



Global Research Trends and Thematic Development on the Biological Protective Effects of Boron: A Comprehensive Bibliometric Analysis (1990-2025)

Aşkın TEKİN*

Giresun University, Şebinkarahisar Health Services Vocational School, Giresun, Türkiye

Received: 29.08.2025

Accepted: 31.10.2025

Published: 30.11.2025

How to cite: Tekin, A. (2025). Global research trends and thematic development on the biological protective effects of boron: A comprehensive bibliometric analysis (1990-2025). *J. Anatol. Env. Anim. Sci.*, 10(6), 844-860. <https://doi.org/10.35229/jaes.1773399>

Atıf yapmak için: Tekin, A. (2025). Borun Biyolojik Korumucu Etkileri Üzerine Küresel Araştırma Eğilimleri ve Tematik Gelişmeler: Kapsamlı Bir Bibliyometrik Analiz (1990-2025). *Anadolu Çev. ve Hay. Dergisi*, 10(6), 844-860. <https://doi.org/10.35229/jaes.1773399>

*ORCID: <https://orcid.org/0000-0002-0362-9387>

*Corresponding author's:

Aşkın TEKİN

Giresun University, Şebinkarahisar Health Services Vocational School, Giresun, Türkiye

✉: askin.tekin@giresun.edu.tr

Abstract: This study aims to provide a comprehensive bibliometric analysis of the biological protective effects of boron, combining quantitative and qualitative approaches to map the field's structural characteristics, conceptual evolution, and research dynamics. Articles published between 1 January 1990 and 6 August 2025 were retrieved from the Web of Science Core Collection using a topic-based search strategy with specific inclusion and exclusion criteria. After filtering by document type, language, and subject categories, a total of 848 articles were included. Data were analyzed using the Bibliometrix R package (version 2025.05.0) and its Biblioshiny interface, while VOSviewer (version 1.6.18) was employed to visualize co-authorship networks at the author and institutional levels.

This study delivers an integrated overview of the current state and thematic orientation of research on the biological protective effects of boron. The results provide a robust reference framework to guide future investigations, foster international collaboration, and promote the strategic development of this interdisciplinary domain.

Keywords: Boron, biological protective effects, oxidative stress, bibliometric analysis.

Borun Biyolojik Korumucu Etkileri Üzerine Küresel Araştırma Eğilimleri ve Tematik Gelişmeler: Kapsamlı Bir Bibliyometrik Analiz (1990-2025)

Öz: Bu çalışma, alanın yapısal özelliklerini, kavramsal gelişimini ve araştırma dinamiklerini haritalandırmak için nicel ve nitel yaklaşımları birleştirerek borun biyolojik koruyucu etkilerine ilişkin kapsamlı bir bibliyometrik analiz sunmayı amaçlamaktadır. 1 Ocak 1990 ile 6 Ağustos 2025 tarihleri arasında yayınlanan makaleler, belirli dahil etme ve hariç tutma kriterleri ile konu bazlı bir arama stratejisi kullanılarak Web of Science Core Collection'dan elde edilmiştir. Belge türü, dil ve konu kategorilerine göre filtrelendikten sonra, toplam 847 makale dahil edilmiştir. Veriler, Bibliometrix R paketi (sürüm 2025.05.0) ve Biblioshiny arayüzü kullanılarak analiz edilirken, VOSviewer (sürüm 1.6.18) yazar ve kurumsal düzeylerde ortak yazarlık ağlarını görselleştirmek için kullanılmıştır.

Bu çalışma, borun biyolojik koruyucu etkileri üzerine yapılan araştırmaların mevcut durumu ve tematik yönelimine ilişkin entegre bir genel bakış sunmaktadır. Sonuçlar, gelecekteki araştırmalara rehberlik etmek, uluslararası işbirliğini teşvik etmek ve bu disiplinlerarası alanın stratejik gelişimini desteklemek için sağlam bir referans çerçevesi sağlamaktadır.

Anahtar Kelimeler: Bor, biyolojik koruyucu etkiler, oksidatif stres, bibliyometrik analiz.

INTRODUCTION

Boron (B) occurs naturally in soils, rocks and waters and is widely used in agriculture as it plays a crucial role in the growth and development of plants; its deficiency or excess can lead to serious yield and economic losses. In addition, boron, which is essential for the metabolic activities of many organisms, is used as a pesticide, antifungal and antimicrobial agent, and also serves as a structural support in cell walls and as a signalling molecule

in cellular communication (Uluisik et al., 2018). There is growing evidence that this vitamin has a variety of pleiotropic effects, ranging from anti-inflammatory and antioxidant benefits to the regulation of many body systems. In recent years, experiments have demonstrated disease-related boron polymorphisms in various species, drawing the attention of scientists to the importance of boron for health (Khaliq et al., 2018). Recent studies on the biological effects of the metalloid element B have shown that it is important as a trace element for a variety of organisms, including humans,

animals, plants, fungi, bacteria and algae, all of which require very small amounts of this element (Cikler-Dulger and Sogut, 2020). Boron is generally used for industrial purposes, but recent research has focused on its effects on metabolism (Aykal et al., 2024).

As a cofactor for certain enzymes involved in cell development and the metabolism of most proteins, carbohydrates and lipids, B is a necessary element (Prashanth et al., 2015). In nature, B is commonly found in borates such as colemanite (Col), ulexite (Ule), boric acid (BA) and borax (BX) (Turkez et al., 2022). Trace element B is essential for many biological processes such as calcium metabolism and the formation and maintenance of bone tissue (Rondanelli et al., 2020). Boron is a versatile trace element that, in adequate doses, provides significant benefits in areas such as immunity, antioxidant capacity, growth, embryonic development, brain function, liver development, osteoporosis, cancer treatment and wound healing. However, further research is needed to reduce its potential risks and increase its benefits (Khaliq et al., 2018). When boron compounds are ingested with food, they are broken down in the digestive tract and converted to boric acid (BA), which forms complexes with its hydroxyl groups with biomolecules such as glycolipids and glycoproteins (Çolak et al., 2022; Güney et al., 2022). The most widely used commercial forms of boron compounds include sodium perborate, colemanite, ulexite, boric acid (BA) and disodium tetraborate (borax) (Ince et al., 2018). Boric acid (H_3BO_3) is a soluble boron molecule that has anticarcinogenic, antioxidant, anti-inflammatory and anti-apoptotic effects. It is a metalloid, acidic, inorganic molecule that is necessary for the proper functioning of living organisms as it regulates membrane potential and enzyme activity (Nielsen, 2008). Boric acid has been shown to support the immune system, reduce inflammation, increase antioxidant levels, reduce oxidative stress and regulate the gut flora of lambs fed milk replacer (Uysal and Yoruk, 2025). Likewise, its protective and therapeutic potential has been demonstrated in various experimental models, including the prevention of cytotoxic, genotoxic, oxidative and apoptotic damage in human embryonic kidney cells (HEK293) exposed to ochratoxin A (Tekin et al., 2025). BA is helpful in minimising the negative effects of drugs used in cancer therapy and in reducing the amount of reactive oxygen species (ROS) due to its antioxidant and anticancer properties (Ogura and Shimosawa, 2014).

