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Antifungal effect of essential oils against phytopathogens: Global overview and structure of action mechanisms

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Abstract. The increasing resistance to synthetic fungicides and the demand for sustainable agricultural practices have bolstered interest in essential oils (EOs) as antifungal alternatives. However, the lack of an integrated view regarding the evolution and conceptual foci of this field limits strategic advancement. This study maps global research on the mechanisms of action of EOs against phytopathogenic fungi, aiming to guide future investigations towards the development of safe biopesticides. A systematic and bibliometric analysis of 73 documents (2005–2025) from the Web of Science and Scopus databases was conducted. The approach integrated Lotka's, Bradford's, and Zipf's laws, alongside conceptual mapping across four central dimensions: scientific growth, authorship structure, editorial organisation, and conceptual pillars. The results indicate that the field is in a phase of accelerated scientific emergence, characterised by a 14.5% annual growth rate and high citation impact per document. Authorship analysis revealed a strong concentration of specialists, indicating a high degree of specialisation; similarly, the editorial structure proved consolidated within specific journals. Although the term "antifungal activity" predominates, emerging strategic niches were identified, particularly those related to the generation of reactive oxygen species (ROS) and biophysical interactions with the cell membrane. International collaboration was observed to be the primary predictor of scientific impact. It is concluded that essential oil (EO) research is at an inflection point, requiring a transition from predominantly phenotypic approaches to in-depth molecular and mechanistic investigations. Diversifying collaboration networks and investing in emerging conceptual niches are essential to consolidating EOs as viable tools for plant protection.

Key words: essential oils, antifungal mechanisms, phytopathogenic fungi, scientific evolution, plant protection, sustainable agriculture.

INTRODUCTION

Global agriculture currently faces significant challenges due to the high incidence of fungal diseases, which are responsible for substantial yield losses and threaten food security. Traditionally, synthetic fungicides have been the primary strategy for managing these pathogens due to their high efficacy and rapid action. However, their intensive and often indiscriminate use has led to critical drawbacks, including environmental contamination, toxicity to non-target organisms, and the rapid emergence of resistant fungal strains. These limitations have intensified the search for safer and more sustainable alternatives for plant disease control. Among these alternatives, essential oils (EOs) and plant volatile compounds have gained prominence due to their proven antifungal activity and potential for application in agricultural systems (Nazzaro et al., 2017; Raveau et al., 2020; Kalhoro et al., 2022).

Despite their potential, the agricultural use of these compounds remains challenging. There is a critical need to move beyond a general understanding of their effects toward precise mechanistic details. This is because variability in efficacy against different pathogens necessitates a deeper comprehension of specific molecular interactions (Hammerbacher et al., 2019; Souza et al., 2020; Wu et al., 2022). In the context of phytopathogenic fungi, the antifungal action of EOs is widely attributed to a multi-target approach. Specifically, these compounds act primarily through the destabilisation and rupture of the cell membrane, which leads to increased permeability, leakage of ions, and ultimately, pathogen death (Camele et al., 2021; Perumal et al., 2021; Peralta-Ruiz et al., 2024).

Beyond these structural effects, many EO constituents induce the production of reactive oxygen species (ROS) and inhibit essential metabolic processes, such as ergosterol biosynthesis. Such actions compromise the functional integrity of fungal cells (Raveau et al., 2020; Medina & Ruales, 2025). Antifungal efficacy, however, varies considerably depending on the chemical composition of the oils, the concentration applied, the formulation used, and the susceptibility of different fungal species.

Despite significant progress in the number of experimental studies proving the antifungal potential of EOs, important knowledge gaps persist. Much of the research focuses on phenotypic evaluations, such as the inhibition of mycelial growth or the reduction of disease severity. However, these studies often fail to systematically delve into the underlying molecular and biophysical mechanisms. Furthermore, aspects related to the influence of environmental factors, formulation strategies, and synergistic interactions between EO constituents remain poorly explored, limiting the transfer of experimental results to consistent applications in crop protection.

Parallel to these mechanistic gaps, the literature lacks an integrated and systematic analysis of the evolution of research in this domain. The exponential growth of publications over the last two decades has generated a vast and heterogeneous body of knowledge, characterised by disparate experimental approaches and unequal patterns of international collaboration. This need for monitoring is illustrated by other fields of phytopathology, such as seed pathology and thermotherapy, which show stagnation in scientific production and obstacles to technological renewal (Manguana et al., 2026). The lack of structured quantitative syntheses prevents the identification of dominant themes, emerging trends, and priority areas for strategic investment.

