Research Article

Indian Journal of Extension Education
Vol. 62, No. 1 (January–March), 2026, (32-40)

ISSN 0537-1996 (Print)
ISSN 2454-552X (Online)

Global Research on Nutraceutical Crops: Bibliometric Analysis and the Latent Potential of Agricultural Extension

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HIGHLIGHTS

- A sharp increase was observed after 2020, aligning with greater health consciousness during the COVID-19 pandemic.
- Only a few terms related to agricultural extension, such as technology transfer and vertical farming, could be identified.
- At the country level, India stood out as the clear global leader, contributing more than twice and far ahead of China

ARTICLE INFO

Keywords: Nutraceuticals, Agricultural extension, Bibliometric analysis, Research trends, Sustainability.

https://doi.org/10.48165/IJEE.2026.62106

Citation: Sekhri, A., Ranawat, R., & Jain, H. (2026). Global research on nutraceutical crops: Bibliometric analysis and the latent potential of agricultural extension. *Indian Journal of Extension Education*, *62*(1), 32-40. https://doi.org/10.48165/IJEE.2026.62106

ABSTRACT

Nutraceutical crops are gaining importance for their role in improving nutrition, supporting health, and promoting sustainable agriculture. Yet, their impact depends on how effectively this knowledge is transferred to farmers through agricultural extension. This study analysed global research on nutraceuticals and agricultural extension using 3,485 Scopus-indexed publications between 2015 and 2024, with the primary objective of assessing the role of agricultural extension in bringing nutraceuticals to the grassroots level. Bibliometric tools (Biblioshiny and VOSviewer) were used to examine publication growth, authors, contributing countries, keyword patterns, thematic clusters, and collaboration networks. The analysis reveals steady progress over time, accelerating after 2020. India emerged as the clear global leader, followed by the USA and China, with institutional participation from universities such as Charles Sturt University and King Saud University. Research activity covered two main areas: themes related to agriculture and sustainability, such as food security, climate change, and farming practices; and studies on plant-derived compounds, including phytochemicals, antioxidants, and bioactive substances. The most important finding of this study is the near absence of extension-related themes. Although the search strategy included extension terms, they did not emerge as clusters or trends, highlighting a significant research gap.

INTRODUCTION

Nutraceuticals are gaining global attention as a crucial link between food, health, and sustainability. Nutraceuticals are defined as substances derived from food items with potential medicinal benefits (Souyoul et al., 2018). The term was introduced in 1989 by combining "nutrition" and "pharmaceutical," though its use has often been ambiguous (Gul et al., 2016). Beyond meeting nutritional requirements, they are valued for their potential to prevent and manage chronic diseases (Anand & Bharadvaja, 2022). It is frequently conflated with "dietary supplements," yet an important distinction exists. Dietary supplements primarily fulfil nutritional deficiencies, while nutraceuticals aim to prevent or support treatment of diseases (Mukherjee et al., 2017). This convergence of food and medicine has become a cornerstone of nutrition, with benefits ranging from improved immunity to chronic disease management (Telessy, 2019). Commonly studied nutraceuticals include omega-3 fatty acids, turmeric, garlic, and green tea, recognized for their therapeutic potential (Keservani et al., 2017; Vinayagam et al., 2023; Hay et al., 2019; Sarma et al., 2023).

Received 26-09-2025; Accepted 11-11-2025

Consumption of nutraceuticals has risen steadily, particularly after the Covid-19 pandemic. Increased health awareness has generated strong consumer demand (Santini et al., 2023). However, consumer interest alone is insufficient unless availability is ensured across geographies. Engaging farmers is therefore crucial to bring nutraceuticals to the food chain. In the Indian context, this is particularly important given the country's immense agricultural potential, being the second largest producer of rice and wheat and the top producer of pulses globally (Malik et al., 2023). Agricultural extension can play an essential role in ensuring that advances in nutraceutical science are translated into practice by equipping farmers with the knowledge and skills to cultivate and promote nutraceutical crops. Extension services can also provide platforms for organizing and applying knowledge across the agricultural sector, enabling research outcomes to be effectively adapted at the grassroots level (Nain et al., 2024).

Furthermore, recognizing farmer-led innovations is equally vital, as grassroots efforts often provide low-cost solutions for value addition and marketability. Yet such innovations remain under-recognised and lack institutional support, limiting their contribution to agricultural development (Nain et al., 2019). Nutraceutical crops may provide grassroots farmers with opportunities for crop diversification, entry into high-value markets, and potentially better profits than traditional staples (Mbelebele et al., 2024). Agriculture in India is evolving from traditional small-scale farming to approaches that focus on profitability and market opportunities, creating a need to support farmers in exploring innovative crop options. In this context, agricultural extension services play a key role by providing technical guidance, entrepreneurial support, and institutional connections that may help farmers adopt nutraceutical crops as sustainable sources of income (Kademani et al., 2024). The primary objective of this study is to identify and assess the role of agricultural extension, if any, in translating nutraceutical science from research settings to the grassroots level.