Recent studies have demonstrated the positive effects of boron on human health, highlighting its significant role in the treatment of gastric ulcers, cardiovascular and reproductive system diseases, DNA damage and cellular defence mechanisms, cancer, histological disorders, regulation of the antioxidant system and sepsis-induced acute lung injury (Gündoğdu et al, 2024; Al Khalif and

Sezer, 2025; Başer et al, 2025; Moussa et al, 2025; Keyif and Hacıoglu, 2025; Erguven et al, 2025; Zhang et al, 2025). Despite the considerable and growing body of evidence for the diverse biological functions of boron, the literature in this area is still spread across multiple disciplines, making it difficult to capture the full scope of research progress and thematic interrelationships. In such contexts, bibliometric analysis serves as a powerful methodological framework to systematically map the intellectual structure, highlight research fronts and identify emerging themes, thus providing a comprehensive overview of the field's development and future directions (Aria and Cuccurullo, 2017; Donthu et al., 2021).

Bibliometrics has become an important tool in both basic medical research and clinical research, providing quantitative insights into the growth of scientific knowledge, research productivity and collaborative practises. In the basic biological sciences, bibliometric methods help to track the emergence of new disciplines, identify fundamental discoveries and map intellectual structures (Guo et al., 2024; Abdelwahab et al., 2025). Numerous bibliometric and visualisation tools already exist to analyse research priorities and trends in a particular field of study (Tang et al., 2022; Wei and Jiang, 2023; Li et al., 2025; Abdelwahab et al., 2025; Zhang et al., 2025). It is important to take the results of bibliometric analyses with a grain of salt. Although such analyses can reveal trends and structural patterns in the research field, they alone are not sufficient to assess the development of the field or the significance of individual contributions. Therefore, in order to understand the dynamics of the field more comprehensively, a comprehensive approach was chosen that utilises both quantitative data and qualitative assessments (Zhong et al., 2024). To the best of our knowledge, previous bibliometric studies have focused on specific modalities such as boron neutron capture therapy (BNCT) or on boron-free topics such as biomaterials and oxidative stress. No previous bibliometric study has comprehensively positioned compound-specific tags such as boric acid, borax, and colemanite alongside biomedical themes within a unified co-occurrence network. (Cong et al., 2024; Wang et al., 2022). Our study addresses this gap by providing the first integrated visualisation that directly links compound-level distinctions to biomedical outcomes. Accordingly, this study systematically investigates the issue of the biological protective effect of boron by utilising advanced bibliometric analysis tools, including the Bibliometrix and VOSviewer. Moreover, according to our literature search, no bibliometric study has focused on the biological protective effect of boron so far. This paper presents the first comprehensive bibliometric synthesis of the multidisciplinary global literature (1990-2025) on the biological protective effects of boron, including antioxidant and oxidative stress

modulation, anti-inflammatory, antibacterial, anticancer, tissue repair, and biomaterial integration functions. No previous studies have treated these protective effects as a central theme or mapped their keyword co-occurrence and thematic evolution specifically for boron compounds (boric acid, borax, colemanite) (Araújo et al., 2024). The analysis aims not only to provide a comprehensive overview of the current state of the field, but also to identify prominent research topics, emerging trends and potential patterns in the literature. Furthermore, it maps the intellectual structure of the field by visualising the networks of interaction and collaboration between scientific publications. To this end, a total of 847 articles from the Web of Science (WoS) Core Collection database were analysed, representing one of the most comprehensive bibliometric assessments on this topic ever conducted.

MATERIAL AND METHOD

Methodology: The methodological framework adopted in this study, based on the integrative use of the Bibliometrix package in RStudio and VOSviewer software, aligns with recent global bibliometric investigations across diverse disciplines such as alternative food supply chains, mathematical economics, service innovation, and monoclonal antibody research. This dual-software strategy has been widely implemented and academically validated as a robust analytical approach (Tsilika, 2023; Kumar et al., 2024; Abdelwahab et al., 2025; Xi and Suhaiza, 2025).

This section provides a detailed explanation of the methodology used to review existing studies on the biological protective effects of boron using bibliometric analysis techniques. The process includes the following steps: Determining the data source, optimising the search terms, creating a search strategy, extracting the data, applying pre-processing and cleaning steps and incorporating the data into the analysis. A search was conducted in the Web of Science Core Collection database and articles published between 1 January 1990 and 6 August 2025 were found. The data were retrieved from the Web of Science Core Collection on 6 August 2025. The data obtained from these articles were analysed and bibliometric and visualisation analyses were performed using the Bibliometrix package in R (RStudio) and the VOSviewer software. Scopus and Dimensions offer broader coverage, including proceedings, book series, and preprints, and provide faster ingestion. However, this breadth tends to inflate recent-year counts and necessitates multi-stage de-duplication and reclassification to prevent topic drift. For the present purpose of mapping the biological protective effects of boron, the Web of Science Core Collection (WoSCC) provides a transparent baseline that aligns with prevailing scientometric practice. A targeted sensitivity check for the last three years indicated that incorporating Scopus records

does not alter the top 10 trends (keywords and leading countries), with only minor reordering beyond the top 10. The WoSCC is a prestigious academic database that catalogues high-quality articles and publications across all fields (Ma et al., 2022; Cheng et al., 2025). Although various alternative databases, including Scopus and Google Scholar, can support literature searches and bibliometric analysis, the WoSCC was selected as the preferred database for this study due to its esteemed reputation as the most appropriate platform for bibliometrics (Han et al., 2024). Temporal truncation was applied to avoid right-censoring. To minimise bias from indexing lag, we restricted the analysis window to 1990–2025 (cut-off 6 August 2025) and excluded 2026 from all trend and network summaries. This prevents artificial declines or spikes in annual output and topic trajectories.

Data Collection and Preparation: The analysis was mainly based on Clarivate Analytics' Web of Science (WoS) database, which is recognised for its uniqueness, reliability and completeness (Ayanwale et al., 2024). WoS is widely recognised for its superior authenticity and reliability when it comes to peer-reviewed academic publications (Pranckutė, 2021).

The bibliometric dataset for this study was compiled from the Web of Science (WoS) Core Collection, one of the most comprehensive and reputable databases for scientific literature. The search was conducted using the Topic field, which searches article titles, abstracts, author keywords and Keywords Plus. Articles published between 1 January 1990 and 6 August 2025 were searched to ensure broad temporal coverage of the research landscape on the biological protective effects of boron. The initial search returned 2,783 records. After applying these filters, the dataset was reduced to 847 articles. Table 1 summarizes the key inclusion/exclusion criteria, threshold settings, normalization methods, and clustering algorithms applied during the bibliometric and network analysis stages.

