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Three decades of collaboration in rheumatology: a comprehensive co-authorship network analysis (1994–2023)

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Abstract

Introduction: This study investigated the evolution of collaborative research in rheumatology over 3 decades (1994–2023), utilizing co-authorship network analysis to uncover key contributors, structural trends, and global collaboration patterns. The analysis aimed to provide insights into the dynamics of research cooperation and the factors influencing its development.

Material and methods: A total of 31,231 publications on rheumatology, indexed in the Web of Science (WoS) Core Collection, were analyzed. The co-authorship network was constructed using Python (Version 3.10.5) in the PyCharm environment (Version 2022.1.3). Macro-level metrics, including network density, clustering coefficient, components, and average path length, were evaluated alongside micro-level indicators such as degree centrality, closeness centrality, and betweenness centrality to characterize the network's structure and dynamics. Additionally, temporal trends were examined to assess changes in collaboration patterns over time.

Results: The analysis revealed an expansion in publication volume and collaboration over the 3 decades, with persistent fragmentation evidenced by low network density (below 0.0005) and numerous disconnected components. The number of active researchers and institutions participating in collaborations increased significantly, contributing to enhanced regional cooperation. Key researchers, including Nicolino Ruperto, Josef S. Smolen, and Yoshiya Tanaka, emerged as central figures, consistently facilitating knowledge exchange and collaboration. Localized, tight-knit collaboration patterns, indicated by high clustering coefficients, persisted despite limited global integration. These findings suggest that while rheumatology research networks are becoming more inclusive, significant disparities in connectivity across regions remain.

Conclusions: This comprehensive analysis highlights the dual trends of growth and fragmentation in rheumatology research collaboration. While local collaborations thrive, broader integration remains a challenge, underscoring the need for initiatives fostering global connectivity in the research community. Enhancing international collaboration and reducing resource gaps between regions could accelerate advancements in rheumatology research, benefiting both the scientific community and patients worldwide.

Key words: rheumatoid arthritis, co-authorship network analysis, network analysis.

Introduction

Rheumatology addresses various diseases affecting joints, muscles, and connective tissues that profoundly impact patient quality of life (QoL) [1]. The field has undergone transformative advancements in diagnostics, therapeutics, and disease management over the past 3 decades. The introduction of glucocorticosteroids therapy and the widespread adoption of disease-modifying antirheumatic drugs (DMARDs), such as methotrexate, marked early treatment approaches [2]. These methods delivered significant relief but carried substantial side effects and limitations. The emergence of biological DMARDs and small molecule signal transduction inhibitors has transformed the landscape of rheumatology. These modern therapies target specific disease pathways, leading to improved

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patient outcomes and QoL. However, significant challenges remain in early diagnosis, disease remission, and equitable access to care [2, 3]. Early diagnosis improves long-term prognosis, yet delayed detection hinders optimal patient outcomes. Additionally, disparities in healthcare resources, particularly in developing regions, pose substantial barriers to comprehensive care [4, 5].

There are still a number of regional issues in spite of the revolutionary developments. Inadequate healthcare infrastructure restricts access to cutting-edge diagnostics and treatments in low- and middle-income nations [5, 6]. For instance, there is a severe scarcity of qualified rheumatologists in sub-Saharan Africa, which frequently leads to cases being misdiagnosed or delayed [7, 8]. Despite the existence of clinical indications, underutilization of biological DMARDs has occurred in India as a result of unequal access to these medications due to their high cost [9, 10].

Meanwhile, a lack of transportation infrastructure and geographic obstacles make care delivery delays even worse in rural Latin America. Various approaches are needed to address these disparities, such as increasing funding for international research collaborations, improving healthcare infrastructure, and increasing accessibility [11]. Brazil's Telessaúde program for instance has effectively used telemedicine to deliver rheumatology services to marginalized communities, offering a model that other areas can follow [12, 13].

The prevalence of rheumatological diseases has increased globally, driven partly by aging populations [3, 14]. Europe and North America have made substantial progress in innovative treatments, though rural areas face a shortage of rheumatology specialists [5]. Countries such as Japan, China, and South Korea have witnessed rapid advancements in research and clinical care [15], although regional disparities persist across Asia [16]. In Latin America, economic and cultural barriers challenge the delivery of consistent, high-quality care, particularly in rural settings [17].

Knowledge gap and practical significance

International collaboration

International collaboration in rheumatology research is becoming increasingly important, but there are still few thorough studies that assess long-term co-authorship trends and their effects on resource distribution, innovation and knowledge sharing. In order to tackle the intricate problems in rheumatology, the incorporation of interdisciplinary methods such as artificial intelligence (AI), precision medicine, and collaborative network analysis is essential [18]. By methodically examining 3 decades of co-authorship networks, this study closes a significant gap and demonstrates how collaborations have influenced rheumatology research. Furthermore, it identifies opportunities to use cooperative networks to enhance fair resource access, promote innovative treatments, and alleviate regional inequalities.

Importance of collaborative network analysis

Co-authorship network analysis provides a powerful lens through which to identify collaborative structures, influential researchers, and key institutions in the field [19]. This study's evaluation of these networks emphasizes the usefulness of encouraging cross-border and interdisciplinary cooperation in order to hasten rheumatology research. Finding influential researchers, for instance, can help mentorship programs, and mapping institutional collaborations can help allocate resources as efficiently as possible for extensive clinical trials and cutting-edge therapies.