METHODOLOGY

This study was designed to conduct a bibliometric analysis of research on nutraceutical crops and agricultural extension. Data were collected from the Scopus database, which provides comprehensive coverage of peer-reviewed journals, books, and conference proceedings across agricultural sciences, life sciences, and allied disciplines. To ensure accuracy, breadth, and relevance, a carefully refined search string was constructed using the "ALL" field tag in Scopus to cover the core concepts: ALL ("Nutraceuticals" OR "Medicinal plants" OR "Phytochemicals" OR "Natural products" OR "Nutri-crops") AND ("Agricultural extension" OR "Extension services" OR "Farmer education" OR "Technology transfer" OR "Advisory services" OR "Agricultural innovation").

The initial execution of this search string retrieved 4,971 documents. A time filter was then applied to restrict the publication period from 2015 to 2024, which reduced the results to 3,746 documents. Documents were further filtered by selecting four specific categories, Article, Review, Conference Paper, and Book Chapter, a step that yielded 3,573 documents. Finally, an English language filter was applied, resulting in a retrieval count of 3,485 documents. This final dataset was retrieved for further analysis, ensuring a sufficiently large and representative dataset for meaningful interpretation.

The dataset was analysed using Bibliometrix (Biblioshiny 4.5.0), which generated descriptive indicators such as annual scientific production, prolific authors, institutional output, country-wise contributions, and keyword dynamics (Aria & Cuccurullo, 2017; Roy et al., 2024). Bibliometrix provided both quantitative and visual insights into publication trends, authorship patterns, institutional collaborations, and thematic evolution, thereby ensuring a multidimensional representation of the field. To complement these results and strengthen interpretation, network-based mapping was performed using VOSviewer (version 1.6.20), which created keyword co-occurrence networks using author keywords and visualized 420 keywords divided into eight clusters of related research topics, thus offering an additional layer of analytical depth (Wong, 2018). The bibliometric measures applied in this study included annual publication growth, leading authors, contributing institutions and countries, keyword frequency and co-occurrence, thematic mapping, and collaboration networks. All analyses were carried out following established bibliometric procedures to ensure reproducibility, transparency, and validity. The combined use of descriptive indicators, science-mapping, and network analyses therefore provides a more nuanced, reliable, and critically informed understanding of research activity, scholarly influence, and thematic development in the field of nutraceuticals and agricultural extension during the study period. During the initial processing phase in Biblioshiny, the software automatically removed 45 documents due to incomplete metadata, resulting in a dataset of 3,440 documents for the bibliometric analysis.

RESULTS

The results of the bibliometric analysis, based on 3,485 Scopus-indexed publications, provide a comprehensive overview of global research activity in the field of nutraceutical crops. Annual scientific production is first shown to illustrate the growth trajectory of publications over the last decade. Country- and institution-wise contributions were then reported to identify regional leadership and international participation. The conceptual structure of research is revealed through keyword co-occurrence patterns, thematic clusters, and the evolution of research themes across time slices, offering insights into the changing priorities of the field. Thematic mapping was further presented to differentiate between well-established, emerging, and niche areas of investigation. The intellectual structure has been demonstrated through core journals that formed the scholarly foundation of this research, while the social structure has been described by mapping collaboration networks among countries.

Descriptive analysis

The annual scientific production showed steady growth over the last decade, increasing from 112 documents in 2015 to a peak of 666 in 2024 (Figure 1). A sharp increase was observed after 2020, aligning with greater health consciousness during the COVID-19 pandemic. This suggests that nutraceuticals are increasingly being recognized as part of the solution to health resilience and sustainable agriculture.