The datasets were exported in two formats: (1) in BibTeX format for use with the Bibliometrix and (2) as a tab-delimited text file for use with VOSviewer. Pre-processing included removal of duplicates, standardisation of author and institution names, and harmonisation of keywords to ensure accuracy and consistency of data prior to analysis (Figure 1).

Keyword Selection and Search Strategy: A systematic keyword selection and search strategy was developed to ensure the relevance and comprehensiveness of the dataset. The search was conducted in the Topic field of the Web of Science (WoS) Core Collection, which includes the title, abstract, author keywords, and Keywords Plus. The final search query was formulated as: *boron* AND ("protective" OR "oxidative stress" OR "apoptosis inhibition*" OR "DNA protection*" OR "antioxidant

activity*" OR "cell viability*" OR "cell protection*" OR "cytoprotection" OR "anti-inflammatory effect*"). This combination of general and specific terms was designed to capture publications addressing various aspects of the biological protective effects of boron, including its

antioxidant, anti-inflammatory, cytoprotective, and cellular viability enhancing properties. After applying document type, language, and subject category filters, only records directly aligned with the research scope were retained for further analysis.

Table 1. Supplementary Inclusion Criteria and Excluded Web of Science Categories.

Section	Description / Content
Inclusion Criteria	<ul style="list-style-type: none"> - Peer-reviewed journal articles investigating the biological or biochemical protective effects of boron, including antioxidant, anti-inflammatory, cytoprotective, antibacterial, and DNA-protective properties. - Publications must explicitly address boron's role in biological protection, cell viability, oxidative stress modulation, or inflammatory processes within biological systems. - Studies focusing on biomedical, biochemical, and physiological mechanisms of boron's protective roles were prioritized. - Only articles written in English and published between 1 January 1990 and 6 August 2025 were included.
Exclusion Criteria	<ul style="list-style-type: none"> - Non-research documents: Reviews, conference papers, book chapters, editorials, letters, and corrections. - Non-biological subject categories: Articles belonging to Web of Science categories unrelated to biological, medical, or biochemical research (listed below). - Research focused on non-biological aspects of boron, such as industrial boriding, surface coatings, metallurgy, nuclear technology, or material engineering.
Excluded Web of Science Categories (Detailed List)	<p>Materials Science Multidisciplinary, Materials Science Composites, Materials Science Characterisation Testing, Materials Science Textiles, Materials Science Paper Wood, Polymer Science, Applied Physics, Physical Chemistry, Spectroscopy, Thermodynamics, Nanoscience Nanotechnology, Metallurgy Metallurgical Engineering, Materials Science Coatings Films, Physics Condensed Matter, Materials Science Ceramics, Chemical Engineering, Analytical Chemistry, Electrochemistry, Physics Fluids Plasmas, Physics Particle Fields, Crystallography, Optics, Physics Multidisciplinary, Physics Nuclear, Inorganic Chemistry</p> <p>Mechanical Engineering, Environmental Engineering, Electrical Engineering Electronics, Engineering Manufacturing, Engineering Civil Engineering, Civil Engineering Building Services, Engineering Aerospace, Engineering Petroleum, Automation Control Systems, Engineering Industrial, Engineering Multidisciplinary, Instruments & Instrumentation</p> <p>Plant Science, Agricultural Science, Food Science Technology, Agriculture Dairy Animal Science, Agricultural Engineering, Agriculture Multidisciplinary, Soil Science, Horticulture</p> <p>Energy Resources, Water Resources, Green Sustainable Science Technology, Mineralogy, Mining Minerals Processing, Marine and Freshwater Biology, Environmental Engineering</p> <p>Computer Science Interdisciplinary Applications, Computer Science Artificial Intelligence, Computer Science Information Systems, Mathematical Computational Biology, Mathematics Interdisciplinary Applications, Statistics Probability, Information Science Library Science, Quantum Science Technology</p> <p>Biophysics, Medicine General Internal, Fisheries, Meteorology Atmospheric Sciences, Astronomy Astrophysics</p>

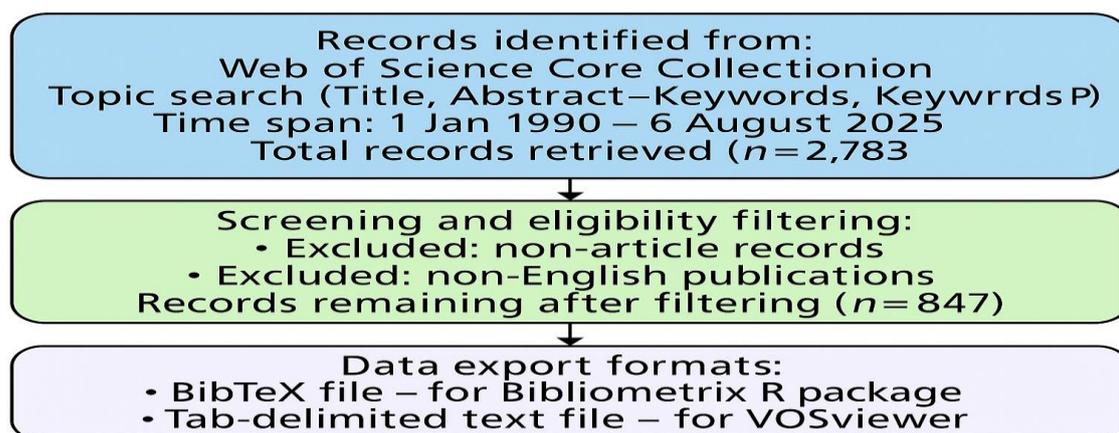


Figure 1. Workflow of Data Collection, Screening, and Export Process.

Visualisation and Interpretation of the Data:

Bibliometric analysis can assess the research capacity of authors and national institutions in the relevant field by examining current publications and analysing specific data, including nations or regions, institutions, journals and authors (Zhang et al., 2025). A variety of quantitative research methods are available in the Bibliometrix. It is

developed on an open-source platform and ecosystem using the R programming language. The strongest features of the software are the integrated data visualisation functions, meaningful and effective statistical algorithms and superior numerical operations. An open-source programme called Bibliometrix was developed for quantitative scientometric and bibliometric research and

covers a variety of bibliometric analysis techniques (Aria and Cuccurullo, 2017). Biblioshiny is the web-based version of the R tool Bibliometrix. The R programme Bibliometrix and the associated Biblioshiny online interface facilitate quantitative research in the fields of scientometrics and bibliometrics by providing comprehensive tools for converting bibliographic data into understandable information (Vătămănescu et al., 2024). The VOSViewer tool, developed for the creation and interpretation of bibliometric maps, was used to analyse the global publication environment (Mahanta et al., 2025).