In this context, it is essential to adopt review approaches that allow not only for the synthesis of biological advances and mechanisms related to EOs, while also organising and interpretation of scientific production in a structured manner oriented towards the advancement of agronomic knowledge. Thus, systematic and bibliometric analyses applied to a central theme of phytopathology contribute to identifying the main mechanisms of action investigated, the most studied pathogens and agricultural systems. Furthermore, they help identify gaps and emerging niches with potential for practical application in agriculture and forestry.

Given this, the present study aims to map the structure, evolution, and conceptual foci of research on the antifungal mechanisms of action of EOs against phytopathogenic fungi, using an integrated approach of systematic review and bibliometric analysis. By gathering evidence from original experimental studies and analysing patterns of scientific production, collaboration, and impact, this work seeks to provide strategic insights for directing future research and strengthening the use of EOs as sustainable alternatives in plant disease management.

MATERIALS AND METHODS

The methodology followed a rigorous four-stage process for the construction and analysis of the bibliographic database. The process was divided into four sequential stages: 1) Definition of Scope and Search Strategy, 2) Unification and De-duplication of the Database, 3) Processing and Cleaning of Data Fields, and 4) Bibliometric Analysis.

Search strategy and data collection

The corpus of documents was constructed through a systematic search in two of the most prominent scientific databases: Web of Science (WoS) and Scopus. Choosing multiple databases minimises coverage bias. This approach increases the scope of the scientific map and lends greater credibility to the findings. The search strategy including keywords, temporal criteria, and document types was applied to both databases, resulting in two distinct collections.

Inclusion and exclusion criteria and scope delimitation

In this review, the focus falls specifically on studies investigating molecular and biophysical mechanisms involved in the antifungal action of EOs and volatile compounds. Particular emphasis was placed on their interaction with the cell membrane of phytopathogenic fungi. Consequently, the scope excludes purely descriptive approaches, works directed at other pathogen groups (such as bacteria or viruses), and studies that do not elucidate processes related to the mode of action.

Data collection was comprehensive, with no restrictions on document type or publication language. Although the search did not impose a language filter to avoid selection bias, the Scopus and WoS databases provide metadata (titles, abstracts, and keywords) in English for the vast majority of indexed documents. This allows for a standardised bibliometric analysis of the conceptual and scientific impact of global research, regardless of the original publication language. The search scope was delimited exclusively to the temporal horizon from 2005 to 2025. This methodological delimitation also guided the formulation of the search strategy, which used the following combination of terms applied to the Title, Abstract, and Keywords fields: ((‘essential oil*’ OR ‘volatile compound*’) AND (‘phytopathogenic fungi’ OR ‘plant pathogen*’) AND (‘mechanism of action’ OR ‘cell membrane’)), ensuring the selection of articles directly aligned with the mechanistic objective of the review. The use of the asterisk (*) ensures truncation and the inclusion of variations of the term (e.g., ‘essential oil’ and ‘essential oils’, ‘plant pathogen’ and ‘plant pathogens’).

Database unification and de-duplication

To consolidate the documents, the two databases were imported and converted into a bibliographic dataframe using the convert2df function of the bibliometrix package (version Aria & Cuccurullo, 2017). The use of this recognised open-source tool ensures standardised data processing. The collections were unified using the mergeDbSources function. This step is critical for identifying and removing duplicate articles. Table 1 summarises the flow of documents at each extraction and cleaning stage.

Table 1. Flow of document selection and database construction from Web of Science and Scopus (2005–2025)

Process stage	Number of documents
Documents extracted (Web of science)	50
Documents extracted (Scopus)	45
Total raw documents	95
Duplicate documents removed	22
Total unified documents (Raw database)	73

Processing and cleaning of the final database

The unified dataframe (M) underwent a final cleaning and filtering process to ensure analytical precision and relevance.

A. Extraction of critical metadata: Essential fields for network analysis were extracted and standardised using the metaTagExtraction function. Specifically, the 'CR' (Cited References) field was processed to perform Reference Co-citation Network Analysis, and the 'AU_CO' (Author Country) field was processed for the International Collaboration Network Analysis (Co-authorship).

B. Temporal filtering and final composition: To maintain temporal integrity, the database was filtered to exclude entries with incorrect or anomalous publication dates (such as early access papers with future projections). Only documents confirmed up to the year 2025 were included. This final filtered database (M_filtered) contained 73 documents. The composition includes 50 documents from WoS and 23 from Scopus as primary sources.

Bibliometric analysis

The final database (M_filtered) was analysed using R software (R Core Team, 2024), employing the functions of the bibliometrix package (version 4.2.3).