Impact of artificial intelligence and precision medicine

The study acknowledges the revolutionary influence of new domains such as AI and precision medicine on the dynamics of research collaboration in addition to historical patterns. Clinicians, geneticists, and bioinformaticians must collaborate across disciplinary boundaries as precision medicine emphasizes customized treatment plans. Similar to this, AI technologies – which range from automated diagnostic tools to predictive modeling for disease progression – require partnerships that combine knowledge from data analytics, computer science and rheumatology. These developments not only broaden the field of study but also reinterpret the character of partnerships, creating networks that cut across conventional disciplinary lines. It is essential to investigate these intersections to comprehend the future directions of rheumatology scientific collaboration in this new era.

This study analyzed the co-authorship network structure in rheumatology research from 1994 to 2023, using the WoS core collection data. Through evaluation of macro- and micro-level network indicators, this research examined the dynamics of collaboration and the role of influential researchers and institutions in advancing the field. As depicted in Figure 1, the number of rheumatology-related publications has shown a steady upward trend over the past 3 decades. Furthermore, Figure 2 highlights the dominance of contributions from the United States, the United Kingdom, Canada, and Germany, while countries such as China, Japan, and India have made significant strides in Asia. Similarly, Brazil and Mexico have emerged as leaders in rheumatology research in Latin America.

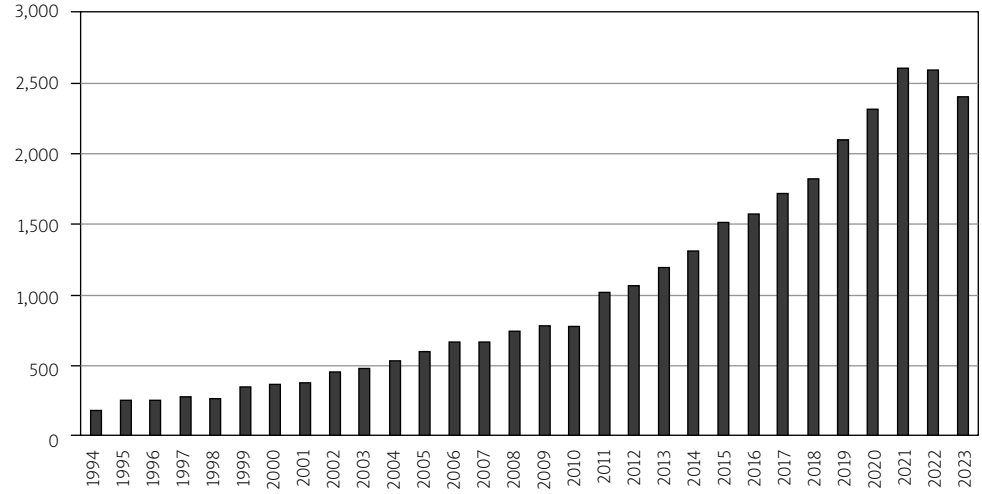

Fig. 1. Trend of the number of articles published in the Web of Science Core Collection.

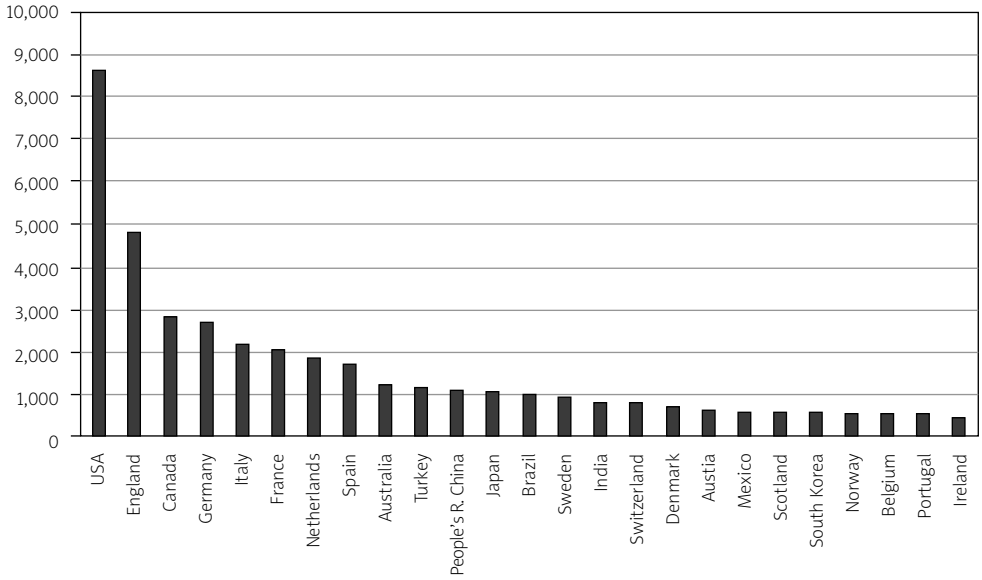

Fig. 2. Total number of articles published by country in the Web of Science Core Collection (1994–2023).

Scope of the study

This investigation analyzed 31,231 rheumatology research publications from the WoS Core Collection spanning 1994 to 2023. The data collection, completed on November 12, 2024, incorporated author information to enable co-authorship network analysis. The analytical framework employed Python programming language in the PyCharm integrated development environment to examine macro- and micro-level indicators.

Significance of the study

This research contributes significantly to understanding collaboration in rheumatology through several key aspects:

- **Identification of key researchers and institutions:** The study identified influential researchers and leading institutions, shedding light on their pivotal roles in shaping the field. These insights can guide emerging researchers and institutions seeking impactful collaborations.
- **Evaluation of international collaborations:** Analysis of international collaboration evolution highlights the synergistic potential of diverse research networks in driving innovation. Understanding success factors in these partnerships can inform future research strategies.
- **Network structure and trend analysis:** The study examined the structural characteristics of the research network, elucidating knowledge flow and interconnec-

tedness among various actors over time. This analysis revealed gaps and opportunities within the collaborative ecosystem.
- **Future direction development:** Evaluation of historical trends and current dynamics provides a roadmap for the future, emphasizing the importance of global collaboration. This analysis underscores how strategic partnerships can address pressing challenges such as resource disparities, treatment innovation, and equitable care delivery.