In this study, the bibliometric data were analysed using the Bibliometrix and its web-based interface Biblioshiny in combination with VOSviewer (version 1.6.18). The Bibliometrix was used to perform advanced statistical analyses, generate performance indicators and create integrated visualisations for various bibliometric indicators, including annual scientific production, thematic development and patterns of keyword co-occurrence. In contrast, VOSviewer was used exclusively to visualise co-authorship networks at both author and organizational level. These visualisations provided valuable insights into the structures of collaboration within the field and helped to identify the main academic clusters and dominant research perspectives related to the biological protection

effects of boron. The use of both tools ensured that the analysis captured not only the quantitative trends, but also the structural and collaborative dynamics of the research field.

RESULTS

The bibliometric dataset retrieved from the Web of Science database comprises 847 documents published between 1990 and 2025 across 369 sources. The annual growth rate of 12.62% indicates that the research field is rapidly expanding and attracting increasing scholarly attention. A total of 4,442 authors contributed to these publications, with an average of 6.7 co-authors per paper, demonstrating a highly collaborative and interdisciplinary research culture. Approximately 22.67% of the works involved international co-authorship, reflecting the global engagement of this scientific community. The average document age of 7.01 years suggests that most studies are recent and aligned with current research trends. The dataset contains 35,485 references and an average of 29.06 citations per document, indicating a moderate to high research impact. In addition, the presence of 2,451 author keywords reveals the thematic diversity and richness of the research topics represented within the field (Figure 2).



Figure 2. Summary of Data Used for Analysis.

Evolving Words Source Growth: Table 2 presents the cumulative publication trends of the six most productive journals in the dataset from 1990 to 2025. Among these, Biological Trace Element Research has shown a remarkable and continuous increase since 2010, becoming the leading source with 71 cumulative publications by 2025. The Journal of Trace Elements in Medicine and Biology ranks second, exhibiting steady but moderate growth. The Journal of the American Chemical Society has maintained consistent output over time, reflecting its stable yet specialised contribution to the field. In contrast, ACS Omega, Ecotoxicology and Environmental Safety, and Scientific Reports show later but noticeable increases after 2016, indicating that these journals have more recently begun to publish actively on

the topic. Overall, the data suggest that research dissemination has diversified across multiple journals, with growing visibility in both chemistry- and environment-oriented outlets. A marked increase in publications has been observed after 2017, coinciding with the rapid expansion of research on boron-based nanomaterials and oxidative stress-related biomedical applications.

Network Analysis of the Common Occurrence of all Keywords: The co-occurrence network of author keywords, constructed using VOSviewer from the Web of Science Core Collection, reveals the conceptual landscape of research linking boron and oxidative stress. Two major thematic centres structure the network and connect four distinct clusters of related terms. Within this framework, boron-specific subtopics such as boric acid, borax, and

and oxidative mechanisms constitute the core of a multidisciplinary framework spanning materials science, toxicology, and biomedical applications (Figure 4).

Thematic Development: The thematic development map, generated through bibliometric analysis of author keywords, illustrates the temporal evolution of research themes related to boron and oxidative stress between 1990–2019 and 2020–2025. The visualisation connects earlier and more recent periods, showing how the main conceptual areas have changed over time. Each rectangle represents a keyword cluster, and the arrows indicate thematic continuity or divergence, highlighting how fundamental topics have evolved, fragmented, or merged into new interdisciplinary directions. The analysis shows that boron and oxidative stress remain the central nodes linking diverse thematic areas, including antioxidant

mechanisms, toxicity pathways, and disease associations. In the post-2020 period, both have advanced from foundational to motor themes, demonstrating increasing conceptual maturity and centrality in current research. Broader early concepts such as behaviour have gradually evolved into more specific topics, reflecting a methodological shift towards precision, application, and cross-disciplinary integration. Moreover, the emergence of graphene, boron nitride, BNCT, and scaffolds highlights the growing convergence of materials science and biomedical research, positioning boron-based studies as innovative drivers of both fundamental and applied research. Overall, the thematic development underscores a dynamic and transformative research landscape in which boron compounds bridge chemical, biological, and technological domains (Figure 5).

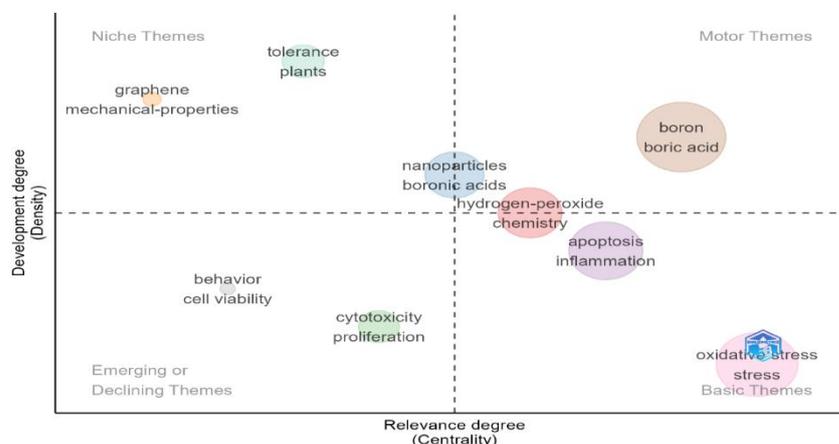


Figure 4. Thematic Mapping.

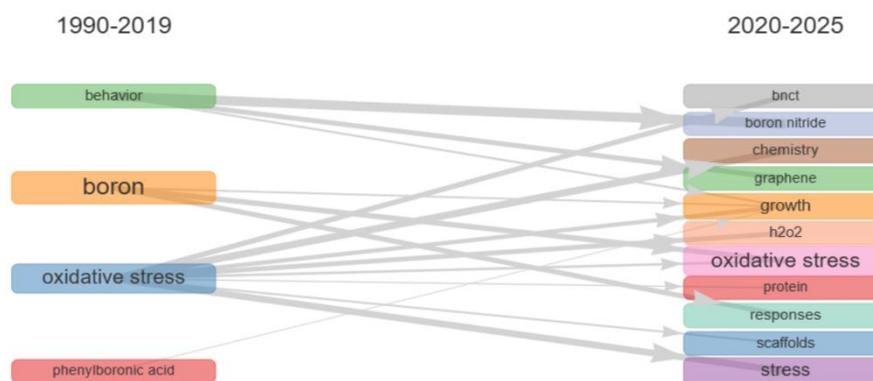


Figure 5. Thematic Evolution.