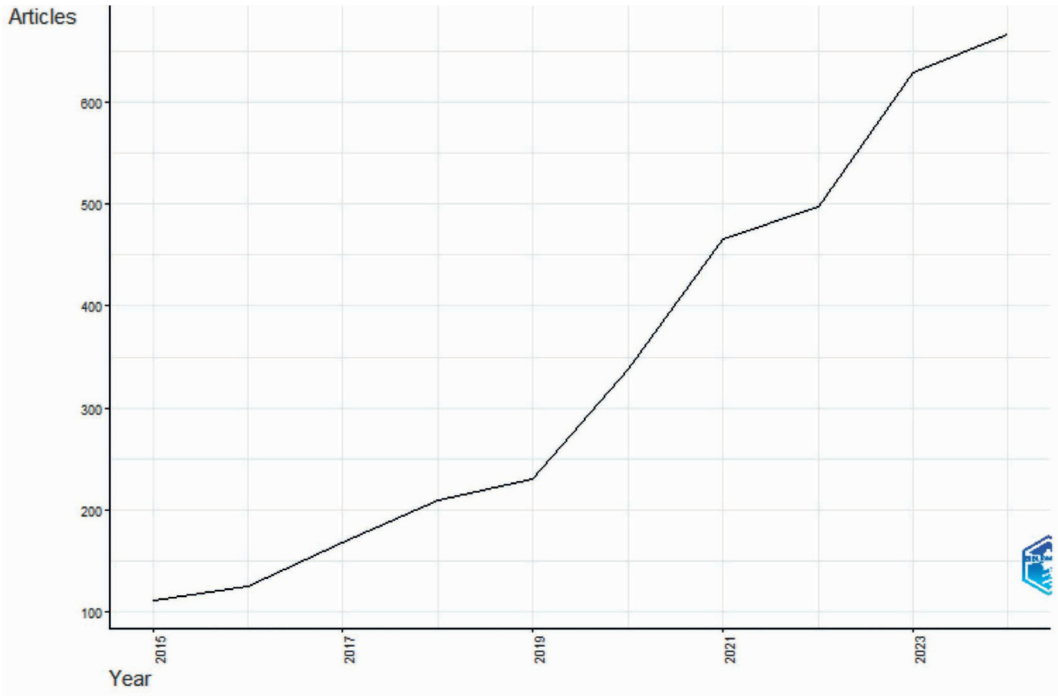


Figure 1. Annual scientific production

When looking at institutions, Charles Sturt University led with 180 publications, followed by King Saud University and the Vietnam Academy of Science and Technology with 60 each (Table 1). Among the most relevant affiliations, Indian institutions also featured, reflecting the country's strong institutional presence and leadership in nutraceutical research.

Conceptual structure of research

The keyword co-occurrence analysis organized 420 author keywords into eight clear clusters (Figure 2). These clusters represent diverse research themes ranging from agroecology and sustainable farming, natural compounds and phytomedicine, allelopathy and stress biology, ethnobotany and indigenous knowledge, anti-inflammatory agents, antioxidant activity, to fermentation and traditional foods. Together, these themes illustrate the dual orientation of the field towards system-level agricultural sustainability and detailed bioactive compound research. Within the keyword co-occurrence analysis, only a few terms related to agricultural extension, such as technology transfer and vertical farming, could be identified. Even within the clusters, these appeared with very limited visibility, suggesting that extension-oriented themes occupy only a marginal position in the overall research landscape.

Table 1. Most relevant affiliations

Affiliation	Articles
Charles Sturt University	180
King Saud University	60
Vietnam Academy of Science and Technology	60
School of Biosciences and Technology	57
Graduate University of Science and Technology	54
Prince of Songkla University	52
Jouf University	47
Maejo University	46
VIT School of Agricultural Innovations and Advanced Learning (VAIAL)	46
Chiang Mai University	45
University of Agriculture	44
Government College University Faisalabad	43
Shoolini University of Biotechnology and Management Sciences	43
Kyungpook National University	42
Tamil Nadu Agricultural University	42

The trend topics analysis (Figure 3) shows how the focus of research had shifted over time. In the early phase (2015–2017), themes such as weed management, organic agriculture, and biorefinery were more prominent, reflecting attention to farming practices and ecological management. By 2018–2020, the emphasis moved towards plant-based mechanisms, with keywords like polyphenols and allelopathy highlighting interest in phytochemical properties and plant interactions. In recent years (2021–2024), research has increasingly focused on antioxidants, food security, and climate change. This progression demonstrated a transition from practice-oriented agricultural themes to compound-focused investigations and, more recently, to health-oriented and sustainability-driven topics. Extension-related keywords were absent from the trend map, which reflects a gap in current research and point to the need for greater attention on how this knowledge could be disseminated effectively to farmers and stakeholders through agricultural extension.