The findings map three decades of research collaboration while providing actionable insights for fostering a more interconnected and effective research community in rheumatology. As the field continues to evolve, understanding these networks will prove instrumental in addressing unmet needs and advancing global health outcomes.

Material and methods

Data collection

This study drew data from the WoS Core Collection, using "rheumatology" as the topic search term. The search identified 31,231 publications in rheumatology between 1994 and 2023, with data collection concluding on November 12, 2024. The dataset contains comprehensive author information and publication years, which served as the foundation for constructing the co-authorship network.

Analytical tools and environment (selection and functions)

Python programming language (Version 3.10.5) was chosen for this project because of its flexibility, simple-to-read syntax, and widespread library focus on data analysis and visualization. PyCharm integrated development environment (IDE) (version 2022.1.3) was used. Important libraries worth mentioning are NetworkX, used to build and analyze complex networks, and Pandas, which allows for efficient data manipulation and preprocessing. NetworkX has specific functions to run on the network metrics, and Pandas also handles the large dataset smoothly, which provides effortless continuity between the stages of the analysis.

Network analysis methods

The construction of the co-authorship network reflects collaborative relationships between authors who published jointly during the specified period. The analysis employed multiple metrics at both macro and micro levels to evaluate the network structure, following established methodological approaches [20–22].

Macro-level metrics

Network density: This metric represents the ratio of actual edges to maximum possible edges, indicating the network's overall connectivity level.

Clustering coefficient: This measure quantifies the tendency of nodes to form tight-knit groups, revealing patterns of local cohesion within the network.

Components: The analysis identifies sub-networks where all nodes maintain either direct or indirect connections, revealing distinct research communities within the field of rheumatology.

Average path length: This metric calculates the mean shortest path length between all node pairs, providing insight into the network's communication efficiency.

Micro-level metrics

Degree centrality: This measurement quantifies each node's direct connections, identifying authors with the highest frequency of collaboration.

Closeness centrality: This metric evaluates the proximity of each node to all others, revealing authors' positions within the collaborative structure.

Betweenness centrality: This measure identifies researchers who serve as network bridges by calculating how frequently a node lies on the shortest paths between other nodes.

The proposed methodological framework provides a comprehensive context for the analyzed metrics, facilitating comparisons with previous scholarly research. By examining the evolution of co-authorship practices over decades, this study provides significant insights. For instance, the current findings on network density and clustering coefficient substantially confirmed the work by Erfanmanesh et al. [23] on co-authorship networks in metrics analysis. This approach builds upon the fundamental principles of network analysis as outlined by Wasserman and Faust [20].

Similarly, the centrality measures calculated here agree with the findings of Narang et al. [24], who emphasized the importance of such indicators in tracing key researchers and co-publication dynamics in citation networks. These findings are also supported by Newman's work on scientific collaboration networks [21], which emphasizes the significance of shortest paths, weighted networks, and centrality measures. These comparisons not only validate the approach in this study but also highlight the utility of the metrics used to capture the dynamic co-authorship networks. Furthermore, the study on the structure of scientific collaboration networks by Newman provides additional context for understanding the collaborative behaviors observed in this analysis [22].

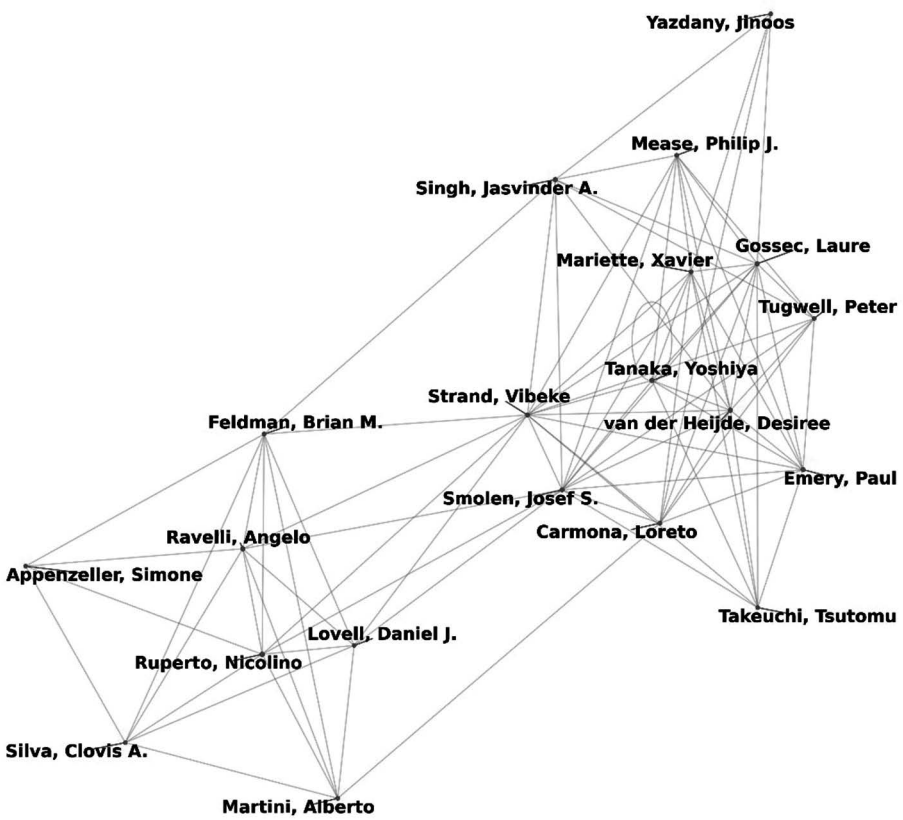

Fig. 3. Top 20 Rheumatology Researcher Network from 1994 to 2003.