Multiple Correspondence Analysis: The conceptual structure map was constructed using multiple correspondence analysis (MCA) and hierarchical clustering to explore the intellectual organization of studies related to boron compounds and oxidative stress. Each point on the map represents an author keyword, with spatial proximity reflecting conceptual similarity. The two main dimensions (explaining 40.33% of the total variance) illustrate the relationships among terms, while color-coded

clusters indicate distinct thematic domains. Five main clusters were identified, corresponding to toxicological, biochemical, and organ-specific research subfields. The red cluster encompasses toxicology-oriented studies focusing on boron compounds, borax, acrylamide, lipid peroxidation, and cyclophosphamide, representing investigations into oxidative damage and chemical toxicity. The blue cluster highlights biochemical and cellular mechanisms such as apoptosis, cytotoxicity,

reactive oxygen species, and inflammation, reflecting the molecular basis of oxidative injury. The green cluster is associated with kidney and liver studies, suggesting research into organ-specific oxidative stress responses. Two peripheral zones emerge around glutathione and oxidative stress, representing specialised but conceptually focused topics—one emphasising antioxidant defence mechanisms, the other serving as a unifying concept across the entire field. The clustering of related terms such as cadmium, copper, boron, and hydrogen peroxide further indicates a continuing emphasis on the molecular mechanisms of oxidative stress and boron's biochemical interactions. Overall, the conceptual structure reveals a cohesive yet multidisciplinary field in which oxidative stress acts as both a mechanistic foundation and an integrative framework for toxicological, biochemical, and biomedical research (Figure 6).

Participating Countries: This map of country-specific collaboration illustrates the geographical structure

of global scientific production and collaboration networks, with the United States, China and Western European countries clearly the main players in both production and collaboration. The United States appears as the leading hub with intensive and frequent collaboration, especially with China and several European countries, as indicated by thick connecting lines. Intra-European links show strong cohesion, while Turkey appears as a regional link between European and Asian research. Canada, Australia and selected emerging countries (e.g. Brazil, South Africa) also show a notable presence within the network. However, large parts of Africa, South Asia and parts of Latin America are only represented to a limited extent, which emphasises the global inequalities. The overall structure points to a hub-and-spoke model, where most international collaborations are driven by a few leading producers rather than widely distributed multilateral networks (Figure 7).

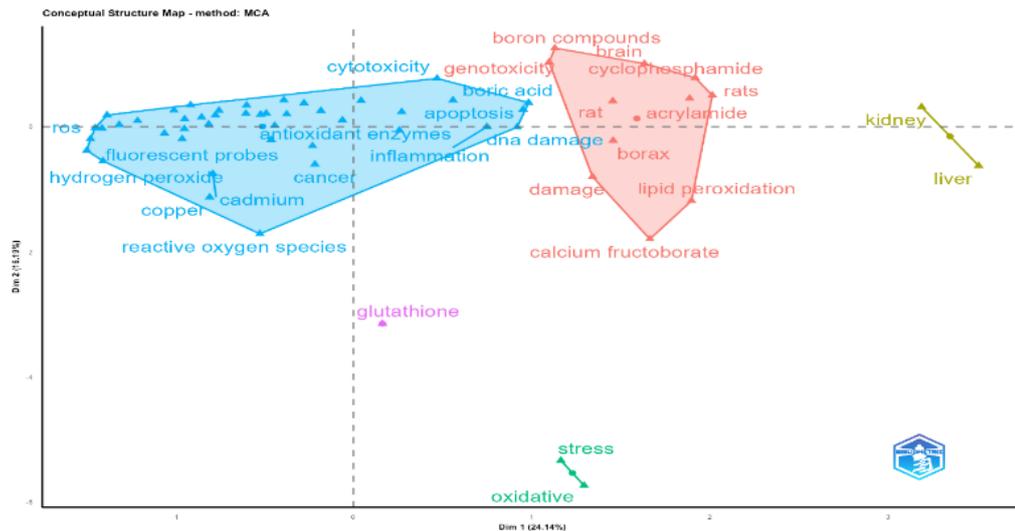


Figure 6. Conceptual Structure Map of Research on the Biological Protective Effects of Boron Using Multiple Correspondence Analysis (MCA).



Figure 7. Map of National and Regional Cooperation

This country-specific cooperation network illustrates a polycentric structure in global scientific cooperation, with the USA, China and Turkey as central players. The colored clusters represent cooperation communities: The blue cluster reflects a broad, globally integrated network centred on the US and China; the red cluster reflects a Euro-Mediterranean cooperation pattern led by Turkey; and the green cluster includes more isolated players such as the UAE and South Africa. The extensive connections of the US and China indicate their dominant position in international research networks, while Turkey plays a central role within its regional community, linking various European and neighbouring countries. This structure suggests that scientific cooperation is influenced not only by research priorities, but also by geographical proximity, shared history and strategic positioning (Figure 8).

Although both maps focus on international scientific cooperation, they offer different perspectives: The map of country-specific collaboration emphasises research output and the intensity of bilateral co-authorship, highlighting global research centres such as the USA, China and Turkey. In contrast, the network-based cooperation map shows the structural clustering of countries using the Walktrap algorithm and shows Turkey as a regional bridge within the Euro-Mediterranean cluster, while the US and China form the core of a globally integrated network. Taken together, these two views illustrate that scientific collaboration is not only a function of publication volume, but also of strategic positioning within interconnected research communities. This dual perspective emphasises the importance of analysing both quantitative output and qualitative structural roles and offers valuable insights for national science policy aimed at improving global visibility and impact.

Trend Themes by Year: In this analysis, the visualisation of the “trending topics” clearly shows the

thematic development of the research area over time. At the beginning (2005–2010), terms such as “protein”, “cataract” and “ascorbic acid” dominated, reflecting the focus on fundamental biochemical and physiological concepts. From 2011 onwards, terms such as “oxidative stress”, “antioxidant”, “boron” and “apoptosis” emerged strongly, indicating a shift towards cellular stress mechanisms and toxicological studies. In the most recent period (2018–2025), the emergence of terms such as “gene”, “hydrogel”, “scaffolds” and “antibacterial” marks a transition to more advanced biomedical applications, including gene-level interventions and biomaterials research. The increasing size of the bubbles illustrates the growing attention to these topics, while narrow IQR bands reflect the consistency of term usage within specific years. Overall, this development shows a clear thematic leap from molecular processes to applied translational research within the field (Figure 9).

Word Cloud Analysis: The word cloud analysis provides a visual representation of the most frequently occurring keywords in the analysed corpus. Dominant terms such as “oxidative stress”, “boron”, “boric acid”, “toxicity”, “apoptosis” and “antioxidant” clearly indicate the central focus of the research. These keywords reflect a strong thematic focus on cellular oxidative mechanisms, the biological and toxicological effects of boron and its compounds, and cell death pathways such as apoptosis. In addition, terms such as “dietary boron”, “inflammation”, “genotoxicity” and “lipid peroxidation” indicate multidisciplinary research involving nutrition, biochemistry and toxicology. The presence of terms such as “nanoparticles” and “cancer” indicates emerging overlaps with nanomedicine and disease modelling. This visualisation effectively underlines the thematic coherence of the dataset and highlights key concepts that are driving the research agenda in this area (Figure 10).