The three-fields plot (Figure 4) shows an overview of the relationships between prolific authors, frequently used keywords, and institutional affiliations in the field of nutraceutical crops and agricultural extension. While the exact linkages between individual authors, keywords, and institutions are less distinct in the visualization, the plot as a whole highlights the diversity of research contributions and the spread of scientific activity across different themes and organizations. Authors such as Hussain M., Radha R., Senapathy M., and Kumar M. appeared among the most productive

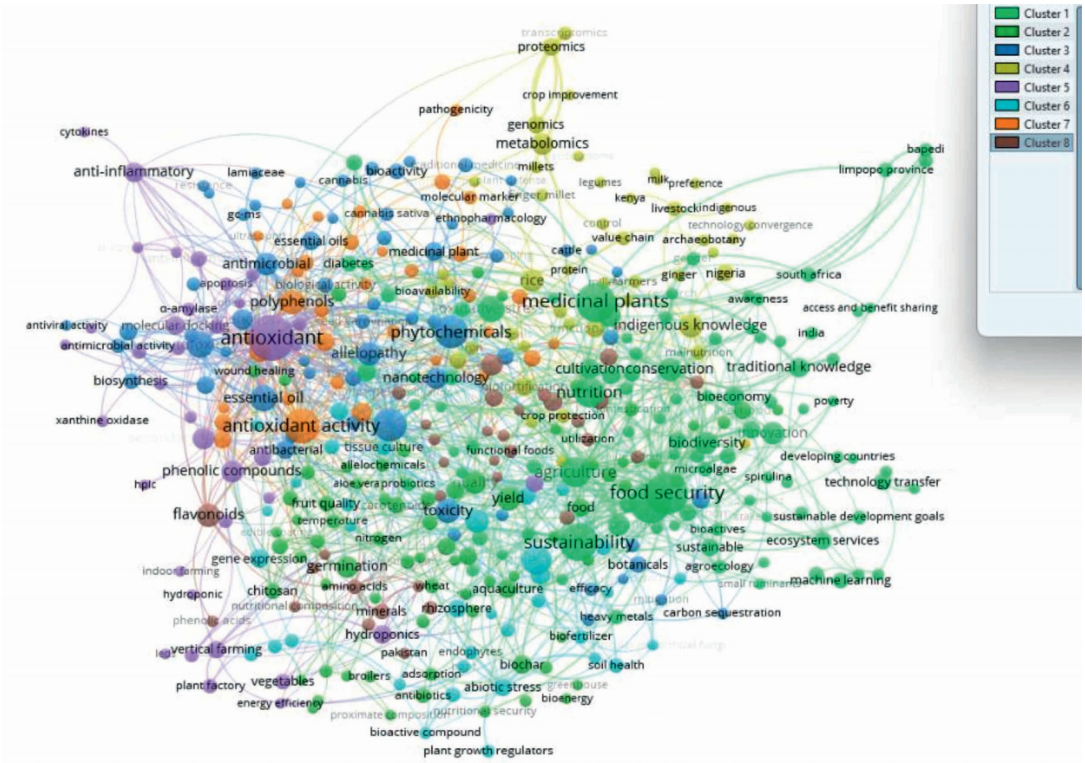


Figure 2. Keyword co-occurrence map

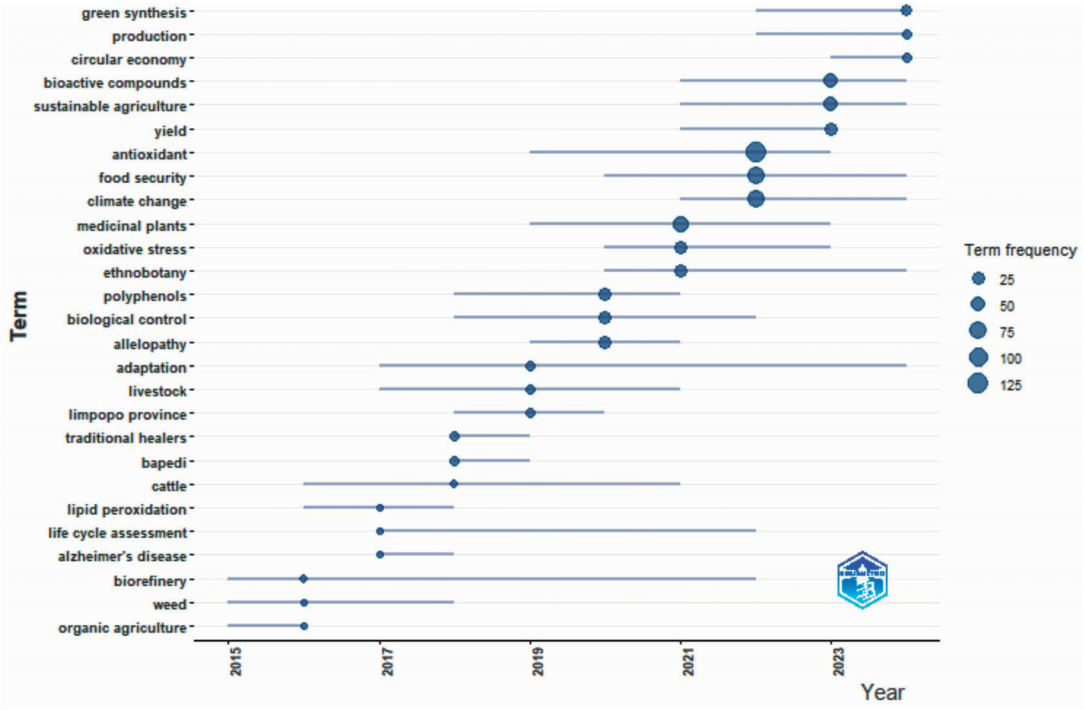


Figure 3. Keyword trend analysis

contributors, with keywords like antioxidant, medicinal plants, and phytochemicals standing out as recurring areas of focus. Prominent institutions included Charles Sturt University, King