Tracing the Roots and Growth of Mathematical Ecology: A Bibliometric Review of Research Contributions and Impact.

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ABSTRACT
Mathematical ecology, the application of mathematical models to study ecological systems, enables analysis and prediction of population dynamics, species interactions, and ecosystem processes, supporting conservation and sustainable management. This bibliometric analysis explores the development and research trends within mathematical ecology using data from the Scopus database. Tools such as Biblioshiny and VOSviewer were employed to analyze annual scientific production, authors' contributions over time, and the most relevant sources in the field. A Three-Field Plot highlights the relationships between journals, authors, and keywords, illustrating the interdisciplinary nature of the research. Trend topics and a thematic map provide insights into evolving research focuses, blending traditional ecological themes with emerging computational techniques. A co-occurrence network of keywords uncovers key thematic clusters, emphasizing interdisciplinary approaches and connections within the field. Bibliographic coupling reveals influential sources driving foundational and modern advancements in mathematical ecology. The analysis of co-authorship by country highlights global collaboration, with the United States, China, and the United Kingdom emerging as central contributors. Despite a plateau in annual growth, the field demonstrates dynamic intellectual progress, particularly in areas like machine learning and sustainability. This study underscores the pivotal role of mathematical ecology in addressing complex ecological challenges through collaborative and interdisciplinary research.

1. Introduction

Mathematical ecology is a field that applies mathematical methods and models to explore and understand ecological systems[1], [2]. It serves as a bridge between mathematics and ecology, allowing researchers to quantify ecological processes and make predictions about ecological dynamics[3], [4]. By creating mathematical representations of biological interactions, scientists can better analyze complex ecological systems, often impossible to study directly in the natural world[5]. This approach helps ecologists simulate and predict changes in populations, communities, and ecosystems under various conditions, such as climate change, habitat loss, or species invasions[6].

One of the core areas of mathematical ecology is population dynamics, which focuses on understanding how and why populations of species change over time[7]. Mathematical models are used to study factors influencing population growth, decline, and stability, including birth and death rates, competition, and environmental carrying capacity[8]. These models are often expressed through differential equations, which provide insights into phenomena like predator-prey cycles, population explosions, or extinctions[9]. For example, the classic Lotka-Volterra equations describe how predator and prey populations interact and fluctuate over time, offering a foundational tool for ecologists studying wildlife management and conservation[10].

Beyond population studies, mathematical ecology also examines species interactions within communities, encompassing relationships like competition, mutualism, and parasitism[11]. These interactions can be modeled to explore how different species coexist or outcompete one another in a shared environment, revealing insights into biodiversity and ecosystem stability[12]. Spatial ecology models, which consider the movement and distribution of organisms across landscapes, are another essential tool[13]. These models help ecologists understand patterns of species dispersal and how landscape fragmentation or habitat corridors impact ecosystems[2]. Such analyses are crucial for conservation planning, especially for migratory species and species confined to small, isolated habitats[11].

Mathematical ecology is not only valuable for academic study but also for practical applications in environmental policy, conservation, and resource management[14]. It allows scientists and policymakers to make informed decisions about preserving biodiversity, managing fisheries, and controlling invasive species[15]. Moreover, mathematical models in ecology can incorporate stochastic factors—random events like natural disasters—that affect ecological stability and resilience[16]. By integrating these models with field data, researchers can generate more accurate forecasts of ecological outcomes, supporting sustainable management practices and helping society anticipate and mitigate environmental challenges[17]. Through its mathematical rigor, mathematical ecology thus plays a vital role in understanding and protecting our natural world.

Bibliometric analysis offers a systematic approach to understanding research trends, influential contributions, and emerging topics within a field, making it an ideal method to examine the development of mathematical ecology[18]. As an interdisciplinary field that integrates mathematics with ecological studies to model population dynamics, species interactions, and ecosystem processes, mathematical ecology benefits from a structured analysis of its research landscape. Tools like Biblioshiny and VOSviewer are essential in conducting this analysis, providing intuitive visualizations and robust metrics to evaluate patterns in publication, citation, and collaboration[19], [20].