Table I. Network metrics of rheumatology research (1994–2023)

Metric	1994–2003	2004–2013	2014–2023
Network density	0.000189	0.000428	0.000291
Average clustering coefficient	0.86575	0.87861	0.87436
Number of components	4,153	1,735	2,877
Average distance	inf	inf	inf

The analysis reveals patterns in research collaboration, shedding light on how academic partnerships have evolved. By examining these metrics over time, this study offers valuable insights into the evolving landscape of research collaboration. Consistent with previous research findings, the increased reliability of the results highlights areas where the field has progressed. This approach opens up new avenues for understanding the complex relationships that drive scientific progress in the modern era.

Results

Early collaboration trends in rheumatology research (1994–2003)

The co-authorship network in rheumatology research exhibited low connectivity during the initial decade (Fig. 3), with a network density of 0.000189 (Table I). The high average clustering coefficient (0.86575) indicated strong local collaborations among researchers, despite the sparse network structure (Table I). The network contained 4,153 disconnected components (Table I), and the infinite average distance reflected the absence of a global network structure [25].

Nicolino Ruperto demonstrated the highest degree centrality (0.0106), followed by Angelo Ravelli (0.0093) and Jasvinder A. Singh (0.0092), each serving central roles within their local collaboration clusters (Table II). Josef S. Smolen (closeness centrality: 0.2349) and Maxime Dougados (0.2324) emerged as the most accessible figures (Table III), while Clifton O. Bingham III (betweenness centrality: 0.0546) functioned as a critical bridge between isolated groups (Table IV).

Table II. Top 20 nodes by degree centrality (1994–2023)

Rank	Name (1994–2003)	Degree centrality (1994–2003)	Name (2004–2013)	Degree centrality (2004–2013)	Name (2014–2023)	Degree centrality (2014–2023)
1	Ruperto, Nicolino	0.0106	Emery, Paul	0.0242	Ruperto, Nicolino	0.0121
2	Ravelli, Angelo	0.0093	Dougados, Maxime	0.0213	Singh, Jasvinder A.	0.0117
3	Singh, Jasvinder A.	0.0092	Furst, Daniel E.	0.0169	Tanaka, Yoshiya	0.0115
4	Tanaka, Yoshiya	0.0090	Strand, Vibeke	0.0145	Gossec, Laure	0.0113
5	Gossec, Laure	0.0090	Martini, Alberto	0.0134	Ravelli, Angelo	0.0104
6	Strand, Vibeke	0.0089	Ruperto, Nicolino	0.0133	van der Heijde, Desiree	0.0102
7	van der Heijde, Desiree	0.0088	Ravelli, Angelo	0.0112	Strand, Vibeke	0.0101
8	Emery, Paul	0.0085	Tak, Paul P.	0.0096	Mariette, Xavier	0.0095
9	Smolen, Josef S.	0.0083	Lovell, Daniel J.	0.0094	Smolen, Josef S.	0.0092
10	Martini, Alberto	0.0077	Smolen, Josef S.	0.0090	Carmona, Loreto	0.0092
11	Mariette, Xavier	0.0076	Khanna, Dinesh	0.0090	Yazdany, Jinoos	0.0090
12	Takeuchi, Tsutomu	0.0072	Pistorio, Angela	0.0087	Takeuchi, Tsutomu	0.0090
13	Mease, Philip J.	0.0072	Boers, Maarten	0.0084	Appenzeller, Simone	0.0089
14	Yazdany, Jinoos	0.0072	van der Heijde, Desiree	0.0084	Emery, Paul	0.0086
15	Carmona, Loreto	0.0071	Combe, Bernard	0.0076	Machado, Pedro M.	0.0084
16	Feldman, Brian M.	0.0071	Giannini, Edward H.	0.0075	Feldman, Brian M.	0.0084
17	Lovell, Daniel J.	0.0069	Kvien, Tore K.	0.0073	Christensen, Robin	0.0084
18	Silva, Clovis A.	0.0068	Kavanaugh, Arthur	0.0073	Silva, Clovis A.	0.0083
19	Appenzeller, Simone	0.0068	Bombardieri, Stefano	0.0072	Mease, Philip J.	0.0082
20	Tugwell, Peter	0.0067	Ozen, Seza	0.0068	Cimaz, Rolando	0.0082

Consolidation of networks (2004–2013)

Network cohesion grew significantly in the second decade (Fig. 4), as evidenced by increased network density (0.000428) and fewer disconnected components (1,735). The average clustering coefficient of 0.87861 indicated sustained reliance on tight-knit collaboration groups (Table I) [25].

Paul Emery (degree centrality: 0.0242) and Maxime Dougados (0.0213) emerged as the most active collaborators, strengthening network cohesion by connecting smaller clusters (Table II). Paul Emery (closeness centrality: 0.2161) and Maxime Dougados (0.2156) gained influence through strong connectivity (Table III). Maxime Dougados (betweenness centrality: 0.0866) and Paul Emery (0.0780) served as key intermediaries, facilitating cross-group collaborations (Table IV).

Modern collaboration landscape (2014–2023)

The most recent decade showed a decreased network density of 0.000291 and increased disconnected components (2,877) (Table I). The stable average clustering coefficient of 0.874 reflected persistent strong local collaboration patterns (Fig. 5) [25].