Saud University, and the Vietnam Academy of Science and Technology feature strongly, reflecting the global distribution of research capacity. Indian researchers and institutions feature strongly in the plot, reflecting the country's leading contribution identified in the country-level analysis. Taken together, the plot highlights the collaborative and cross-disciplinary nature of this field and suggests how clusters of authors, keywords, and institutions collectively shape its growth. It also signals potential opportunities for strengthening networks and expanding the reach of nutraceutical research into extension contexts.

The thematic map (Figure 5) highlighted 10 research clusters across two dimensions: centrality (relevance) and density (development). Motor themes such as sustainable agriculture,

Figure 4. Three-fields plot

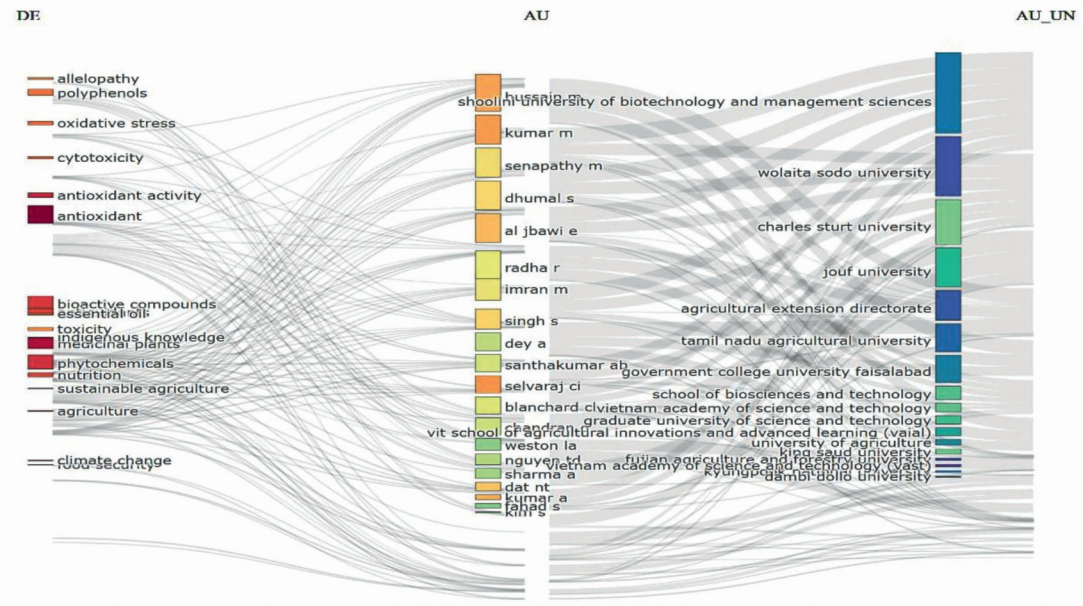
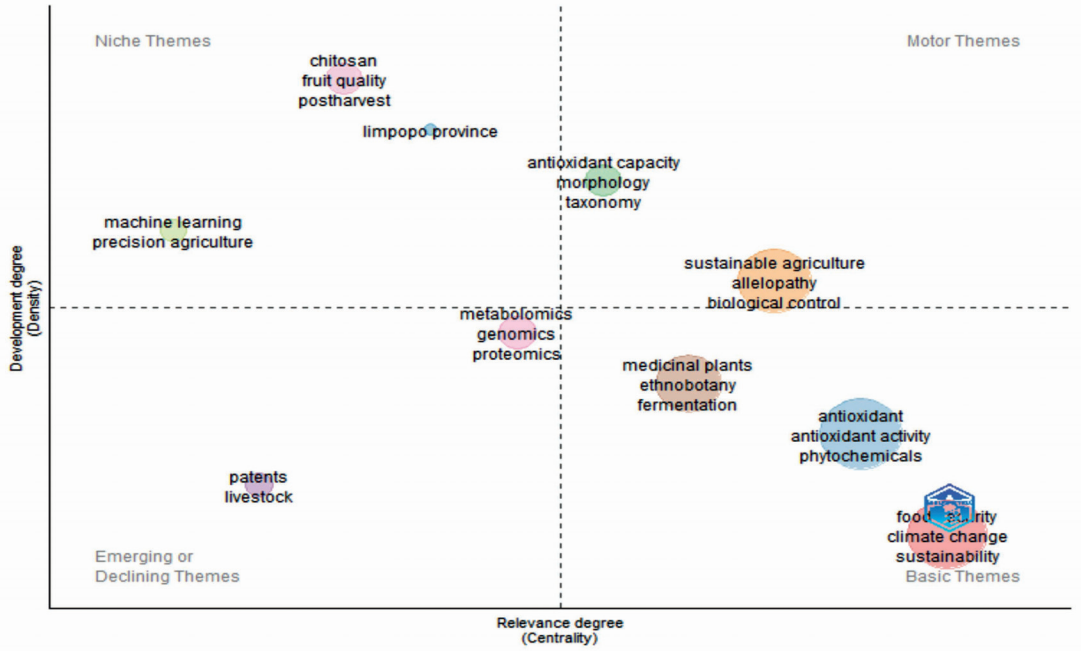