Using Biblioshiny, a web-based extension of the Bibliometrix R package, researchers can conduct a detailed bibliometric analysis of mathematical ecology by importing bibliographic data from major research databases such as Web of Science or Scopus or Dimensions[19], [21], [22]. Biblioshiny facilitates the exploration of various indicators, including the most cited publications, top contributing authors, and the growth trajectory of research output over time[23]. Through visual tools such as word clouds, thematic maps, and citation trend graphs, Biblioshiny provides a dynamic view of key research themes and evolving areas in mathematical ecology, such as spatial ecology, disease modeling, and population dynamics. These insights help to highlight the historical development of the field as well as emerging areas of interest, providing valuable context for researchers aiming to contribute to cutting-edge topics.

VOSviewer complements Biblioshiny by allowing for the creation of network maps that illustrate relationships between authors, institutions, and research themes. With its focus on co-authorship, co-citation, and keyword co-occurrence networks, VOSviewer reveals the intellectual structure of mathematical ecology, identifying clusters of related research and highlighting prominent collaborations and influential studies[19], [24]. By visualizing these connections, VOSviewer helps uncover the collaborative networks driving innovation in mathematical ecology and reveals research communities that are shaping the field's direction[25], [26]. Together, Biblioshiny and VOSviewer offer a comprehensive toolkit for bibliometric analysis, enabling a nuanced understanding of the knowledge landscape in mathematical ecology and guiding future research directions.

The key objectives of conducting a bibliometric analysis on mathematical ecology include identifying research trends and the growth trajectory of the field to understand its development over time, as well as pinpointing key contributors and influential works to highlight foundational studies and prominent researchers. Another objective is to map collaborative networks and research communities through co-authorship analysis, revealing the collaborations that drive innovation. Additionally, bibliometric analysis aims to identify emerging themes and research hotspots by examining keyword co-occurrence and thematic trends, providing insight into new directions within the field. Finally, assessing the intellectual structure and knowledge gaps through co-citation and clustering analysis helps to understand the interconnectedness of research areas within mathematical ecology, guiding future research and uncovering areas for further exploration.

2. Materials and Methods

We obtained the scientific publications related to the investigation from the Scopus database [27], [28], [29]. We conducted a search using specific keywords such as "Mathematical Ecology" or "Mathematics" and "Ecology". The search was not restricted to any particular language, and the data included articles from peer-reviewed journals, book chapters, and conference papers. We collected 2084 articles from 931 different sources, spanning 1957 to 2024. To ensure accuracy, we screened the

Scopus records to remove any duplicates. The results were saved as a "CSV" file, and we performed bibliometric analysis on the data using VOSviewer andBibloshiny software.

3. Results and Findings

3.1. Critical Aspects of the Investigations

Table 1 presents critical aspects of the investigation of the bibliometric analysis of mathematical ecology highlights a well-established and impactful field with steady research contributions spanning from 1957 to 2024. With 2,084 documents and an extensive citation network totaling 68,866 references, the field's research is foundational, with an average document age of 15.5 years and 33.52 citations per paper, reflecting both the longevity and influence of core studies. Despite this impact, the field shows an annual growth rate of 0%, suggesting a potential plateau in publication output or a shift in research focus. The substantial diversity in topics is evident from the high number of Keywords Plus (11,381) and Author's Keywords (5,488), highlighting the broad range of research areas within mathematical ecology. Author collaboration is notable, with an average of three co-authors per document and 19.24% of works involving international co-authorship, though 485 single-authored documents indicate that there remains room for increased collaboration. The predominant document type is journal articles (1,695), supplemented by conference papers (313) and book chapters (76), underscoring the field's preference for peer-reviewed articles. Overall, the analysis portrays mathematical ecology as a collaborative and diverse research domain, with a well-cited foundation and opportunities for growth through interdisciplinary and global partnerships.

