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Stagnation and opportunities in seed pathology and thermotherapy research

G.D. Manguana[1,*], M.H. Cardoso[1], M.H.P. Martínez[1], L.L. Manhique[2], M.R. Oliveira[1], M.A. Nhantumbo Júnior[2], S. de Carvalho Neto[1], H.F. da Silva[1], G.S. Nobre[1], M.C. de Souza[1], A.A.B. Pimentel[1], E.C. da Silva[1] and L.C. do Nascimento[1]

[1]Federal University of Paraíba (UFPB), Center of Agricultural Sciences, Department of Phytopathology, Areia, PB, Brazil
[2]Eduardo Mondlane University (UEM), School of Business and Entrepreneurship of Chibuto (ESNEC), Chibuto District, Gaza Province, Mozambique
[*]Correspondence: georginadavidcumbe@gmail.com

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Abstract. Ensuring the supply of high-quality, pathogen-free seeds is crucial for global food security. Despite its importance, research integrating seed pathology and thermotherapy lacks a comprehensive analysis. This study employs a bibliometric approach to map the research landscape of these fields by analysing 2,562 documents from 462 sources retrieved from the Web of Science and Scopus databases (2005–2023). The results reveal a scientific output characterd by sustained growth and high productivity**,** with a strong annual growth rate of +11.1%, indicating a dynamic and expanding field with continued research interest. The research is characterd by an overwhelming predominance of national studies, while international collaboration remains exceptionally low (only 1.037%). The thematic focus is primarily on fundamental physiological topics such as Germination and Vigor, although the relevance of Seed Treatment and pathogen control is increasing. Innovative approaches such as thermotherapy thus represent a strategic opportunity. To transform this scenario, we propose a new paradigm that combines interdisciplinary approaches, digital technologies, and global cooperation to develop sustainable solutions for emerging seed health challenges. This study provides the first comprehensive assessment of gaps and trends in this integrated field, offering practical tools to prioritise future research in thermotherapy and international collaboration, with significant implications for developing climate-smart agriculture.

Key words: agricultural sustainability; bibliometric analysis; scientific collaboration; seed health; thermal treatment; physiological quality.

INTRODUCTION

Despite robust growth in seed pathology and thermotherapy research, international collaboration remains exceptionally low, limiting innovation and global impact. High-quality, disease-free, and vigorous seeds are fundamental for global food security,

boosting agricultural productivity, diversifying diets, and enhancing the resilience of rural communities (Moreno et al., 2022; Bailly & Roldan, 2023; Tiwari & Park, 2024). However, seed-borne pathogens pose a direct threat to these systems, causing devastating losses of up to 100% and facilitating global epidemics through international trade (Gaur et al., 2020; Gebeyaw, 2020; Akhtar & Kumar, 2024). In this critical context, the field of seed pathology is dedicated to studying and managing these threats (Chauhan et al., 2021; Mulesa et al., 2021; Moreno et al., 2022; Nabuuma et al., 2022; Javed et al., 2023; Vásquez & Andersen, 2023; Kumar et al., 2024; Salonga et al., 2024). Parallel to this, the development of non-chemical and ecologically sustainable methods for disease control, such as thermotherapy, has gained prominence as an innovative solution (Peixoto et al., 2018).

Understanding the evolution and research trends in these interconnected areas is crucial for identifying advances, key players, and future directions (Cobo et al., 2011). While bibliometric analysis is a powerful tool for mapping scientific fields, a significant gap in the literature persists: no comprehensive bibliometric study has integrated research on both seed pathology and thermotherapy in a unified manner. Existing studies tend to focus on a single aspect or provide a more generic overview of plant health, thereby failing to capture the complete scenario of scientific and technological development in seed disease management.

Therefore, this research presents a pioneering analysis by conducting a comprehensive bibliometric study of scientific production in these integrated fields from 2005 to 2023. Our primary objective is to map the research trajectory, identify production and collaboration patterns, and highlight strategic opportunities for revitalizing the field. By doing so, we provide a novel view of the research landscape and a diagnosis of its key challenges, particularly the low international co-authorship that limits global impact and innovation.

Fundamentals of Seed Thermotherapy in Seed Pathology

Thermotherapy is a non-chemical and environmentally sustainable method used to eliminate seed-borne pathogens through the controlled application of heat, based on the differential sensitivity between seed tissues and microorganisms. Several methods are applied, including hot-water treatment (HWT), dry heat, steam treatment, and solarisation. Dry heat has shown effective results in safflower seeds (Menegaes et al., 2020), while aerated steam has proven highly efficient in controlling *Colletotrichum acutatum* in strawberry (Marin et al., 2025).

The effectiveness of thermotherapy depends mainly on temperature, exposure time, and seed moisture content. Inadequate thermal regimes may negatively affect seed germination and vigour, as demonstrated in tomato seeds (Divsalar et al., 2014), reinforcing the need for precise protocol calibration. Thermotherapy has demonstrated high efficacy against economically important pathogens such as *Colletotrichum* spp., *Xanthomonas* spp. and *Alternaria* spp., with improvements in both sanitary and physiological seed quality reported in maize (Vieira et al., 2019). Thermal seed treatments have also been successfully applied in wheat and barley for the control of snow mould and loose smut (Bänziger et al., 2022). Nevertheless, heat tolerance varies among species and cultivars, requiring crop-specific calibration.

Recent advances include real-time thermal monitoring and digital modelling tools that support protocol optimisation. In the context of sustainable agriculture and the reduction of chemical seed treatments, thermotherapy remains a highly promising strategy for seed health management.

These technical and applied advances in seed thermotherapy help to explain the thematic dynamics observed in the bibliometric analysis presented in this study. The growing diversity of thermotherapy techniques, their successful application across different crops and pathogens, and the increasing demand for sustainable, non-chemical disease control strategies have directly influenced the expansion of research topics, keywords, and publication outputs identified in the following sections. Therefore, the bibliometric trends reported here reflect not only quantitative growth, but also the progressive technological and methodological maturation of seed thermotherapy research.