Figure 5. Thematic map



allelopathy, and biological control represented well-established areas driving the field. Niche themes like chitosan, fruit quality, and post-harvest were highly developed but less central. Emerging or declining themes including metabolomics, genomics, and proteomics required further exploration, while basic themes such as food security, climate change, and sustainability remained highly relevant yet demanded more structured research.

Thematic evolution across the three periods (2015-2020, 2021-2023, and 2024) shows how research on nutraceutical crops has gradually moved from narrow biochemical studies to broader and more technologically advanced approaches. In the first phase, most work focused on identifying and describing compounds such as antioxidants and polyphenols, reflecting an early effort to establish their health benefits. The second phase highlighted themes such as climate change, metabolomics, and antioxidant activity, showing that nutraceutical research was expanding to include both environmental concerns and advanced analytical tools. In the most recent period, topics such as food security, genomics, and antioxidants have gained prominence, pointing to renewed attention on sustainability and health outcomes alongside the use of cutting-edge molecular approaches.

Intellectual structure of research

The intellectual base of research on nutraceutical crops and agricultural extension is spread across a diverse range of journals, which reflect the interdisciplinary nature of this field (Figure 7). Important contributions were found in outlets such as *Asian Pacific Journal of Science and Technology, Plants, Sustainability*, and *Agronomy*. Each of these journals highlights a different perspective, from plant sciences and crop management to health, sustainability,