Table 1. Key aspects of the investigation

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1957:2024
Sources (Journals, Books, etc)	931
Documents	2084
Annual Growth Rate %	0
Document Average Age	15.5
Average citations per doc	33.52
References	68866
DOCUMENT CONTENTS	
Keywords Plus (ID)	11381
Author's Keywords (DE)	5488
AUTHORS	
Authors	5476
Authors of single-authored docs	423
AUTHORS COLLABORATION	
Single-authored docs	485
Co-Authors per Doc	3
International co-authorships %	19.24
DOCUMENT TYPES	
article	1695
book chapter	76
conference paper	313

3.2. Annual Scientific Productions

Figure 1 shows the annual scientific production in mathematical ecology, which shows a gradual increase from the late 1950s to the 1960s, with low initial activity and occasional years with no publications. The field began to gain momentum in the 1970s, with steady growth continuing through the 1980s and 1990s. Significant expansion occurred in the 2000s, with article counts jumping from under 40 to nearly 60 by 2007. The 2010s saw a sharp rise in output, peaking in 2015 and 2016 with over 110 articles each year, reflecting a surge in research interest and possibly technological advancements. Although publication numbers dipped slightly after 2016, they remained high, with an average of 80–100 articles annually through 2024, indicating a sustained and robust research community in mathematical ecology.

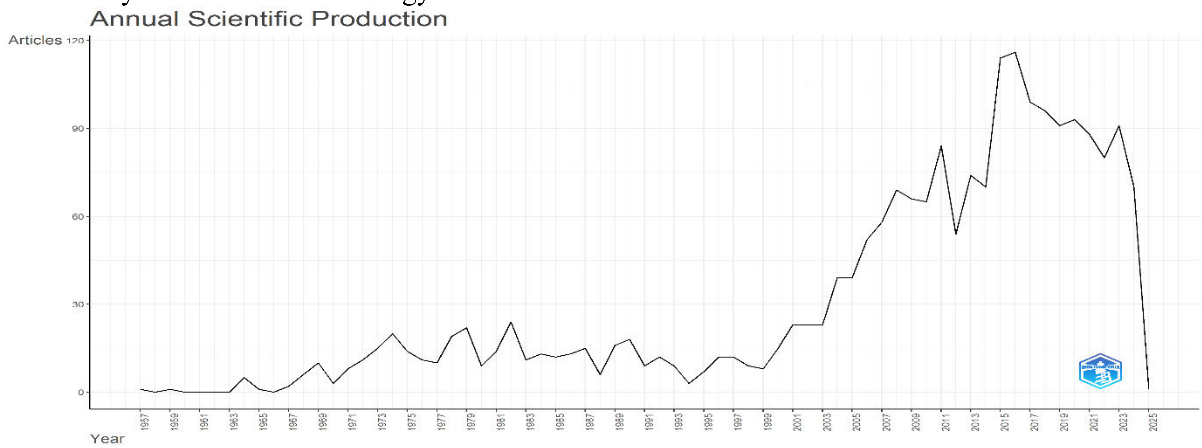

Figure 1.Publication trends in mathematical ecology

3.3. Authors' Production over Time

Figure 2 showcases the research activity of notable authors in mathematical ecology, displaying the quantity and impact of their publications across the years. Each author is represented by a row, where dots indicate the number of articles published per year; larger dots represent more publications, while darker shades correspond to higher citations, signifying greater influence. Authors like González-Olivares, Eduardo, and Takeuchi, Yasuhiro, demonstrate consistent contributions over extended periods, while others, such as Tang, Sanyi, show concentrated bursts of productivity and impact in recent years. This visualization highlights key contributors, reveals trends in research productivity, and illustrates shifts in scholarly influence within the field over time.