Nicolino Ruperto (degree centrality: 0.0121), Jasvinder A. Singh (0.0117), and Yoshiya Tanaka (0.0115) demonstrated extensive collaborative reach (Table II). Laure Gossec (closeness centrality: 0.2621) and Josef S. Smolen (0.2589) maintained central positions with high network accessibility (Table III). Zhanguo Li (betweenness centrality: 0.0146) and Yoshiya Tanaka (0.0141) distinguished themselves by connecting distant network segments, promoting broader scientific collaboration (Table IV).

Summary of trends: comparative observations across decades (1994–2023)

The rheumatology research network expanded throughout the three decades, though fragmentation persisted, as evidenced by numerous disconnected components and infinite average distance. Several researchers maintained central positions consistently,

Table III. Top 20 nodes by closeness centrality (1994–2023)

Rank	Name (1994–2003)	Closeness centrality (1994–2003)	Name (2004–2013)	Closeness centrality (2004–2013)	Name (2014–2023)	Closeness centrality (2014–2023)
1	Smolen, Josef S.	0.2349	Emery, Paul	0.2161	Gossec, Laure	0.2621
2	Dougados, Maxime	0.2324	Dougados, Maxime	0.2156	Smolen, Josef S.	0.2589
3	Gossec, Laure	0.2323	Strand, Vibeke	0.2099	Iagnocco, Annamaria	0.2583
4	Strand, Vibeke	0.2304	Furst, Daniel E	0.2044	van der Heijde, Desiree	0.2576
5	van der Heijde, Desiree	0.2302	van der Heijde, Desiree	0.2009	Strand, Vibeke	0.2569
6	Bingham, Clifton O., III	0.2301	Smolen, Josef S.	0.2001	Carmona, Loreto	0.2562
7	Iagnocco, Annamaria	0.2297	Khanna, Dinesh	0.1990	Dougados, Maxime	0.2559
8	Emery, Paul	0.2296	Boers, Maarten	0.1984	Mariette, Xavier	0.2546
9	Mariette, Xavier	0.2290	Kavanaugh, Arthur	0.1975	Machado, Pedro M.	0.2539
10	Tanaka, Yoshiya	0.2281	Burmester, Gerd R.	0.1968	Hyrich, Kimme L.	0.2537
11	Singh, Jasvinder A.	0.2277	Kvien, Tore K.	0.1967	Singh, Jasvinder A.	0.2529
12	Kvien, Tore K.	0.2277	Tak, Paul P.	0.1966	Tanaka, Yoshiya	0.2525
13	Burmester, Gerd R.	0.2276	Keystone, Edward	0.1963	Cutolo, Maurizio	0.2524
14	Khanna, Dinesh	0.2274	Combe, Bernard	0.1958	Nikiphorou, Elena	0.2522
15	Boers, Maarten	0.2273	Aletaha, Daniel	0.1948	Aletaha, Daniel	0.2512
16	Carmona, Loreto	0.2271	Wolfe, Frederick	0.1946	Grainger, Rebecca	0.2511
17	Gladman, Dafna D.	0.2259	Neogi, Tuhina	0.1945	Boers, Maarten	0.2505
18	Aletaha, Daniel	0.2258	Pincus, Theodore	0.1944	Tugwell, Peter	0.2502
19	de Wit, Maarten	0.2250	Matucci-Cerinic, Marco	0.1935	Kvien, Tore K.	0.2501
20	Tugwell, Peter	0.2249	Hawker, Gillian	0.1935	Ramiro, Sofia	0.2498

facilitating collaboration and connecting separate groups. The stable clustering coefficient across decades highlights the enduring significance of localized, tight-knit research collaborations in field advancement. However, the analysis highlighted significant regional disparities in research contributions. While the United States, United Kingdom, and Germany consistently led in network metrics, other regions such as Africa, South America, and parts of Asia showed lower connectivity and participation in the global research network. Structural and socioeconomic factors likely contribute to these disparities, including unequal access to funding, research infrastructure, and training opportunities.

Supporting underrepresented researchers for future direction

To address these disparities, initiatives to support underrepresented researchers in resource-limited regions are essential. Collaborative programs, such as research exchange initiatives, mentorship opportunities, and grants targeted at emerging economies, can help bridge these gaps. For instance, expanding models like Brazil's Telessaúde Initiative could enhance accessibility to research collaborations and improve healthcare outcomes in underrepresented regions.

Artificial intelligence for predictive research collaboration

Artificial intelligence technologies can offer approaches to predict potential research collaborations in rheumatology through machine learning models trained on historical co-authorship data. This analytical framework identifies emerging collaborative patterns and publication trends by detecting relationships. The implementation of AI-driven predictive systems especially benefits regions with historically limited international engagement and underrepresented researchers.

Discussion

This study presents a comprehensive analysis of collaborative network evolution in rheumatology research

Table IV. Top 20 nodes by betweenness centrality (1994–2023)