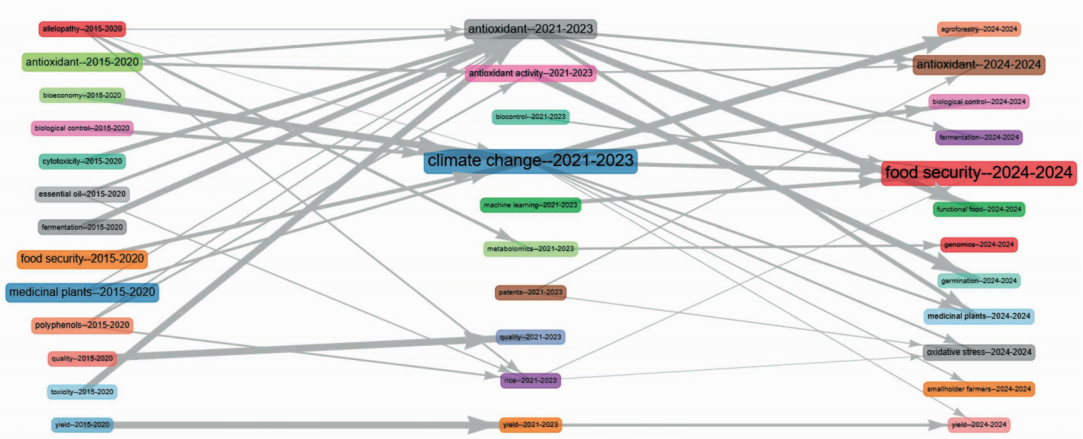


Figure 6. Thematic evolution

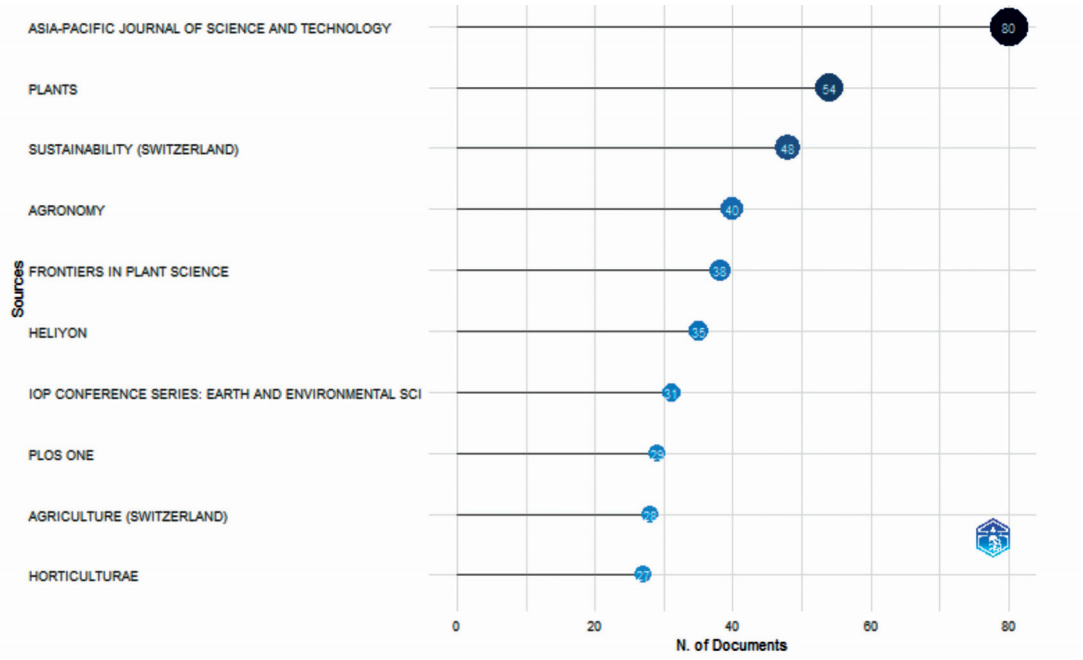


Figure 7. Most relevant sources

and policy. The distribution shows that nutraceutical research is not confined to one discipline but is drawn from agriculture, life sciences, food technology, and environmental studies.

Taken together, the journals form a layered structure. Some remain centred on compounds and health outcomes, others give priority to agricultural practices and productivity, while a growing share situates nutraceuticals within the broader sustainability agenda. This mix shows that the field is dynamic and strategically located at the intersection of agriculture, nutrition, health, and environmental responsibility. At the same time, extension-focused journals were largely absent from this picture. Their absence underlines the earlier finding that farmer education, technology transfer, and grassroots dissemination have not yet become integral to the intellectual foundations of nutraceutical research. Addressing this gap would help ensure that the growing body of knowledge reaches farming communities and contributes more directly to practice.

Social structure of research

The social structure of research on nutraceutical crops is shaped by international collaboration, with India, the United States, and China emerging as the leading hubs (Table 2). At the country level, India stood out as the clear global leader with 2,005 publications, contributing more than twice as much as the USA (920) and far ahead of China (689) (Table 2).

The significant output by India demonstrates a strong commitment to the field of nutraceuticals and establishes India as the most influential source of nutraceutical publications globally. Across Asia, the overall contribution was strong, but progress was uneven. Countries like India, China, and South Korea published heavily, while others such as Malaysia and Bangladesh remained on the margins, indicating that leadership was concentrated in only a few centres. African countries were also less visible in these networks.

DISCUSSION

The bibliometric analysis highlights the steady rise of research on nutraceutical crops and agricultural extension, with a sharp increase after 2020 reflecting health awareness and sustainability concerns. India emerged as the global leader, followed by the USA and China, reflecting its roots in Ayurveda and a growing research