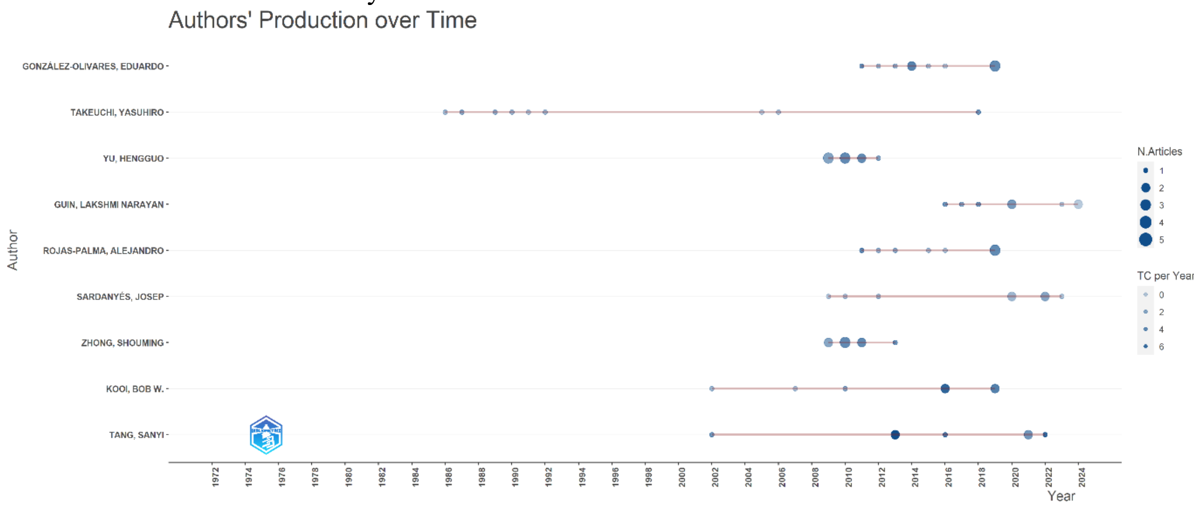

Figure 2. Authors' Production over Time

3.4. Most Relevant Sources

Table 2 lists the top journals and conference proceedings by the number of articles published in mathematical ecology. Leading the list is *Ecological Modelling* with 62 articles, followed closely by *Mathematical Biosciences* with 59 articles, and *Journal of Theoretical Biology* with 50 articles. Other significant sources include the *International Journal of Bifurcation and Chaos* (33 articles), *Bulletin of Mathematical Biology* (32 articles), and *Journal of Mathematical Biology* (31 articles), indicating a strong presence of interdisciplinary and theoretical journals. Additionally, journals such as *Chaos,* *Solitons and Fractals* (30 articles) and *Ecological Indicators* (28 articles) highlight the focus on complex systems and ecological metrics. Conference proceedings like the *ACM International Conference Proceeding Series* (26 articles) and the journal *Science* (24 articles) round out the list, showcasing a blend of both specialized and broad scientific platforms that contribute to the field's literature. This ranking demonstrates the diverse academic channels through which mathematical ecology research is disseminated.

Table 4. Most relevant Sources

Sources	Articles
ECOLOGICAL MODELLING	62
MATHEMATICAL BIOSCIENCES	59
JOURNAL OF THEORETICAL BIOLOGY	50
INTERNATIONAL JOURNAL OF BIFURCATION AND CHAOS	33
BULLETIN OF MATHEMATICAL BIOLOGY	32
JOURNAL OF MATHEMATICAL BIOLOGY	31
CHAOS, SOLITONS AND FRACTALS	30
ECOLOGICAL INDICATORS	28
ACM INTERNATIONAL CONFERENCE PROCEEDING SERIES	26
SCIENCE	24

3.5. Three-Field Plot

Figure 3, the Three-Field Plot, illustrates the relationships among sources (journals), authors, and keywords in mathematical ecology research. It highlights publication trends and research focuses within the field. Key journals like *Ecological Modelling*, *Chaos, Solitons and Fractals*, and *Journal of Mathematical Biology* are central in publishing mathematical ecology works and connect with prominent authors such as González-Olivares, Eduardo, and Rojas-Palma, Alejandro, indicating their substantial contributions. Major research themes, represented by keywords like "bifurcation," "stability," "predator-prey model," and "periodic solution," show the prevalent topics within mathematical ecology. The plot reveals how these sources publish works from influential authors and how each author's research aligns with specific topics, showcasing the interdisciplinary and collaborative nature of the field and providing insight into the primary research interests and contributions of leading authors.