MATERIALS AND METHODS

Data retrieval and search strategy

To conduct this bibliometric study, data were retrieved from the Web of Science Core Collection (WoSCC) and Scopus databases. These databases were selected due to their recognised comprehensiveness and scientific rigor, providing access to a vast range of high-impact publications (Clarivate Analytics, 2024; Elsevier, 2024). The inclusion of two major databases was essential to minimise database selection bias and ensure more complete coverage of the literature on the topic. Data collection was performed in July 2025, covering the period from 2005 to 2023.

A comprehensive search strategy was designed to retrieve relevant documents on seed pathology and thermotherapy. The search string was applied to the TS (Topic Search) field in Web of Science and the equivalent TITLE-ABS-KEY field in Scopus. The TS field in Web of Science searches the Title, Abstract, Author Keywords (DE), and Keywords Plus (ID) fields, optimizing the retrieval of documents pertinent to the study's core theme.

The search string was constructed by combining terms related to three conceptual groups:

1. Seed pathology (e.g., ‘seed disease*’, ‘seedborne pathogen*’).
2. Seed health and quality (e.g., ‘seed health’, ‘seed quality’).
3. Seed thermotherapy and treatment (e.g., ‘seed thermotherapy’, ‘seed heat treatment’).

Boolean operators were used with ‘OR’ within each conceptual group and ‘OR’ to combine the groups, ensuring broad coverage. The final search string was: ((‘seed disease*’ OR ‘seedborne pathogen*’ OR ‘seed-borne disease*’ OR ‘seed infection’) OR (‘seed health’ OR ‘seed quality’ OR ‘seed testing’ OR ‘pathogen detection seed’ OR ‘seed vigor pathogen*’) OR (‘seed treatment’ OR ‘disease control seed*’ OR ‘seed protection’ OR ‘plant quarantine seed’ OR ‘seed thermotherapy’ OR ‘seed heat treatment’)). The asterisk (*) was used as a wildcard to include morphological variations (e.g., ‘disease’ and ‘diseases’).

Data filtering and processing

Specific filtering criteria were applied to refine the initial dataset. The search was restricted to documents published in English, Portuguese, or Spanish. Only original research articles and review articles were included; other document types (e.g., editorials, conference proceedings) were excluded. This initial search retrieved 1,072 documents from the Web of Science and 1,825 documents from Scopus. After applying language filters, the datasets were exported in the format 'txt' (WoS) and 'csv' (Scopus) and imported into R for processing. Using the Bibliometrix package, duplicate documents were identified and removed, resulting in a final curated corpus of 2,562 documents for bibliometric analysis. In this process, 282 duplicate records were excluded.

Data from Web of Science were exported in Plain Text File format (*.txt) using the 'Full Record and Cited References' option. Data from Scopus were exported in Bibtex format. The two datasets were imported, merged, and deduplicated using the bibliometrix package (version 5.0.1; Aria & Cuccurullo, 2017) in RStudio (version 4.4.3) and further explored through Biblioshiny, the web interface of Bibliometrix, to facilitate bibliometric analysis. The mergeDbSources function with the argument remove.duplicated = TRUE was used to ensure data integrity and uniqueness.

Bibliometric analysis

The following bibliometric analyses were performed on the final dataset:

1. Analysis of annual scientific production trends.
2. Identification of the most relevant journals and institutions.
3. Examination of collaboration networks (e.g., co-authorship).
4. Mapping of keywords and thematic trends, including co-occurrence analysis and thematic mapping.

Limitations

A limitation of the dataset concerns the completeness of the cited references (CR field). Consequently, in-depth citation analyses–such as identifying the most cited works or authors based on direct citation counts–were not feasible. This analysis therefore focuses on production, collaboration, and thematic metrics.

RESULTS AND DISCUSSION

Overview and trajectory of scientific production

The bibliometric analysis of research on seed pathology and thermotherapy reveals a dynamic and expanding field, with a robust annual growth rate of 11.1% a dynamic and expanding field, with a robust annual growth rate of 11.1% from 2005 to 2023 (Table 1). The field is characterised

Table 1. General Information about the data

Value	Data
Timespan	2005–2023
Documents	2,562
Annual Growth Rate (%)	11.1
Document Average Age	8
Average Citations per Document	15.29
Average Citations per Year per Document	1.91

Note: This table presents general information about the analyzed bibliometric dataset.

by consistently high publication volumes, reaching significant peaks in 2018 (174 articles) and 2023 (173 articles) (Table 2 and Fig. 1). The total corpus comprises 2,562 documents, demonstrating sustained relevance and continued scientific production over nearly two decades. The fluctuations observed in recent years may indicate a phase of consolidation, in which established research themes coexist with the gradual emergence of new applications and research niches.

Table 2. Publications per Year

Year	Articles	Year	Article
2005	26	2016	171
2006	108	2017	169
2007	113	2018	174
2008	109	2019	150
2009	127	2020	139
2010	128	2021	139
2011	131	2022	157
2012	144	2023	173
2013	135	'2024'	'125'
2014	128	'2025'	'12'
2015	141	'---'	'---'

Note: Data for '2024' and '2025' are partial and incomplete due to the ongoing nature of the year and database indexing lag.