Table 2. Country scientific production

Region	Frequency
India	2005
USA	920
China	689
South Korea	674
Pakistan	597
Thailand	534
Australia	454
South Africa	382
Nigeria	325
Italy	321
Indonesia	277
Saudi Arabia	264
Bangladesh	230
Malaysia	230
Ethiopia	217

base in agricultural and life science universities (Kizhakkeveettil et al., 2024; Kaur & Chakraborty, 2025). It underlines India's central role in shaping nutraceutical research through both cultural heritage and modern innovation (Silpi, 2025). China's research leadership is partly rooted in its long history of traditional medicine, providing a strong foundation for modern nutraceutical studies (Shen et al., 2017). The United States led through its powerful research infrastructure funding, and global influence in agriculture and health sciences (Odeyemi et al., 2024). While Africa and parts of Asia remain underrepresented, regional collaboration can foster inclusivity in nutraceutical research. In Nigeria, the high level of smart phone ownership and willingness to use generative AI tools indicated strong potential for digital transformation in agriculture and advocated digital literacy, infrastructure development, and inclusive access to extension services and AI-based tools (Shitu et al., 2025). Institutions such as Charles Sturt University and King Saud University were among the leading contributors, but several Indian universities also stood out as important affiliations. This highlights that regional priorities and traditional knowledge continue to shape global nutraceutical research, with India's strong presence in the three-fields plot reflecting its central and expanding role in the field (Malve & Bhalerao, 2023).

The conceptual analysis shows two orientations; system-level themes such as agroecology, food security, and sustainability, and compound-level research on phytochemicals, antioxidants, and bioactive metabolites. Over time, research shifted from traditional plant-based studies to advanced, technology-driven approaches like metabolomics and genome editing. India mirrors this progression, moving from studies on medicinal plants to research integrating sustainability and modern analytical tools (Pramanik et al., 2025). The intellectual analysis reveals how earlier publications were more commonly placed in plant science and pharmacology journals, emphasizing the identification of bioactive compounds and their therapeutic potential. Recently, research has shifted towards sustainability and agronomy journals, reflecting a broader focus on food security, climate resilience, and public health (Wichienchot & Ishak, 2017). This trend also aligns with the global shift towards plant-based diets, driven by the environmental and ethical costs of livestock production, including high greenhouse gas emissions, resource use, and biodiversity loss (Chen & Carcea, 2023). Nutraceutical crops are now positioned within this movement, valued for their health benefits and as part of sustainable food systems, including cereals, legumes, fruits, nuts, and emerging sources such as algae and mushrooms.

A striking observation of this study is the near invisibility of agricultural extension in the global nutraceutical research landscape. Although extension-related terms were included in the search, they did not form significant clusters or trends. This absence reflects a structural gap, as systems for translating nutraceutical knowledge to farmers and communities remain underdeveloped. The findings have important implications. Policymakers can use this evidence to develop extension strategies that integrate nutraceutical crops into mainstream agriculture and public health initiatives. Lessons may be drawn from climate-smart agriculture, where extension services promoted productivity, resilience, and sustainability by raising farmer awareness, promoting ICT tools, and facilitating joint learning among farmers, researchers, and extension workers (Raj & Garlapati, 2020). Similar innovative and participatory approaches can be adapted to ensure that nutraceutical crops move beyond laboratory and field trials and are embedded in farmer-oriented programs and community-level initiatives.

Extension workers can help farmers understand the benefits of nutraceutical crops, provide training on cultivation practices, and support value addition and marketing at the local level (Msuya et al., 2017; Singh et al., 2023). Including nutraceuticals in extension programs allows farmers to gain income and improve community nutrition. Farmer-led innovations, often simple, low-cost, and locally adapted, can be scaled through extension networks (Usadadiya & Rathod, 2025).

CONCLUSION

This study mapped global research on nutraceutical crops and agricultural extension between 2015 and 2024, confirming consistent growth and strong contributions from Asia. The analysis revealed dual themes: system-level topics like sustainability and food security, and compound-level studies on bioactive metabolites, reflecting the field's interdisciplinary nature. The absence of extension-related themes is the most pressing gap. For nutraceutical crops to benefit farmers, future research must move beyond lab and field trials to embed extension strategies that ensure effective dissemination, adoption, and value creation. Future priorities include emerging technologies, regional comparisons, and international collaborations to strengthen nutraceuticals' role in public health and sustainable agriculture. Recommendations include taking initiatives to integrate these crops into mainstream agriculture and drawing lessons from participatory climate-smart agriculture approaches. Extension workers should be utilized to provide cultivation training, support local value addition, and actively scale up farmer-led innovations.

DECLARATIONS

Ethics approval and informed consent: Informed consent was not required as the study is a desk research using Bibliometric Analysis.

Conflict of interest: The authors declare that the research was conducted in the absence of any commercial or financial

relationships that could be construed as a potential conflict of interest.

The authors declare that during the preparation of this work, they thoroughly reviewed, revised, and edited the content as needed. The authors take full responsibility for the final content of this publication.

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