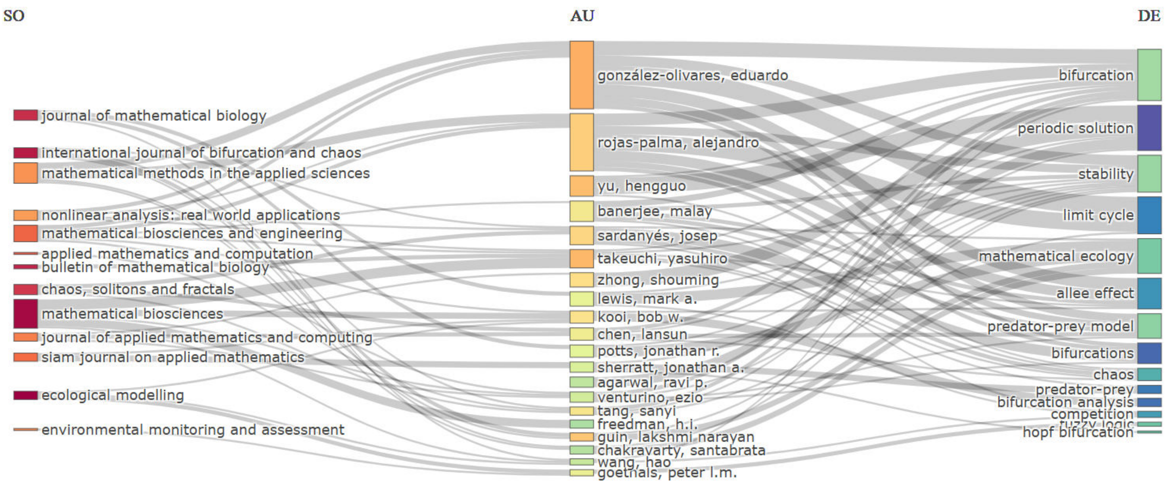

Figure 3. Three-Field Plot among sources (journals), authors, and keywords

3.6. Trend Topics

Figure 4 displays the evolution of key research terms in mathematical ecology over time, highlighting both the emergence and frequency of these terms. Each row represents a term, with dots marking years when the term appeared in publications. The size of the dots reflects term frequency, with larger dots indicating a higher occurrence in a given year. This trend analysis offers insights into shifting research focuses and emerging areas of interest within mathematical ecology.Key observations include the prominence of terms like "predator-prey model," "bifurcation," and "stability," which have been frequently explored topics, especially in recent years, as indicated by large dots. Other terms, such as "machine learning" and "sustainable development," have gained relevance more recently, reflecting modern approaches and interdisciplinary integration within the field. Terms like "fuzzy logic," "fuzzy comprehensive evaluation," and "analytic hierarchy process" suggest an increasing interest in complex and computational methods for ecological analysis. The sustained frequency of foundational terms like "population dynamics" and "mathematical modeling" underscores the enduring importance of these core concepts. Overall, the chart highlights the field’s evolving landscape, with recent trends showing a blend of traditional ecological topics and contemporary computational techniques.