Rank	Name (1994–2003)	Betweenness centrality (1994–2003)	Name (2004–2013)	Betweenness centrality (2004–2013)	Name (2014–2023)	Betweenness centrality (2014–2023)
1	Bingham, Clifton O., III	0.0546	Dougados, Maxime	0.0866	Li, Zhanguo	0.0146
2	Sloan, Victor	0.0538	Emery, Paul	0.0780	Tanaka, Yoshiya	0.0141
3	Tavares, Viviana	0.0242	Strand, Vibeke	0.0535	Iagnocco, Annamaria	0.0128
4	Berenbaum, Francis	0.0205	Furst, Daniel E.	0.0338	Schulze-Koops, H.	0.0100
5	da Silva, J. A. P.	0.0201	Bombardieri, Stefano	0.0128	Singh, Jasvinder A.	0.0098
6	Cervera, Ricard	0.0160	Takeuchi, Tsutomu	0.0123	Smolen, Josef S.	0.0088
7	Cavazzana, Ilaria	0.0141	Boers, Maarten	0.0118	Gossec, Laure	0.0088
8	Dougados, Maxime	0.0137	Ruperto, Nicolino	0.0107	Strand, Vibeke	0.0080
9	Tanaka, Yoshiya	0.0137	Tak, Paul P.	0.0096	Carmona, Loreto	0.0080
10	Zacher, Josef	0.0129	van der Heijde, Desiree	0.0094	van der Heijde, Desiree	0.0079
11	Krammer, Gerhard	0.0123	Gladman, Dafna D.	0.0087	da Silva, J. A. P.	0.0074
12	Emery, Paul	0.0116	McDonagh, Janet E.	0.0083	Guillemin, Francis	0.0069
13	Foeldvari, Ivan	0.0107	Burmester, Gerd R.	0.0080	Scire, Carlo Alberto	0.0069
14	Klotsche, Jens	0.0106	Fautrel, Bruno	0.0076	Takeuchi, Tsutomu	0.0068
15	Tincani, Angela	0.0105	Duffy, Ciaran M.	0.0072	Danda, Debashish	0.0066
16	Bombardieri, Stefano	0.0103	van Vollenhoven, R.F.	0.0067	Dougados, Maxime	0.0064
17	Singh, Jasvinder A.	0.0096	Matucci-Cerinic, Marco	0.0064	Mariette, Xavier	0.0064
18	Li, Zhanguo	0.0094	Hassell, Andrew	0.0062	Naredo, Esperanza	0.0064
19	Smolen, Josef S.	0.0089	Zink, Angela	0.0062	Tugwell, Peter	0.0060
20	Gossec, Laure	0.0089	Zhang, Wei	0.0061	Appenzeller, Simone	0.0056

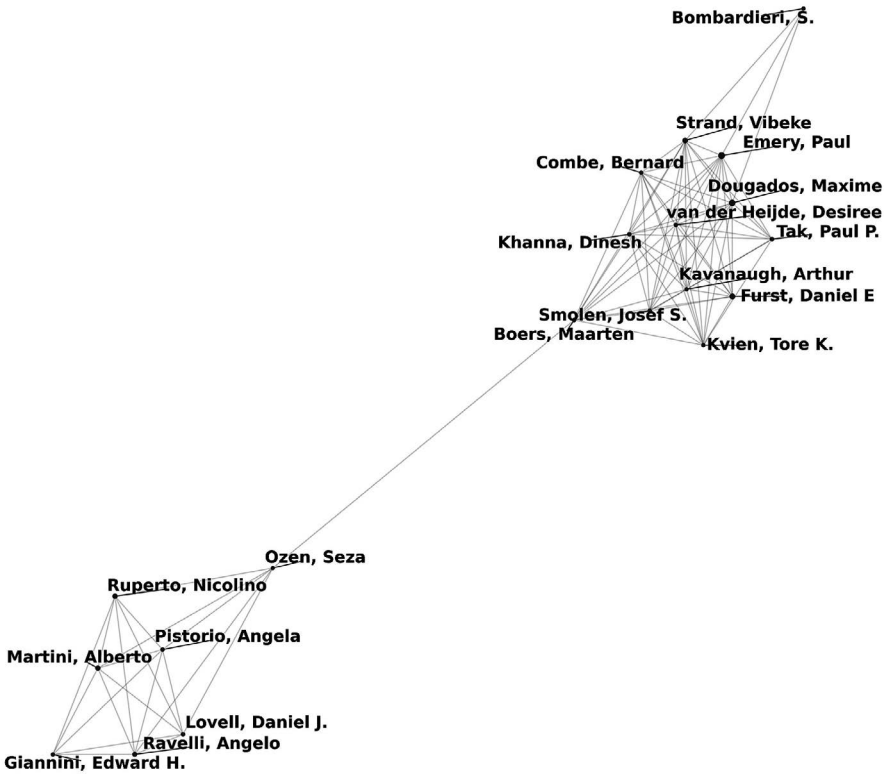

Fig. 4. Top 20 Rheumatology Researcher Network from 2004 to 2013.

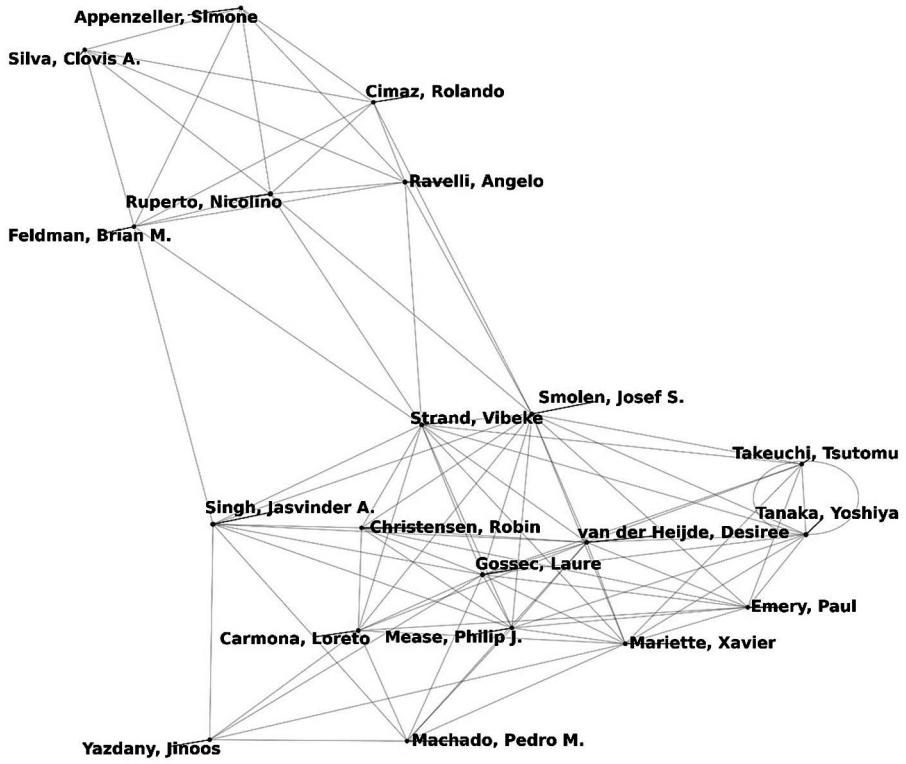

Fig. 5. Top 20 Rheumatology Researcher Network from 2014 to 2023.

from 1994 to 2023. The findings reveal simultaneous integration and fragmentation patterns within the research community. Analysis of macro- and micro-level network indicators illuminates key trends, contributors, and structural features shaping the field.