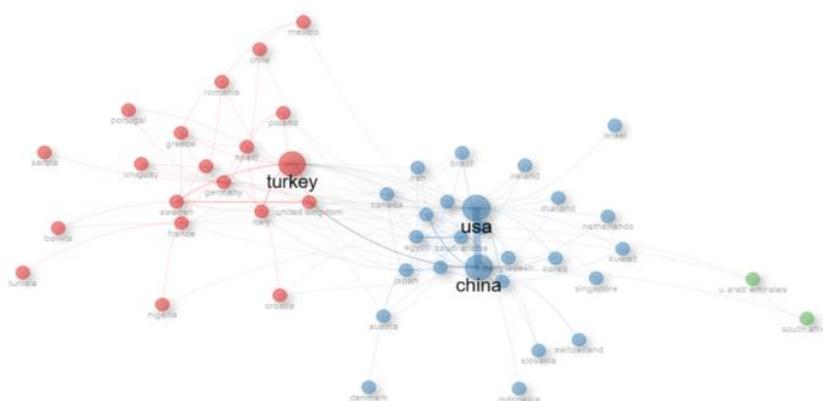


Figure 8. International Collaboration Network of Countries in Research on the Biological Protective Effects of Boron

“inflammation” and “lipid peroxidation” point to a deeper investigation of biochemical pathways and reactions at the cellular level. While Turkey appears to be the central hub, other countries such as China, Pakistan and selected European countries are contributing to a lesser extent. Chinese authors in particular are associated with

specialised topics such as “nanoparticles”. Overall, the analysis shows a research ecosystem that is highly centralised in Turkey, but also reflects emerging international contributions, especially in technically specialised subfields (Figure 12).

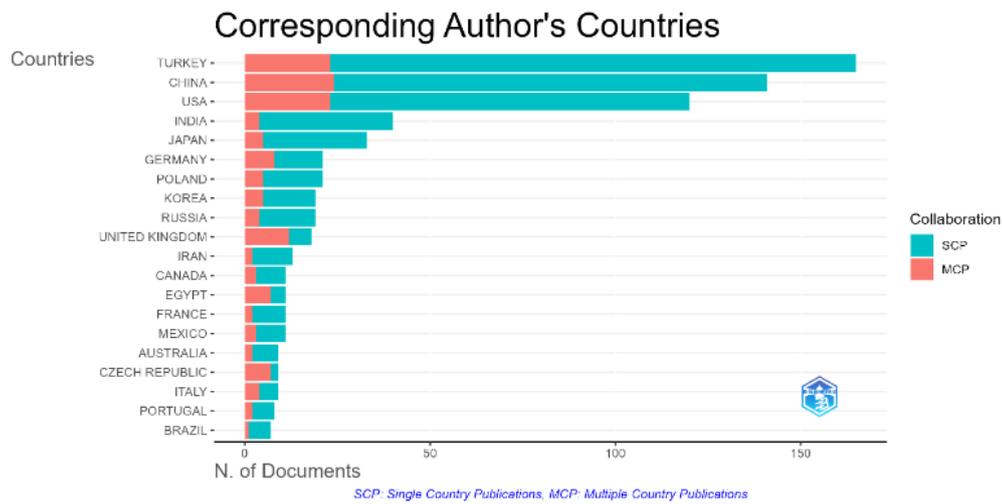


Figure 11. Corresponding Author's Countries.

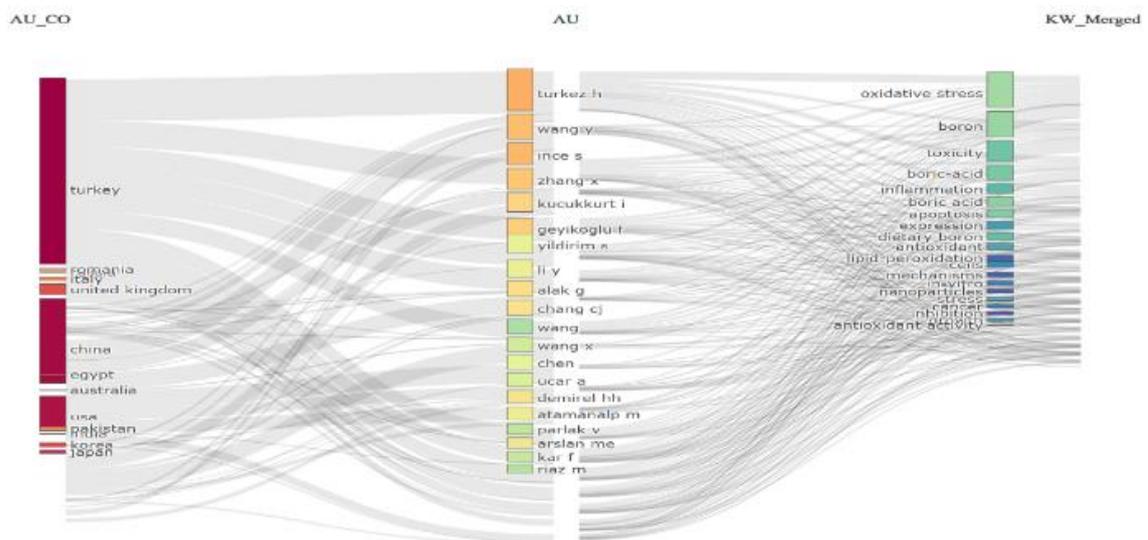


Figure 12. Three-Field Plot of Countries, Authors, and Keywords in Boron Research

Co-authorship Organisations: The “Co-Authorship Organizations” analysis carried out via VOSviewer shows the structure of inter-institutional scientific cooperation networks and identifies the organizations that occupy central positions within these networks. The results show that Atatürk University, with 58 publications and 1,182 citations, has the highest total number of connections (126) and is therefore at the centre of the network in terms of both productivity and academic influence. Afyon Kocatepe University is in second place with 25 publications and 752 citations, while Erzurum Technical University stands out with 21 publications and

323 citations. In terms of the influence of citations, the University of California, Berkeley, leads the international cooperation network with 2,702 citations. The Chinese Academy of Sciences (361 citations, 38 link strength) and Eskişehir Osmangazi University (353 citations, 43 link strength) also show strong collaborative engagement at national and international levels. The overall link strength metrics emphasise the central role of Atatürk University in building solid collaborations across continents, while UC Berkeley and other leading institutions use their high citation counts to maintain their academic prestige (Figure 13).

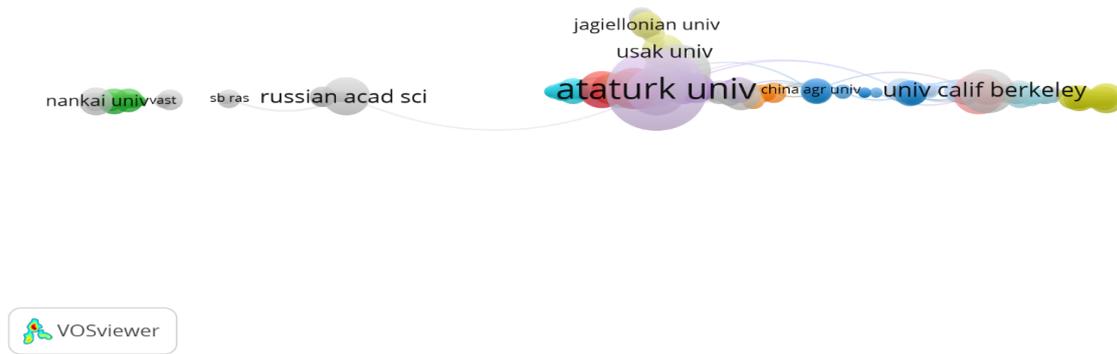


Figure 13. Collaborative Mapping of Research Institutions.