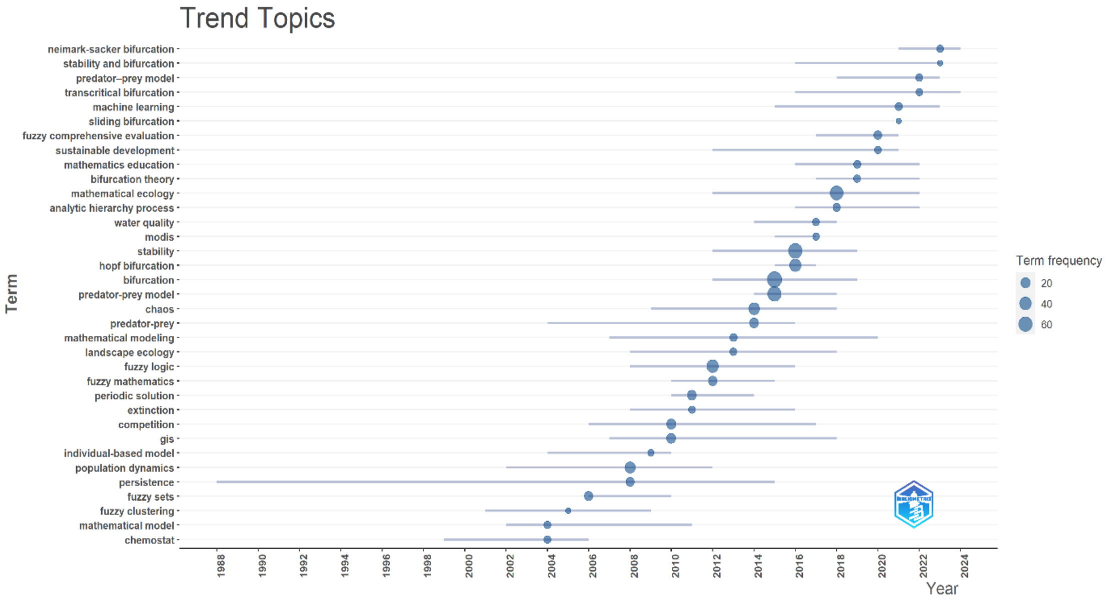

Figure 4. Trending topics in mathematical ecology research

3.7. Thematic Map

Figure 5,the thematic map categorizes keywords in mathematical ecology into four quadrants, highlighting their roles and relevance within the field. In the Basic Themes quadrant (lower right), foundational topics like "ecology," "mathematical ecology," and "population dynamics" are highly central but less developed, representing essential research areas. Nearby, "bifurcation," "stability," and "predator-prey model" are also core themes, showing slightly higher development, indicating their importance in ecological modeling. In the Niche Themes quadrant (upper left), specialized topics such as "fuzzy mathematics," "fuzzy comprehensive evaluation," and "analytic hierarchy process" are well-developed but less central, pointing to narrower areas of study. The Emerging or Declining Themes quadrant (lower left) contains "periodic solution," which may represent a topic that is either gaining interest or fading in relevance. Notably, the Motor Themes quadrant, which would typically contain highly central and developed areas driving the field, is empty, suggesting that mathematical ecology lacks a universally dominant, well-developed theme, instead relying on a foundation of core and niche topics.

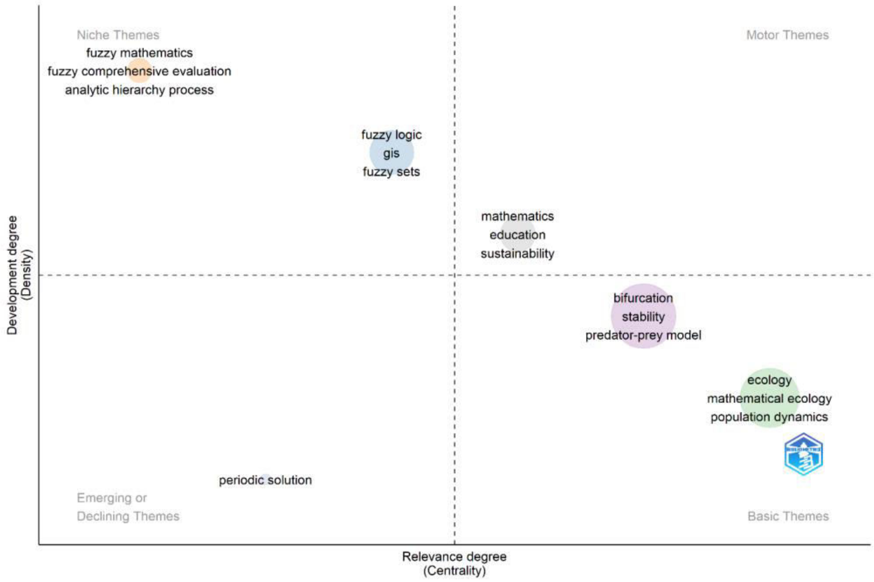

Figure 5. Thematic visualisation of keywords

3.8. Co-occurrence of all keywords

Figure 6, the co-occurrence network map displays the interrelation of keywords in mathematical ecology, illustrating connections among 480 frequently occurring terms, divided into four clusters based on their thematic associations.

Cluster 1 (Red, 222 keywords): This cluster includes terms like "fuzzy mathematics," "trees (mathematics)," "decision making," and "sustainable development," indicating a focus on fuzzy logic, decision sciences, and environmental applications. It emphasizes interdisciplinary approaches, integrating GIS, regional planning, and hydrology, which are relevant for ecosystem analysis and sustainable practices.