Significant opportunities for the development and present status of rheumatology research collaboration are revealed by network metrics which contribute to the advancement of the field. Strong regional research groups are always present when clustering coefficients are high. It is probable that these clusters function as center grounds for creativity and in-depth investigation of fields of study. For instance, close-knit partnerships frequently spur the creation of cutting-edge treatments or unique approaches. By highlighting scholars such as Paul Emery and Nicolino Ruperto as vital centers of cooperation, degree centrality fosters relationships throughout the field. Because of their wide networks, these people play a crucial role in starting extensive studies and obtaining funding. The concept of betweenness centrality highlights the function of middlemen such as Clifton O. Bingham III and Maxime Dougados in fostering interdisciplinary knowledge transfer and uniting disparate groups. They play a critical role in bringing disparate research initiatives together, which is essential for dealing with complicated rheumatological problems.

Successful recent global research cooperation in rheumatology shows how international cooperation can motivate further research projects. For example, the 2023 Global Rheumatology Summit promoted interdisciplinary knowledge sharing and featured state-of-the-art advancements [26]. Through the promotion of global research cooperation, the American College of Rheumatology (ACR) Global Research Exchange Program allowed researchers from various geographical areas to exchange methods and perspectives [27]. Similar to this, Brazil's Telessaúde Initiative showed how telemedicine could improve rheumatological care accessibility and equity, particularly in settings with limited resources [12, 13]. Additionally, the coronavirus disease 2019 (COVID-19) pandemic [28], reported in Wuhan, China in December 2019, spurred global funding initiatives, such as the 2020–2023 joint efforts by the European League Against Rheumatism (EULAR) and the ACR to support research addressing autoimmune and inflammatory conditions linked to COVID-19 [29]. The pandemic led to a surge in remote collaborations, facilitated by digital platforms. Funding opportunities for pandemic-related research further encouraged interdisciplinary approaches, integrating immunology and rheumatology expertise to address the shared challenges posed by autoimmune responses in severe COVID-19 cases. In this study, arti-

cles published up to 2023 were analyzed, so a sudden increase in network density was not measured, but if articles submitted during the COVID-19 pandemic are reflected in the data, this may have an impact on the analysis results, such as network density, in the future analysis. Therefore, these highlight the revolutionary effects of international collaboration on patient outcomes and research.

Practical implications of findings for future research and cooperation strategies

The metrics observed in this study can shape practical implications for future research policies and cooperation strategies.

High betweenness centrality researchers

Specifically, a high betweenness centrality rheumatology researcher could be invited to an international or regional conference to preside over collaborative research. Engaging researchers with high betweenness centrality can improve the sharing of knowledge and close regional gaps.

Network density boost

A more cohesive international research community can also be fostered by boosting network density through cross-regional collaborations. This approach can enhance the overall connectivity and integration of the global research network.

Support for global research partnerships

Funding organizations and legislators should support global partnerships and interdisciplinary research platforms in order to alleviate the fragmentation that has been noticed. Such support can facilitate more robust and sustained international collaborations.

Enhancing global connectivity

Global connectivity can be further improved by using digital tools that allow researchers who are spread out geographically to communicate in real time. Digital platforms, like those employed in Brazil's Telessaúde Initiative, can further enhance real-time collaboration among geographically dispersed researchers, improving global network connectivity.

Strengths and limitations of collaborative structures

The steady increase in rheumatology publications and the expanding co-authorship networks highlight the growing role of collaboration in advancing the field. The analysis identified influential contributors, such as Nicolino Ruperto and Josef S. Smolen, who maintained central positions across multiple metrics. These researchers served as focal points within their networks, facilitating knowledge dissemination and collaboration development.

Despite these advances, numerous disconnected components and low network density indicate limited integration across the global research community. The network density remained below 0.0005 across all decades, indicating sparse interconnectivity. While the clustering coefficient showed strong local collaborations, it highlighted fragmentation of global collaboration. This pattern suggests that researchers collaborate effectively in small groups, while broader integration remains challenging.

Temporal shifts in collaboration dynamics

Temporal analysis reveals significant shifts in collaboration patterns. The early period (1994–2003) showed predominantly localized rheumatology research networks, characterized by small, isolated clusters. This fragmentation restricted exchange of ideas and methodological cross-pollination. The middle period (2004–2013) demonstrated significant consolidation, with researchers such as Paul Emery (University of Leeds, UK) and Maxime Dougados (René Descartes University, France) emerging as key intermediaries. The most recent period (2014–2023) showed a slight reversal, exhibiting increased fragmentation despite community expansion. This trend may reflect growing specialization within rheumatology, as researchers focus on niche areas, potentially reducing global connectivity.