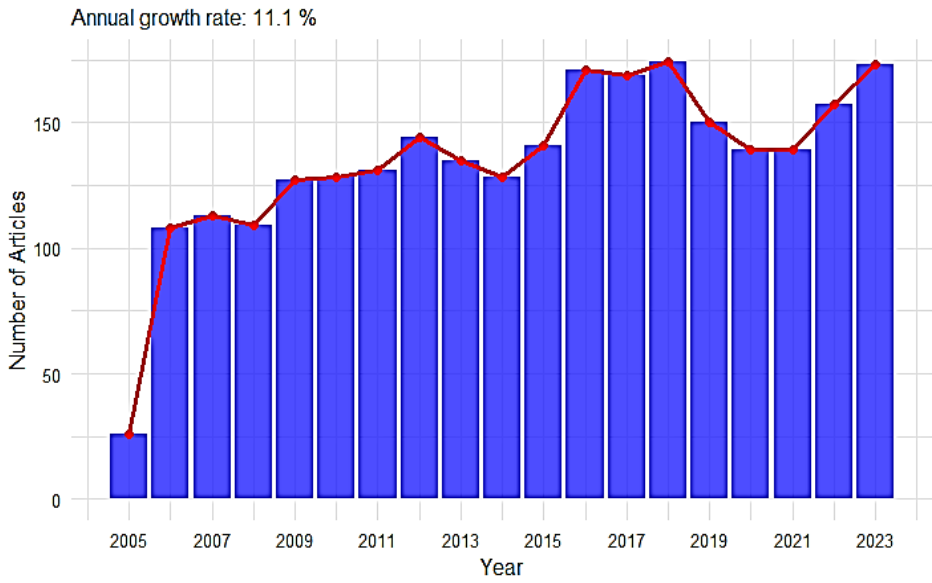

Figure 1. The evolution of the annual publication volume (2005–2023) reveals the field's high productivity and growth trend, with significant peaks in 2018 (174 articles) and 2023 (173 articles). The blue bars represent the actual yearly output, while the red line shows the linear trend calculated for the complete period (2005–2023). Data for 2024 and 2025 are incomplete due to database indexing lag and were excluded from all trend calculations to prevent bias.

Analysis of authors' productivity and collaboration

Contrary to initial visual expectations of a power-law distribution (Fig. 2), a goodness-of-fit test for Lotka's Law was formally rejected ($\chi 2 = 44.257$, df = 9, $p < .001$; Fig. 3). This conflict between visual and statistical evidence reveals a fundamental insight: this research field is characterd by unique and complex authorship dynamics that deviate from the idealised model (Lotka, 1926; Pao, 1985).

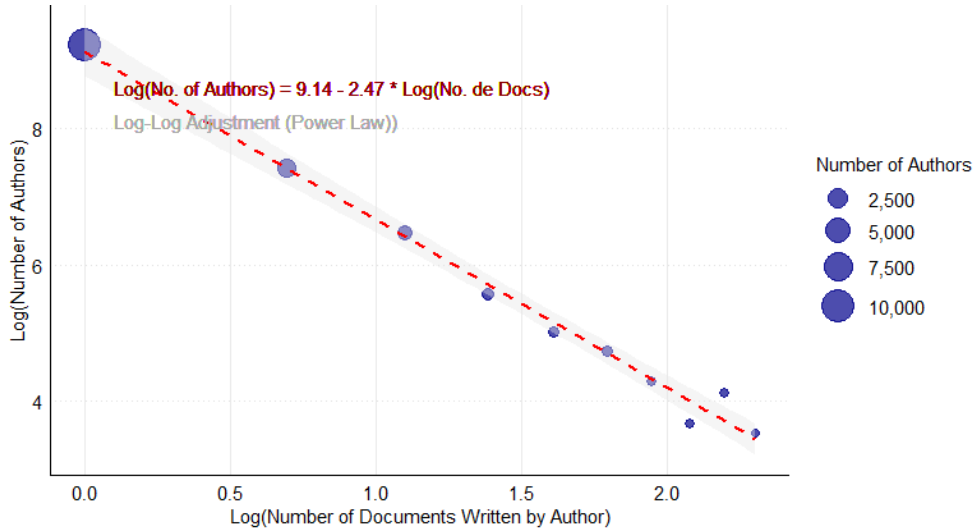

Figure 2. Distribution of author productivity (n = 3,406) on log-log scale. The dashed red line represents the linear fit of transformed data with equation Log (No. Authors) = 9.136581 - 2.473926 × Log (No. Docs). The estimated alpha (α) value of 2.474 suggests high concentration of publications among few authors, indicating an unequal productivity distribution. The gray area shows the regression model's confidence interval.

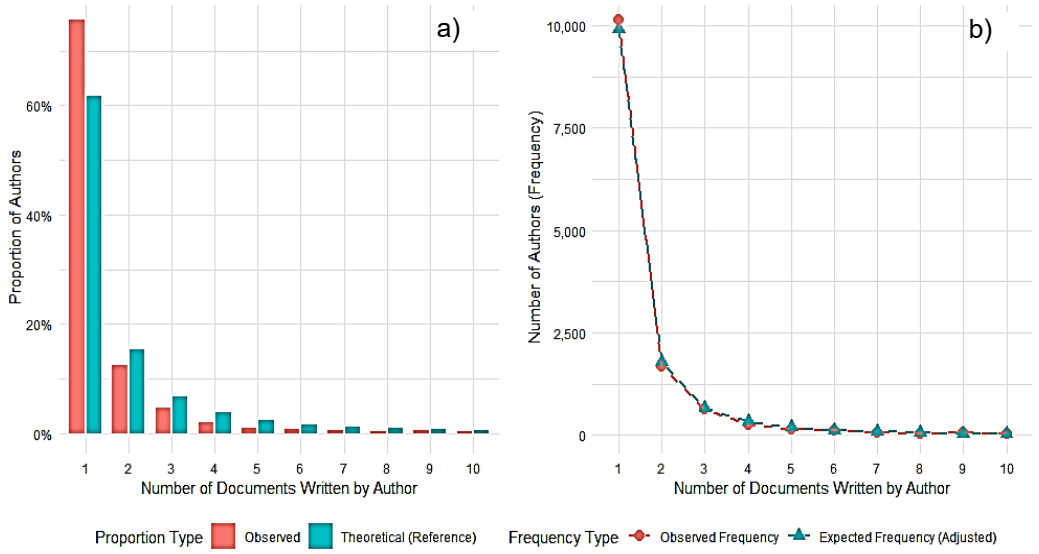

Figure 3. Author distribution according to number of publications, comparing observed frequencies with those expected by the estimated Lotka's Law model. The Chi-square test indicated a significant difference between empirical and theoretical distributions ($\chi 2$ = 44.257; df = 9; p < .001), demonstrating that author productivity does not strictly follow the predicted distribution.