Co-authorship Authors: The VOSviewer-based “Co-Authorship Authors” analysis clarifies the structural characteristics of the scientific collaboration network among authors and identifies the central actors within this network. The results show that Hasan Türkez, with 33 publications, 881 citations and a total link strength of 162, occupies a dominant position in terms of both scientific productivity and structural centrality within the co-authorship network. Sinan İnce (16 publications, 649 citations, 72 link strengths) and Christopher J. Chang (16 publications, 2,616 citations, 51 link strengths) are also prominent nodes with both high output and high citation impact. In terms of citation metrics, Christopher J. Chang

has the highest scientific impact with 2,616 citations, followed by Bryan C. Dickinson with 1,257 citations. The modular structure of the network revealed by a cluster analysis shows distinct research communities in which authors such as Fatime Geyikoğlu, Abdulgani Tatar, Gonca Alak, Veysel Parlak and Serkan Yıldırım have a high degree centrality and dense collaborative links within their respective clusters. These results emphasise that the identified authors play a central role not only in terms of their individual research performance, but also in the formation and sustainability of national and international scientific cooperation networks (Figure 14).

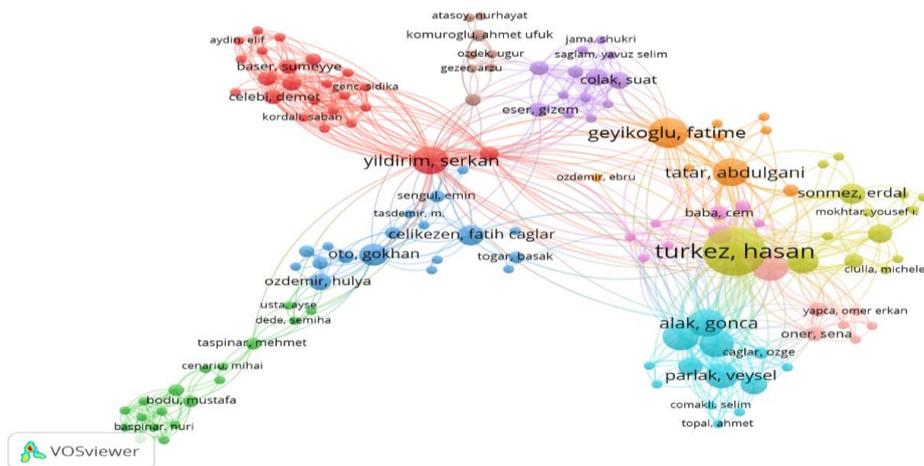


Figure 14. Mapping of Author Collaboration Networks.

DISCUSSION

This study presents a comprehensive bibliometric analysis of the biological protective effects of boron by integrating quantitative indicators (such as scientific output, keyword co-occurrence, citation and collaboration networks) with qualitative tools, including thematic mapping and word cloud visualisations. Based on 847 publications retrieved from the Web of Science Core Collection (1990–2025), the analysis uses Bibliometrix (R)

and VOSviewer to map the structural dynamics and conceptual evolution of the field, providing one of the most in-depth overviews on this topic to date. This study is among the few bibliometric investigations focusing specifically on the bioprotective effects of boron. For example, Du et al. (2024) conducted a bibliometric analysis on oxidative stress and male fertility, while Mustatea et al. (2025) mapped trace element–oxidative stress relationships; in contrast, our work applies the same analytical tools (Bibliometrix and VOSviewer) to the

underexplored nexus of boron, oxidative stress, and protective biological effects. Although several bibliometric analyses have been conducted on boron-related topics, they differ significantly in focus and scope from the present study. In the agricultural and plant nutrition context, Araújo et al. (2024) presented a bibliometric review on soil–plant boron status in eucalyptus, focusing on agronomic productivity, soil management, and plant toxicity or deficiency indicators. This study did not provide a thematic mapping of boron’s antioxidant, anti-inflammatory, or antimicrobial protective effects in human or vertebrate biology, and therefore differs from our study in both scope and purpose. In the therapeutic technology field, Cong et al. (2024) analysed research trends exclusively in Boron Neutron Capture Therapy (BNCT), limiting their study to boron’s role as a therapeutic or carrier agent without addressing its broader biological protective effects or its role within trace element biology. In the material and engineering context, studies such as the “Historical evaluation of the boriding process” (García-León et al., 2021) provide a bibliometric overview of surface engineering processes, but are unrelated to the biomedical or cytoprotective effects of boron.

This study presents a comprehensive bibliometric analysis of the biological protective effects of boron by integrating quantitative indicators (such as scientific output, keyword co-occurrence, citation and collaboration networks) with qualitative tools, including thematic mapping and word cloud visualisations. Based on 848 publications retrieved from the Web of Science Core Collection (1990–2025), the analysis uses Bibliometrix (R) and VOSviewer to map the structural dynamics and conceptual evolution of the field, providing one of the most in-depth overviews on this topic to date. This study is among the few bibliometric investigations focusing specifically on the bioprotective effects of boron. For example, Du et al. (2024) conducted a bibliometric analysis on oxidative stress and male fertility, while Mustatea et al. (2025) mapped trace element–oxidative stress relationships; in contrast, our work applies the same analytical tools (Bibliometrix and VOSviewer) to the underexplored nexus of boron, oxidative stress, and protective biological effects. Although several bibliometric analyses have been conducted on boron-related topics, they differ significantly in focus and scope from the present study. In the agricultural and plant nutrition context, Araújo et al. (2024) presented a bibliometric review on soil–plant boron status in eucalyptus, focusing on agronomic productivity, soil management, and plant toxicity or deficiency indicators. This study did not provide a thematic mapping of boron’s antioxidant, anti-inflammatory, or antimicrobial protective effects in human or vertebrate biology, and therefore differs from our study

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Numerous bibliometric studies exist in the field of oxidative stress; however, none are boron-focused. Bibliometric studies on oxidative stress and male fertility (2014–2023), retina, women’s reproductive disorders, and dry eye disease show methodological similarity (WoSCC, VOSviewer, CiteSpace) to ours, yet they do not address boron or boron compounds as a bioprotective theme. Hence, they do not examine the network or thematic position of terms such as boric acid, borax, colemanite, or boron-based nanomaterials. Despite methodological overlap, the thematic gap remains (Du et al., 2024). The “trace element bioactivity” literature is element-specific and fragmented, and no comprehensive bibliometric analysis exists for boron’s protective effects. For example, studies on selenium and bone focus on a single element and a single biological outcome (Wan et al., 2023). In contrast, our study integrates boron’s multi-mechanistic (antioxidant, anti-inflammatory, anticancer, antibacterial, and tissue-engineering scaffold) protective effects across disciplines within a unified bibliometric framework.