Global disparities and regional contributions

The analysis revealed significant regional disparities in rheumatology research contributions. The United States, the United Kingdom, and Germany consistently dominated the field, reflecting robust academic infrastructure and funding availability. Growing research contributions from China, Japan, and India indicate expanding research capacity in Asia, while Latin American countries such as Brazil and Mexico demonstrate promising progress despite resource constraints. These disparities highlight the need for targeted policies and international collaborations to bridge gaps between resource-rich and resource-constrained regions. Disparities include limited access to high-quality data, fewer opportunities for international collaboration, and a lack of investment in research and development. To enhance global research cooperation and integration, the following recommendations are proposed.

Recommendations for future research and collaboration to promote global integration

Network analysis of co-authorship patterns yields actionable insights for fostering interconnected research communities. Key recommendations include:

- Promoting cross-regional collaborations between high-performing and emerging research regions to enhance global integration.
- Leveraging influential researchers with high betweenness centrality to bridge disconnected components.
- Implementing digital platforms to facilitate communication among geographically dispersed researchers.
- Utilizing open access platforms to create an environment where researchers can share data and research findings in real time.
- Expanding investment in digital platforms to support remote collaborations, learning from successful models such as those implemented during the COVID-19 pandemic.
- Advancing interdisciplinary research by integrating cutting-edge information and communication technologies, AI, and large-scale data analysis.
- Establishing equitable funding mechanisms to prioritize grants for researchers in underrepresented regions, enabling their participation in international collaborations.
- Encouraging interdisciplinary collaborations by integrating rheumatology with adjacent disciplines, such as immunology, epidemiology, internal medicine, medical informatics, information engineering, and data science, to foster innovation and include researchers from diverse backgrounds at global levels.

Artificial intelligence: paving the way to a future with reduced disparities

Global initiatives such as the ACR Global Research Exchange Program have demonstrated remarkable success in connecting diverse research groups across international boundaries. This success validates their essential role in cultivating cross-border scientific partnerships.

The integration of AI technologies into these initiatives promises to amplify their impact through precise identification of high-potential collaborations and continuous monitoring of progress. An Analytics Dashboard (such as Google Analytics Dashboard and Microsoft's Power BI) would enable real-time visualization of active collaborations, quantitative assessment of network connectivity, and data-driven recommendations for enhancing research network cohesion. If integrated with AI technology, such a system could systematically identify underrepresented geographical regions and suggest strategic research partnerships based on complementary research interests and documented collaboration outcomes.

These technological tools align naturally with established programs such as Brazil's Telessaúde Initiative, addressing specific gaps in global research networks while optimizing resource allocation. The AI system could pinpoint regions facing limited access to medical services and generate evidence-based recommendations for targeted infrastructure investments. Furthermore, continuous AI-driven monitoring of these investments would yield actionable insights for optimizing resource distribution, ultimately advancing the goal of equitable access to rheumatological care worldwide.

Limitations

Data limitations warrant consideration. This study only used the WoS Core Collection database, which was selected for its extensive and carefully curated collection of globally recognized scholarly journals. Around 7,300 institutions use WoS, which contains more than 21,000 carefully chosen journals, as a trustworthy resource for university ranking policymaking and decision-making [30]. However, by excluding non-indexed publications, this exclusivity raises the possibility of bias and may leave out important collaborative efforts, particularly from developing research communities or resource-constrained areas.

The WoS Topic Search was used to extract the dataset using the keyword "rheumatology", and the publication years were limited to 1994–2023. Although this targeted extraction guarantees field relevance, it may still miss multidisciplinary works or studies categorized under more general headings. Although the analysis was made more efficient by these criteria, the methodology may unintentionally have limited the range of the results.

To improve the inclusivity and generalizability of findings, future research should consider combining different indexing platforms and more datasets. By adding more bibliographic databases such as Scopus or PubMed, these biases might be lessened, and a more comprehensive picture of international cooperation in rheumatology research could be obtained.

Conclusions

This study analyzed co-authorship network structures in rheumatology research from 1994 to 2023. The analysis revealed evolving dynamics of collaboration, marked by integration and fragmentation across 3 decades. Key researchers, including Nicolino Ruperto (Istituto Giannina Gaslini, Italy) and Josef S. Smolen (Medical University of Vienna, Austria), emerged as central figures who facilitated knowledge dissemination and strengthened collaborative ties within the field.

The number of rheumatology publications increased steadily, reflecting an expanding research community. However, low network density and numerous disconnected components indicate persistent challenges in achieving broader integration. High clustering coefficients demonstrate robust local collaborations, while limited global network connectivity suggests that researchers collaborate effectively within smaller groups but interact less across the broader international community.

Regional disparities are evident, with underrepresented areas, such as Africa, South America, and parts of Asia, exhibiting lower connectivity and participation. Addressing these disparities through targeted initiatives, such as funding and international collaboration opportunities, will be essential for creating a more inclusive global research network.

Temporal analysis revealed significant consolidation during 2004–2013, with key researchers and institutions bridging various clusters. However, the period 2014–2023 saw increased fragmentation, likely due to growing specialization and diversification within rheumatology research themes. This fragmentation, coupled with low network density, highlights the need for better global integration, while high clustering coefficients across decades show strong local collaborations.

Additionally, AI and machine learning technologies have the potential to foster strategic collaborations by utilizing historical data to bridge existing gaps and enhance global connectivity. The global rheumatology research community can make revolutionary strides in patient care and scientific discovery by funding interdisciplinary and international networks.

Future investigations should examine strategies for bridging collaboration gaps and assess the impact of emerging technologies on global network dynamics. Continued mapping and analysis of co-authorship networks will enable the rheumatology field to address patient needs more effectively and accelerate scientific progress.

In conclusion, this study highlights the transformative potential of strategic collaborations in rheumatology research. By addressing network fragmentation and leveraging emerging technologies, the global rheumatology community can foster a more connected, equitable, and innovative research environment.

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