As Table 3. reveals, this productivity profile , where scientific production is less concentrated among a small number of authors compared to more established disciplines, suggests a fragmented research landscape (Gupta et al., 2024). While this dispersion may encourage methodological and approach diversity, it also points to the absence of consolidated international scientific leadership networks. This fragmentation ultimately limits the development of broader research schools and field cohesion (Glänzel & Schubert, 2004). Strategically, expanding collaborations between authors and research groups from different countries could not only enhance field cohesion but also increase the global visibility of the most active researchers.

Table 3. Number of documents by number of authors

Manuscripts	No. of Authors
1	10,135
2	1,672
3	645
4	262
5	150
6	113
7	72
8	39
9	61
10	34

Note: The table shows the distribution of publications across authors, revealing a pattern where a large number of authors (10,135) appear in only one document, while fewer authors contribute to multiple publications.

Analysis of bradford's law and journal concentration

The main publication sources in seed pathology and thermotherapy are led by a core of high-impact, specialised journals. The analysis of Bradford's Law reveals a strong concentration of scientific literature, with only 2.17% of the sources generating over a quarter of the total scientific output (Fig. 4). This confirms the law's applicability and highlights a research landscape heavily centered on a small number of influential venues.

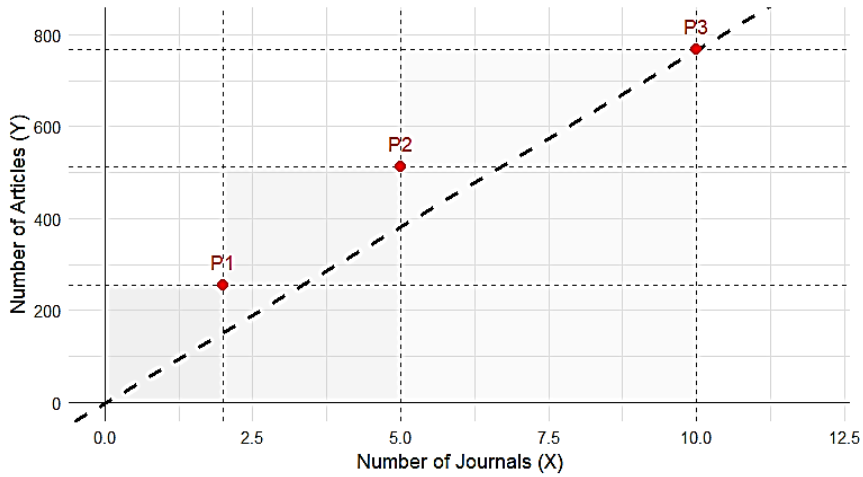

Figure 4. Bradford's Law distribution of journal productivity for seed pathology and thermotherapy research (2005–2023). The cumulative number of articles is plotted against the cumulative number of journals, ranked by decreasing productivity. The curve is divided into three distinct zones (P1, P2, P3), each contributing roughly one-third of the total scientific output. The core zone (P1) contains the most prolific journals (detailed in Table 4), confirming the high concentration of literature in a small core of sources, as predicted by Bradford's Law.

A ranking of the most prolific journals reveals the clear prominence of Brazilian publications, with the Brazilian Journal of Seeds (167 articles) and the Journal of Seed Science (158 articles) emerging as the top two venues (Table 4). The significant influence of national journals like *Rural Science* and *Science and Agrotechnology* underscores the consolidation of Brazilian research in this field. However, the presence of international sources such as *Crop Protection* and *Pest Management Science* demonstrates the field's global visibility and its integration into internationally relevant scientific forums.

Table 4. Publication frequency by journal

R	Journal	Freq	Cum Freq
1	Brazilian Journal of Seeds	167	167
2	Journal of Seed Science	158	325
3	Crop Protection	120	445
4	Pest Management Science	62	507
5	Rural Science	61	568
6	Scientia Horticulturae	45	613
7	Science and Agrotechnology	39	652
8	European Journal of Plant Pathology	39	691
9	Summa Phytopathologica	39	730
10	Journal of Agricultural Science	38	768

Note: R = ranking; Freq = absolute frequency; cumFreq = cumulative frequency.

Most relevant institutions

The analysis of institutional affiliations reveals a strong geographical concentration of scientific production, corroborating the field's national predominance. Of the 2,562 analysed documents, 685 reported affiliation data, with a significant concentration in Brazilian institutions. The top four most prolific institutions are all Brazilian: the Federal University of Lavras (230 documents), the Federal University of Pelotas (205 documents), the University of São Paulo (127 documents), and the Federal University of Santa Maria (123 documents) as detailed in Table 5. The full distribution of institutional productivity is shown in Fig. 5. These institutions form a robust core of research excellence and consolidation in the field, reflecting the historical investments and institutional strength of Brazil's public agricultural research system

Table 5. Most prolific institutions in seed pathology and thermotherapy research (2005–2023)

R	Institution	Docs	% of 685 Docs
1	Federal University of Lavras	230	33.58%
2	Federal University of Pelotas	205	29.93%
3	University of São Paulo	127	18.54%
4	Federal University of Santa Maria	123	17.96%

Note: Based on the subset of 685 documents with reported affiliation data.

This centralisation pattern,consistent with existing literature (Nehring, 2016; Moreddu et al., 2017; Nascimento et al., 2024), reflects both historical investments and the institutional strength of Brazil's public agricultural research system.