Cluster 2 (Blue, 119 keywords): This cluster centers around "mathematics," "population genetics," and "nonbiological model," focusing on theoretical and genetic aspects of ecology. Keywords related to evolution, population models, and molecular biology suggest an emphasis on mathematical models for biological processes, particularly in genetic and evolutionary studies.

Cluster 3 (Green, 115 keywords): This cluster, with terms like "ecology," "bifurcation (mathematics)," and "predator-prey systems," highlights core ecological concepts and mathematical models. Topics like population dynamics, predator-prey interactions, and bifurcation analysis indicate an emphasis on traditional ecological modeling, focusing on the dynamics within ecosystems and mathematical analysis of stability and persistence.

Cluster 4 (Yellow, 24 keywords): This smaller cluster features keywords such as "education," "students," and "engineering education," reflecting an educational theme. It appears to focus on the pedagogical aspects of mathematical ecology, linking the field to topics in education and curriculum development, potentially related to training the next generation of ecologists and mathematicians.

Overall, the network map reveals the field's interdisciplinary nature, with significant clusters focused on applied ecological modeling, genetic and population dynamics, fuzzy logic applications, and educational aspects. The connections among clusters suggest a complex interplay between theoretical, applied, and educational research themes within mathematical ecology.

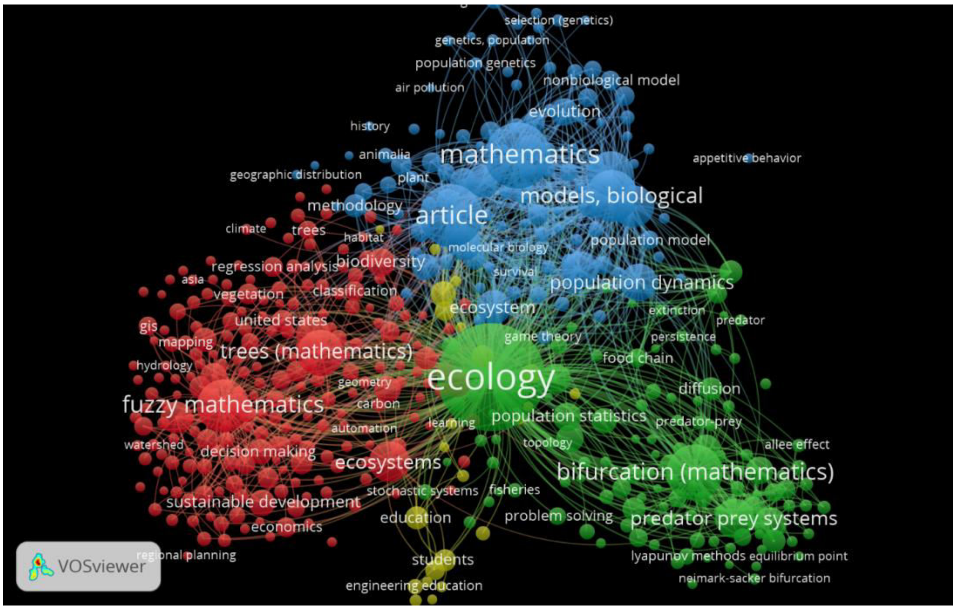

Figure 6. Co-occurrence of all keywords

3.9. Co- authorship of Countries

Figure 7illustrates the collaborative relationships between countries in mathematical ecology research, with the United States serving as the central hub, indicating extensive global partnerships. Prominent contributors like China, the United Kingdom, France, and India also show substantial international connections, reflecting their active roles in the research community. The countries are divided into nine clusters, each highlighting regional and cross-regional collaborations. For instance, a green cluster features European countries like the Netherlands, Switzerland, and the Russian Federation, while a red cluster includes Asian countries such as China, India, and South Korea, demonstrating significant regional networks. South American countries like Brazil, Colombia, and Chile form a yellow cluster, with connections to Europe and North America, showing a blend of regional and international cooperation. The United Kingdom is part of a blue cluster with strong ties to other European countries, showcasing close collaboration within Europe. Smaller clusters, such as those involving Romania and Israel, indicate more isolated but focused partnerships. Overall, the network reflects the global and interconnected nature of mathematical ecology research, where North America, Europe, and Asia are particularly active in cross-regional collaborations, fostering a dynamic environment for shared knowledge and innovation in the field.