This 'all-keywords network' strongly suggests a research landscape that is primarily concerned with the multifaceted role of oxidative stress and boron/boric acid. These observations agree with previous experimental reports demonstrating the antioxidative and antibacterial properties of boric acid in animal and microbial models (Yaylacı, 2021; Başeğmez and Doğan, 2024). The field is highly interdisciplinary and encompasses fundamental biological mechanisms, toxicological assessments, potential therapeutic applications and links to major diseases such as cancer. The central importance of "oxidative stress" shows that it is a key mechanism or outcome that is studied in almost all subtopics, especially with regard to the biological interactions and effects of boron compounds. This is in line with the increasing realisation that oxidative stress plays a central role in the pathophysiology of numerous chronic diseases (Pizzino et al., 2017). Current cancer therapies include conventional chemotherapy, but research into novel drugs with anticancer potential is also progressing. Among these new agents, boron and its compounds are particularly noteworthy (Keyif and Hacıoğlu, 2025).

The "Thematic map with all keywords" created in this study effectively shows how important conceptual clusters such as boron, oxidative stress and related biological processes are structured in the literature by analysing their centrality and density. To fully evaluate the role of boric acid in cancer prevention or supportive care during chemotherapy, future research should investigate a wider range of boric acid doses, different *in vivo* models and more genotoxicity assays (Moussa et al., 2025). Further research is needed to determine the best frequency of administration of substances such as boric acid and to evaluate their effects on the immune system and infection with parasites or diseases (Öz, 2025).

Based on the insights gained through multiple correspondence analysis (MCA), the analyses of conceptual structure and thematic development presented in this study show that oxidative stress and boron compounds have become central and increasingly in-depth topics within the research field, while previously prominent concepts such as behavior have fragmented into more specific subtopics. Research has increasingly focused on toxicological effects, antioxidant defence mechanisms and biological responses at the organ level, providing new opportunities for interdisciplinary approaches. Although boron has been shown to have vital biological effects on minerals, some enzymes and hormones, the exact mechanism underlying these effects is still unknown (Kan and Kucukkurt, 2023). Therefore, further investigations are needed to explore the molecular pathways and physiological processes affected by boron, especially in relation to its antioxidant, anti-inflammatory and cytoprotective properties. The present bibliometric analysis contributes to this goal by mapping the structural and conceptual evolution of research in this field, thus identifying key themes, new topics and potential gaps for future studies.

The map of scientific collaboration shows a highly centralised global structure in which leading producers such as the US, China and Western European nations not only provide the bulk of research output, but also shape the global research agenda through extensive international partnerships. The results highlight Turkey as a dominant hub for academic production, particularly for topics such as "boron," "oxidative stress" and "toxicity," where research is largely driven by local authorship and domestic collaborations. The significant increase in publications after 2017 can be attributed to expanding research on boron-based biomedical nanomaterials (Aung et al., 2021) and the concurrent development of boron neutron capture therapy (BNCT) as a promising clinical application (Luo et al., 2023; Järvinen et al., 2023). One of the main reasons Turkey occupies a central position in the cooperation network is that the country possesses

approximately 70% of the world's boron reserves. China and European countries account for the largest share of Turkey's boron exports (Elevli et al., 2022). Furthermore, nationally targeted funding programmes and industry–university collaborations have acted as catalysts in increasing research output. Together, these elements explain Turkey's high level of collaboration in bibliometric findings within a scientific–political context. The results suggest that these researchers play a crucial role in maintaining the continuity of information flow and the integrity of both national and international scientific networks.

LIMITATIONS

The limitations of this study are related to the fact that the bibliometric analysis was only performed for documents indexed in the Web of Science (WoS) database and that some relevant articles may have been excluded during the data collection phase due to the use of certain keywords. Although WoS is widely used for bibliometric studies and covers a large number of relevant sources, other databases such as Scopus and Google Scholar may contain additional publications not included in this study, which could provide a more comprehensive and multidimensional picture of the research environment on the bioprotective effects of boron. Second, our analysis included only English-language research and review publications; non-English or non-research articles were not included, which would have led to some omissions.

CONCLUSION

This study provides one of the most comprehensive bibliometric evaluations of the bioprotective effects of boron to date, covering 847 publications retrieved from the Web of Science Core Collection between 1 January 1990 and 6 August 2025. By integrating quantitative indicators such as annual scientific production, keyword incidence, citation patterns and collaboration networks with qualitative findings from thematic mapping, thematic development and multiple correspondence analysis, the research provides a multidimensional understanding of the structural profile and conceptual development of the field. The results show that oxidative stress and boron/boric acid form the central conceptual axis linking different research areas from basic biological mechanisms to toxicological assessments and potential therapeutic applications. Emerging clusters, including cytotoxicity, behavior and cell viability, point to developing areas of interest that deserve particular attention. The analyses of co-authorship and institutional collaborations highlight the central role of leading authors, particularly Turkey as a thematic hub, while also demonstrating the influence of key authors and research

groups. Overall, the study not only outlines the current research landscape, but also creates a solid frame of reference to guide future investigations, foster collaboration and drive strategic progress in this interdisciplinary field.

The study of the biological protective properties of boron is a rapidly evolving area of research with promising opportunities for future studies in both basic science and medical applications. While the benefits of boron as a micronutrient for plants and animals have long been recognised, there has recently been increasing evidence of its positive effects on human health. In particular, boron compounds have been associated with reducing oxidative stress, modulating anti-inflammatory responses, preventing DNA damage and strengthening cellular defence mechanisms. Future research should focus on elucidating the specific cellular and molecular pathways underlying these protective effects to enable more effective utilisation of boron's therapeutic potential in both agricultural biotechnology and medical practice. In view of the identified bibliometric gaps, international collaboration, especially between emerging contributors and established research hubs, should be strategically encouraged to enhance knowledge exchange and research capacity. Policymakers may consider prioritising funding for boron-related studies focusing on human health applications, given their increasing relevance. Furthermore, experimental studies addressing underexplored areas such as behavioral outcomes, immune modulation, and the long-term safety of boron compounds could provide valuable data to support translational research.

ACKNOWLEDGEMENTS

Author's Contributions: The author contributed to the entire work on his own. Conceptualisation, Analysis; Writing-review and editing.

Conflict Of Interest: The authors declared that there are no conflicts of interest regarding the publication of this article.

Data availability: The author confirms that data supporting the findings of this study are available within the article.

Funding: None.

Ethical Approval: None

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