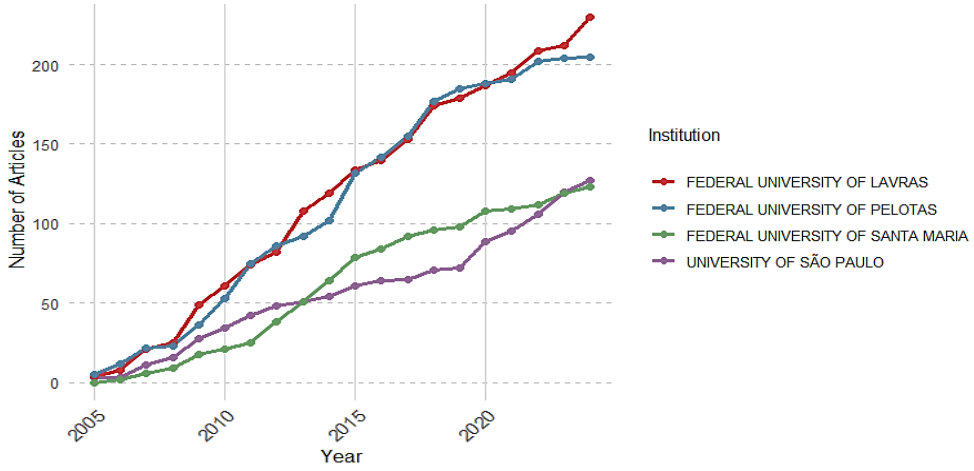

Figure 5. Cumulative growth of articles by leading institutions from 2005 to 2023.

Citation analysis and most influential articles

An analysis of the most influential articles, based on citation counts, reveals a dual dynamic within the field. The top 10 most-cited articles (Table 6) were all published between 2006 and 2014, highlighting the enduring relevance of foundational studies and a 'slow obsolescence' effect common in agricultural sciences where management techniques remain valid over time (Price, 1963; Larivière et al., 2008). The seminal work by MD (2006) stands out with 561 total citations, underscoring its long-lasting impact.

Table 6. Most Influential Articles and Citation Metrics

Paper	DOI	TC	TC/Year	NTC
MD, 2006, EUR. J. AGRON.	10.1016/j.eja.2005.08.001	561	28.05	21.98
GL, 2011, FOOD SECUR.	10.1007/s12571-010-0108-x	489	32.60	28.71
Y, 2011, BIOL. FERTIL. SOILS	10.1007/s00374-011-0556-2	292	19.47	17.15
MO, 2013, J. AGRON. CROP. SCI.	10.1111/j.1439-037X.2012.00521.x	186	14.31	13.96
A, 2014, FOOD BIOPROCESS TECHNOL.	10.1007/s11947-013-1126-4	179	14.92	13.49
D, 2012, NEW PHYTOL.	10.1111/j.1469-8137.2011.03987.x	179	12.79	11.70
FGA, 2007, CROP. PROT.	10.1016/j.cropro.2006.05.006	178	9.37	8.06
D, 2007, FIELD CROP. RES.	10.1016/j.fcr.2007.03.005	175	9.21	7.92
S, 2010, J. BIOSCI.	10.1007/s12038-010-0051-1	171	10.69	12.80
B, 2007, ENVIRON. EXP. BOT.	10.1016/j.envexpbot.2005.12.002	166	8.74	7.51

Note: TC = total citations; TC/Year = total citations per year; NTC = normalised total citations.

However, a closer look at more recent impact metrics, such as citations per year (TC/Year) and normalised citation scores (NTC), provides a more nuanced view. The work by GL (2011) has a higher average of 32.60 citations per year and a top-ranked NTC of 28.71, indicating its greater relevance to contemporary research despite being older. This suggests a progressive renewal of the field driven by emerging topics like

agricultural sustainability and alternative physical seed treatments, such as thermotherapy (Powell & Matthews, 1997).

A notable finding is the predominance of Brazilian articles among the most cited works, which confirms the country's leadership in this research domain. This trend also reveals a concerning dependence on local literature. This citation pattern could limit the internationalisation of reference networks and reduce the likelihood of the field's inclusion in broader global research agendas (Bornmann et al., 2012). Therefore, actively encouraging publications in high-impact international journals is essential to enhance global recognition and accelerate the adoption of innovative approaches.

Collaboration and geographic contributions

Research in seed pathology and thermotherapy demonstrates a high collaboration density, with an average of 9.94 co-authors per document, underscoring its team-based nature. However, this collaboration is overwhelmingly national, with an exceptionally low international co-authorship rate of only 1.037% (Fig. 6), highlighting a critical limitation for the field. The detailed analysis of these scarce transnational connections reveals their strategic importance, as they translate into a substantial citation volume. This constrained pattern is consistent with previous findings on the limited internationalisation of Brazilian agricultural research (Andrade Vargas et al., 2015; Souza Vanz et al., 2023).

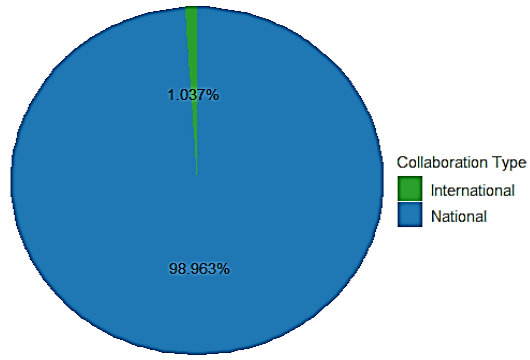

Figure 6. The chart highlights the overwhelming predominance of national collaboration networks, representing 98.963% of total publications. Only 1.037% of documents (28 articles) resulted from international co-authorship.

The analysis of publications by country reveals distinct collaboration patterns. The Netherlands, despite contributing only a single article, demonstrates an exclusively international collaborative research pattern (Table 7). The disproportionate impact of these rare partnerships is evident, as illustrated by Colombia's article which received 13 citations, and Korea's high average citations per article (14) despite a national-focused production. These findings underscore that the quality and impact of international collaborations can vary significantly, highlighting the strategic importance of transnational connections for field visibility (Fig. 7) (Khor & Yu, 2016; Thelwall et al., 2022; Wang et al., 2024).

Table 7. Production by Country

Country	Art	SCP	MCP	MCP	TC	Avg. Cit/ Art
Korea	12	11	1	0.08	168	14
Colombia	1	1	0	0	13	13
Netherlands	1	0	1	1	6	6
Serbia	1	1	0	0	0	0

Note: TC = total citations; SCP = single country publications; MCP = multiple country publications; MCP Ratio = proportion of MCP to total articles.

