structures such as the amygdala and nucleus accumbens, alongside developmental considerations specific to children and adolescents, reflects a nuanced approach bridging neural circuitry and symptomatology [31,32].

The elevated citation scores associated with this body of work underscore its clinical relevance and growing evidence base. Nonetheless, the invasiveness and complexity of these interventions necessitate cautious patient selection and

multidisciplinary evaluation. Future clinical trials should emphasize mechanistic elucidation, robust efficacy endpoints, and ethical frameworks to navigate the challenges inherent in these advanced neuromodulatory techniques.

Finally, a distinct yet interconnected research focus addresses autonomic nervous system modulation through approaches like vagus nerve stimulation, targeting comorbid conditions such as ADHD and schizophrenia [17,33]. The convergence of central and peripheral nervous system modulation highlights the multidimensional nature of ASD and its associated psychiatric symptoms [34]. Elevated citation metrics for terms related to autonomic regulation signify increasing recognition of these pathways' therapeutic potential [35]. However, comprehensive understanding of the bidirectional interactions between autonomic function and neurodevelopmental disorders remains nascent. Subsequent investigations should aim to integrate neurophysiological, behavioral, and autonomic biomarkers to refine intervention targets and elucidate underlying mechanisms, thereby advancing precision neuromodulation strategies.

In summary, the identified thematic clusters collectively portray a vibrant and rapidly evolving research domain that bridges fundamental neuroscience, clinical innovation, and ethical considerations in ASD neuromodulation. To capitalize on this momentum, future research should strive for methodological harmonization, greater inclusivity of diverse populations, and enhanced interdisciplinary collaboration across geographic and disciplinary boundaries. Such efforts will not only deepen mechanistic insight but also accelerate translation into effective, personalized interventions that improve functional outcomes for individuals with ASD.

5. Conclusion

This study maps the evolving landscape of neuromodulation research in autism spectrum disorder, highlighting a shift from foundational neurophysiology to clinical and mechanistic applications. It reveals a growing integration of neuroscience, psychiatry, and rehabilitation, with key themes spanning noninvasive brain stimulation, neurodevelopmental safety, deep brain stimulation, and autonomic modulation. Despite notable progress, challenges persist in standardizing methodologies, fostering cross-regional collaboration, and addressing ASD's clinical heterogeneity. Future efforts should prioritize unified protocols, long-term safety monitoring, and multimodal biomarkers within large-scale, inclusive trials. Advancing personalized neuromodulatory strategies demands integrative frameworks that improve cognitive, social, and behavioral outcomes. This work offers a strategic foundation for guiding future research and enhancing clinical translation in this promising field.

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