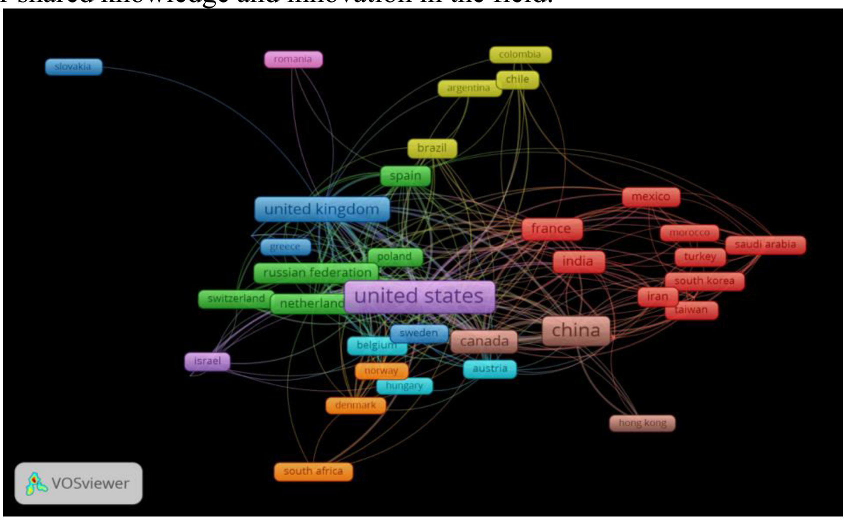

Figure 7. Network visualisation of countries' collaborations

4. Discussions

The bibliometric analysis of mathematical ecology highlights the field's foundational and impactful contributions to understanding ecological systems through mathematical modeling. Spanning from 1957 to 2025, the research demonstrates a robust citation network with a high average citation rate, reflecting its influence on ecological and interdisciplinary studies. Despite an annual growth rate of 0%, indicating a potential plateau, the analysis identifies a wide range of research areas, from population dynamics and predator-prey systems to emerging topics like sustainable development and machine learning. Tools like Biblioshiny and VOSviewer reveal how collaboration and interdisciplinary approaches drive innovation, with notable contributions from international co-authorships and established journals such as Ecological Modelling and Mathematical Biosciences. Thematic trends illustrate a balance between traditional ecological themes and contemporary computational techniques, signaling the field's dynamic evolution.

Key findings from co-authorship and keyword networks underscore the interdisciplinary and global nature of mathematical ecology. Collaborative hubs, especially the United States, China, and the United Kingdom, demonstrate the field's interconnected research environment, fostering knowledge sharing and innovation. Clustered analyses reveal thematic intersections, including theoretical ecology, fuzzy logic, and education, with practical applications in sustainable practices and conservation planning. Additionally, gaps in universally dominant themes suggest opportunities for targeted research growth, emphasizing the importance of diverse, collaborative efforts in addressing ecological challenges. The study affirms mathematical ecology's critical role in advancing ecological understanding, supporting conservation strategies, and integrating new computational methodologies to tackle global environmental concerns.

5. Conclusion

The bibliometric analysis of mathematical ecology reveals it as a foundational yet evolving field, effectively combining mathematical rigor with ecological inquiry to address complex environmental challenges. The steady citation rate and diverse research topics, including population dynamics, species interactions, and sustainable practices, highlight its academic and practical significance. Despite its established impact, the field's annual growth rate indicates a potential need for reinvigoration through interdisciplinary approaches and innovative methodologies. Collaborative efforts, particularly across international research networks, play a crucial role in advancing the field's contributions. To further strengthen mathematical ecology, it is recommended that researchers actively integrate advanced computational tools, such as machine learning and artificial intelligence, to explore novel ecological phenomena. Greater emphasis on fostering global collaborations and increasing participation from underrepresented regions can expand the field's scope and inclusivity. Additionally, targeted research addressing contemporary ecological issues, such as climate change and biodiversity loss, can ensure the field remains relevant and impactful. These efforts can drive the growth of mathematical ecology, reinforcing its critical role in ecological research and environmental sustainability.

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