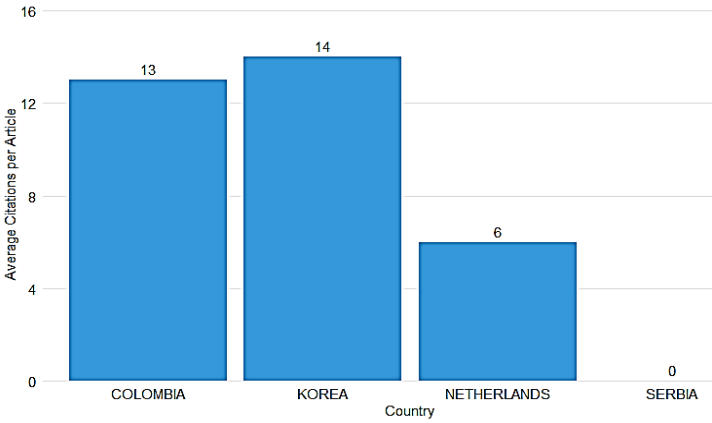

Figure 7. The graph compares the impact of publications from each country on a per-article basis. The data show that although with different production volumes, Colombia (13) and Korea (14) stand out for having the highest average citations per article, a key indicator of the high relevance and impact of their research in the area.

The analysis of the geographical co-authorship network (Fig. 8) and a heat map of connection frequency (Fig. 9) further highlight the asymmetry and geographical concentration of partnerships. Brazil emerges as the leading country in scientific cooperation with 784.5 collaborations, followed by Mexico (229.2) and South Korea (127.2) (Fig. 10). This concentration of most international collaborations in a few countries, along with a strong focus on national collaboration networks, reinforces a scientifically localised production that is less permeable to global trends (Mali et al., 2016; Sã et al., 2016).

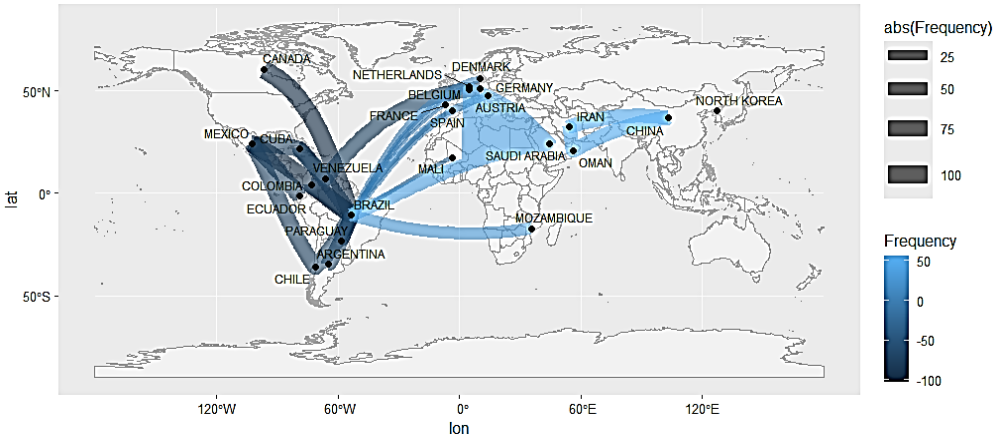

Figure 8. Network of collaboration between countries with the highest frequency of co-authored publications. The thickness of the lines is proportional to the frequency of collaboration, while the colour of the lines indicates the intensity of the partnership: thinner, light blue lines represent less frequent collaborations (1 to 5 co-authored articles), while thicker, dark blue lines indicate more intense collaborations (more than 5 co-authored articles).

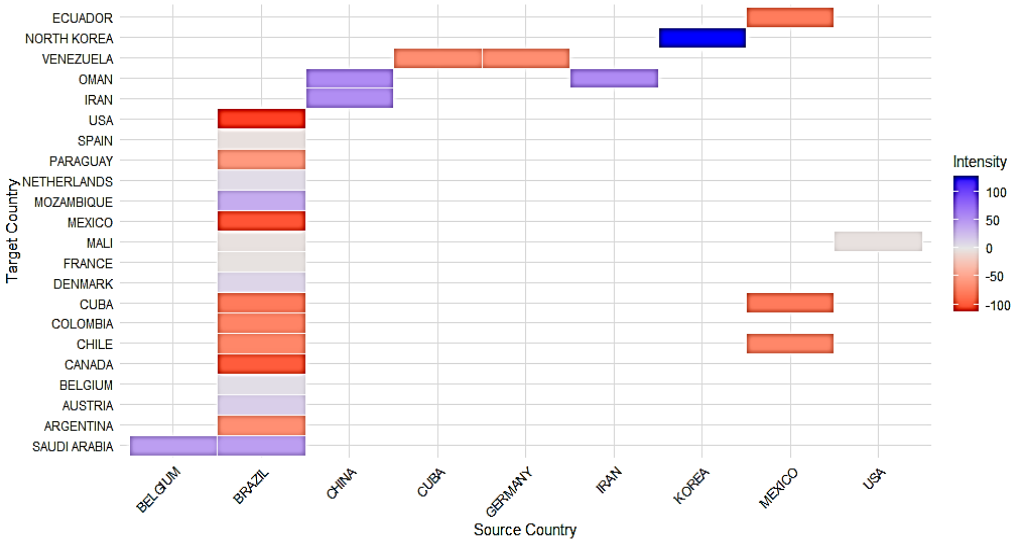

Figure 9. Heat map illustrating the frequency of collaboration between countries. Both axes (X and Y) represent countries, and the colour of each cell indicates the frequency of co-authorship between the corresponding pair of countries.

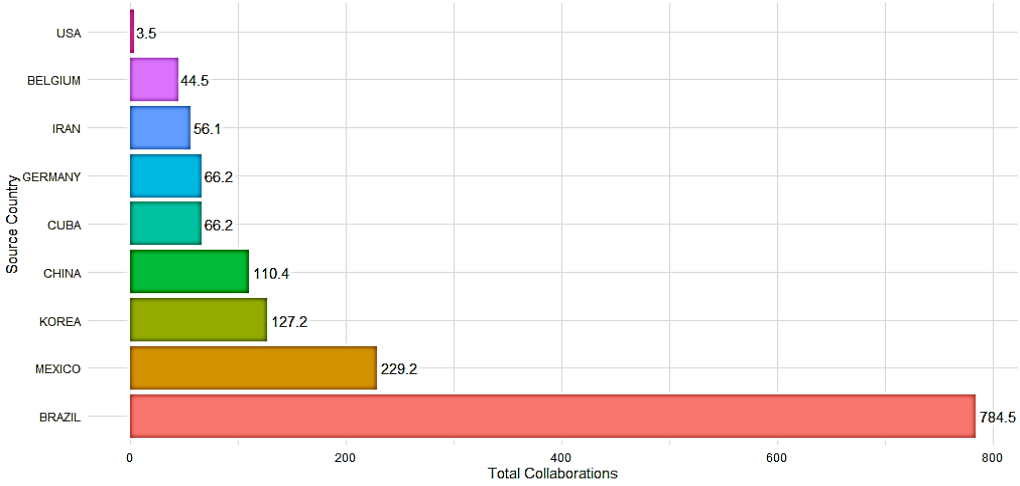

Figure 10. Total international collaborations by country (2005–2023). Brazil leads with 784.5 collaborations, followed by Mexico (229.2), South Korea (127.2) and China (110.4), while other countries such as Cuba, Germany, Iran, Belgium and the USA show lower numbers. The graph evidences the geographical concentration of international partnerships and highlights the countries with the highest participation in scientific collaboration, suggesting that most co-authorships are concentrated in a few countries.

This constrained collaborative pattern suggests that locally generated knowledge may have limited exposure to diverse global perspectives and innovations. The predominance of Portuguese-language publications in high-output Brazilian journals

may also create a linguistic barrier that reduces the international visibility and appeal of this research (Andrade Vargas et al., 2015; Souza Vanz et al., 2023). This is a critical issue, as empirical evidence consistently shows that internationally co-authored publications receive significantly more citations and are associated with higher-quality research outputs (Khor & Yu, 2016; Thelwall et al., 2022; Wang et al., 2024). Consequently, the implementation of targeted policies and incentives to promote research internationalisation becomes imperative for the field's advancement (Mascarello et al., 2024; Nascimento et al., 2024).

Content analysis and thematic trends

An analysis of the most relevant keywords, based on both author-provided terms and the indexing system's keywords, provides a detailed overview of the central themes in the field. The frequency distribution of these terms follows Zipf's Law, demonstrating a predictable power-law pattern where a few high-frequency terms, such as 'Seed Treatment' and 'Germination', dominate the research landscape, while a 'long tail' represents more specific or emerging topics (Figs 11 and 12) (Pao, 1985; Bailón-Moreno et al., 2005; Karam & Karam, 2018). This duality highlights a common pattern in bibliometric studies, where the researcher's focused scope (Author Keywords) differs from the broader, applied themes perceived by the indexing system (Keywords-Plus), such as 'Crop Yield' and 'Disease Control'. This duality reflects the difference between the researcher's focused scope and the practical application perceived by the indexing system, a pattern commonly observed in bibliometric studies (Zhang & Yu, 2016).

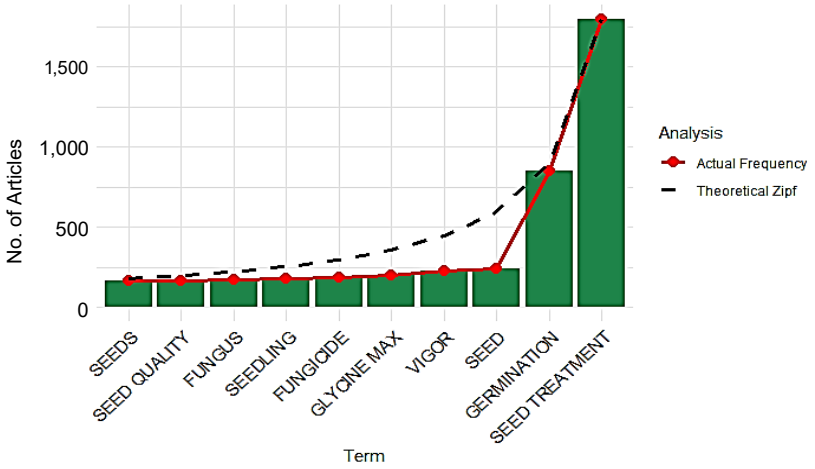

Figure 11. Frequency distribution of the most relevant Keywords-Plus for 'seed pathology' and 'thermotherapy'. The distribution follows Zipf's Law ($\alpha = -0.9069$; $R^2 = 0.9002$), where a few high-frequency terms (e.g., 'Seed Treatment', 'Germination') dominate, followed by a long tail of less frequent terms. The solid line represents the theoretical Zipf distribution.

The frequency distribution of these terms follows Zipf's Law, demonstrating that keyword frequency is not random but follows a predictable pattern, characteristic of linguistic and scientific phenomena (Van Raan, 2019). The temporal analysis further reveals a dynamic evolution toward themes with high economic impact.

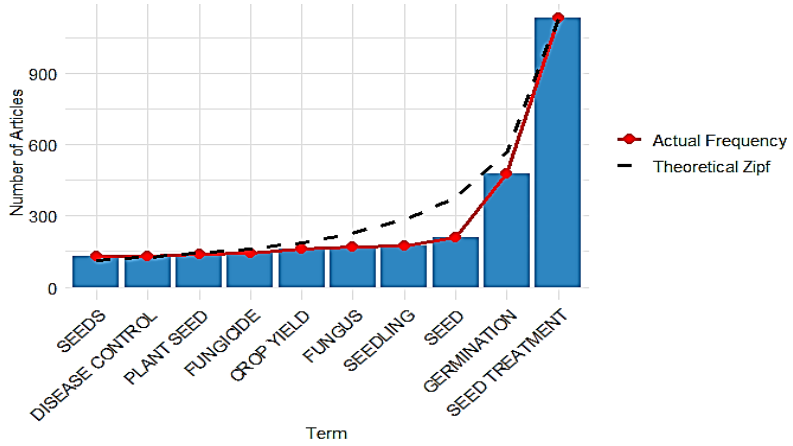

Figure 12. Frequency distribution of the most relevant Author Keywords for 'seed pathology' and 'thermotherapy'. The distribution follows Zipf's Law ($\alpha = -1.0353$; $R^2 = 0.8656$), confirming a strong power-law fit. The concentration of terms like 'Seed Treatment' and 'Germination' reflects core research themes, while the long tail represents niche or emerging topics.

The exponential growth in terms like 'Seed Treatment' and the continuous increase in physiological topics such as 'Germination' and 'Vigor' underscore a clear shift in research toward practical solutions that address the needs of the agricultural sector (Fig. 13) (Mabe & Amin, 2001). While 'seed pathology' remains a foundational theme, the field is actively connecting to more rapidly evolving research themes.

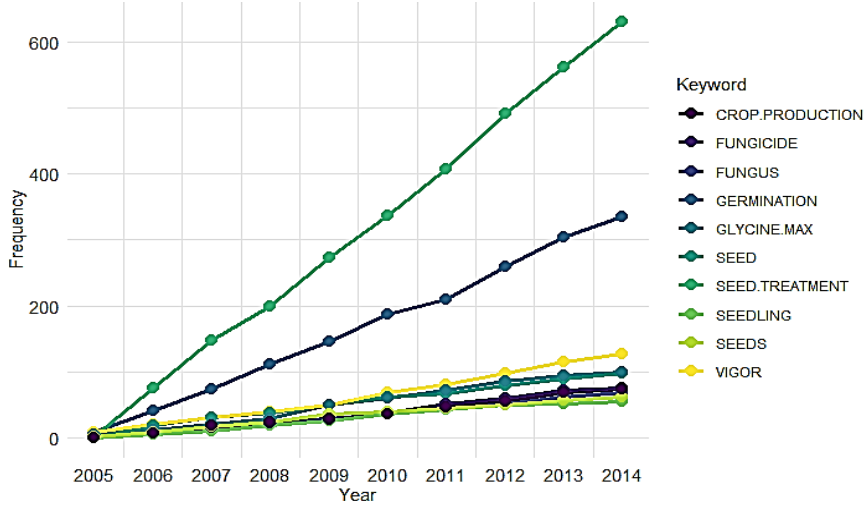

Figure 13. Temporal evolution of the frequency of ten main keywords. The line shows consistent exponential growth in topics such as 'Seed Treatment', indicating significant growth in research interest and scientific production. Other keywords such as 'Germination' and 'Vigor' also show continuous growth, reinforcing the importance of physiological themes in this research area.

Within this context, 'seed thermotherapy', though conceptually related to the 'seed treatment' cluster, has not yet achieved the centrality of the primary driving themes. However, its growing inclusion represents a strategic opportunity for innovation, particularly given the increasing demand for sustainable alternatives to fungicide applications. This indicates that the field is poised to embrace new, disruptive technologies to transform modern seed health management (Powell et al., 2016).

Limitations

This study presents limitations intrinsic to the nature of bibliometric data. First, the observed predominance of Brazilian research and the low rate of international co-authorship (1.037%) may suggest that the sample does not fully reflect the global dynamics of the field. However, this centralisation is a widely documented phenomenon reflecting the historical leadership of the Brazilian agricultural research system (Nascimento et al., 2024). Therefore, the results offer an accurate portrait of a core of excellence in the field, though generalisations should be made with caution. Furthermore, the unavailability of complete citation data in the selected databases restricted in-depth analyses of scientific impact.

Future Research Opportunities in Seed Pathology and Thermotherapy

Based on the gaps identified in this study, three priority axes are proposed to advance research in seed pathology and thermotherapy. The first axis concerns the internationalisation of research through collaborative networks with leading institutions, such as the USDA–ARS (United States) and Wageningen University & Research (The Netherlands), as well as the strengthening of academic mobility programmes. These partnerships are essential to expand global impact and promote protocol standardisation. The second axis highlights the need to develop precision thermotherapy protocols tailored to neglected crops, emerging pathogens, and diverse environmental conditions. Optimising parameters such as temperature, exposure time, and seed moisture content is expected to enhance treatment efficiency while reducing physiological risks. Finally, the third axis involves the integration of innovative technologies, including artificial intelligence for rapid pathogen diagnosis and nanotechnology for seed protection and thermal monitoring. These approaches can transform current limitations into scalable and sustainable solutions for agricultural systems.

CONCLUSIONS

This bibliometric study provides a comprehensive and nuanced diagnosis of integrated research in seed pathology and thermotherapy. While mapping the field's robust growth trajectory of +11.1% per annum, our results expose a fundamental discrepancy: a productive yet profoundly insular research community. The exceptionally low level of international collaboration (1.037%) acts as a critical barrier to innovation and global impact. Overcoming this insularity is not merely a suggestion for improved collaboration; it is the essential catalyst for the next leap in innovation.

To transform this stagnation into an opportunity, we propose three evidence-based strategic pillars: (i) Strategic internationalisation: We recommend establishing structured networks with leading global institutions and implementing joint funding calls to address

the collaboration gap (Wai-Chan, 2017). (ii) Precision thermotherapy: We identified a growing market demand for 'Seed Treatment' but a distinct innovation gap in thermotherapy. The solution lies in developing tailored protocols with real-time thermal monitoring for neglected crops and emerging pathogens (Liu et al., 2020; Research, Society and Development, 2022; Menegaes et al., 2022). (iii) Digital revolution: The field's reliance on classical literature necessitates the integration of disruptive technologies. We propose employing Artificial Intelligence for predictive models and Nanotechnology to enhance the efficacy of thermal treatments (Elmer & White, 2018; González-Rodríguez et al., 2024; Yeasmin et al., 2024).

Implementing these strategies will not only address the identified gaps but will position seed pathology and thermotherapy as a dynamic and indispensable field for safeguarding global food security and developing truly sustainable and resilient agricultural systems. These findings are expected to guide policymakers and researchers in developing international strategies for seed health innovation.

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