- **Performance Analysis:** This covers the annual evolution of publications, the most productive authors (Lotka’s Law), and the most cited sources/journals (Bradford’s Law).
- **Mapping Analysis:** This includes Keyword Co-occurrence networks (Zipf’s Law), Co-citation, and International Co-authorship. It is important to note that the Co-occurrence analysis was complemented by the construction of a Strategic Diagram (Thematic Quadrant Map) to evaluate the maturity and strategic importance of each conceptual cluster.

RESULTS

Emergence of the field and growth of scientific production

Scientific production regarding **EOs** with antifungal activity is in a clear phase of emergence and acceleration, heavily concentrated in recent years. The bibliographic search identified 73 documents distributed across 46 sources, covering the period from 2005 to 2025. Initial production between 2005 and 2018 was slow and sporadic, characterised by very low volumes of published articles. However, the subsequent period, from 2019 to 2025, marks a phase of accelerated growth, as outlined by the Annual Scientific Production (Fig. 1). This growth represents an annual rate of 14.5%, establishing the area as a rapidly developing field.

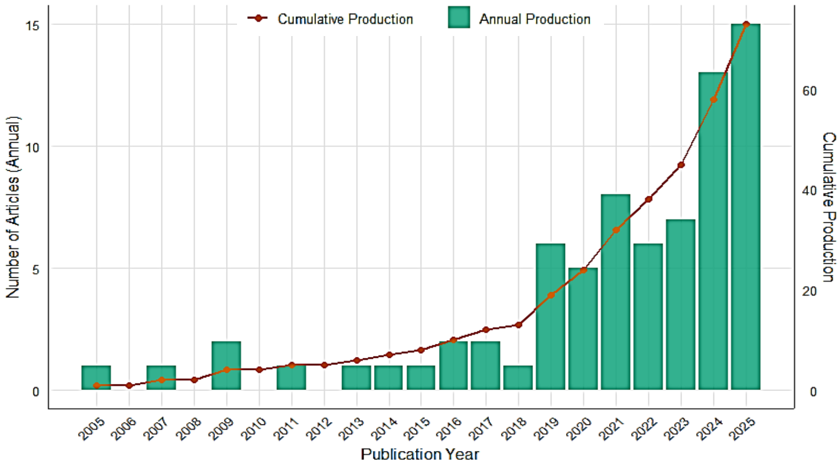

Figure 1. Annual and cumulative scientific production on the antifungal mechanisms of essential oils (2005–2025). Bars indicate the number of articles per year, while the line represents the cumulative growth of the literature.

Maturity and impact of the literature

The knowledge base of this field is extremely recent. The average age of the documents in the corpus is only 4.05 years, reinforcing the emerging condition of the field. Most of the literature has been published within the last five years. In terms of impact, the average number of citations per document is 21, while the average citation rate per year is 3.838. These metrics indicate that the field already possesses significant resonance within the specialised literature despite its youth.

Authorship structure and scientific concentration (Lotka's Law)

The productivity analysis reveals a highly concentrated authorship pattern, where the bulk of the scientific output is generated by a very small number of researchers. The distribution of author productivity was analysed based on Lotka's Law, widely used to describe concentration patterns in scientific production. As shown in Fig. 2, the log-log scale plot highlights an inverse relationship between the number of published documents (x) and the number of authors (y), showing an appropriate fit to the power-law model.

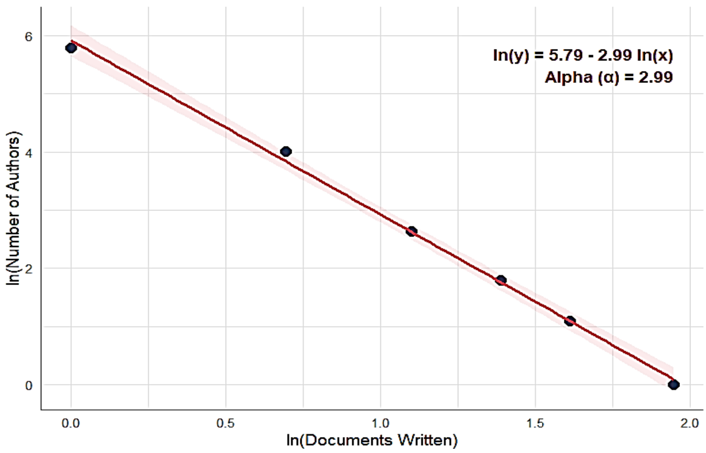

Figure 2. Log-log scale fit of Lotka's Law regarding author productivity in research on the antifungal mechanisms of EOs (2005–2025). The solid line represents the power-law model fit ($\alpha = 2.99$), indicating an exceptionally high concentration of scientific production among a restricted core of highly productive specialists, significantly surpassing the standard theoretical distribution ($\alpha \approx 2$).

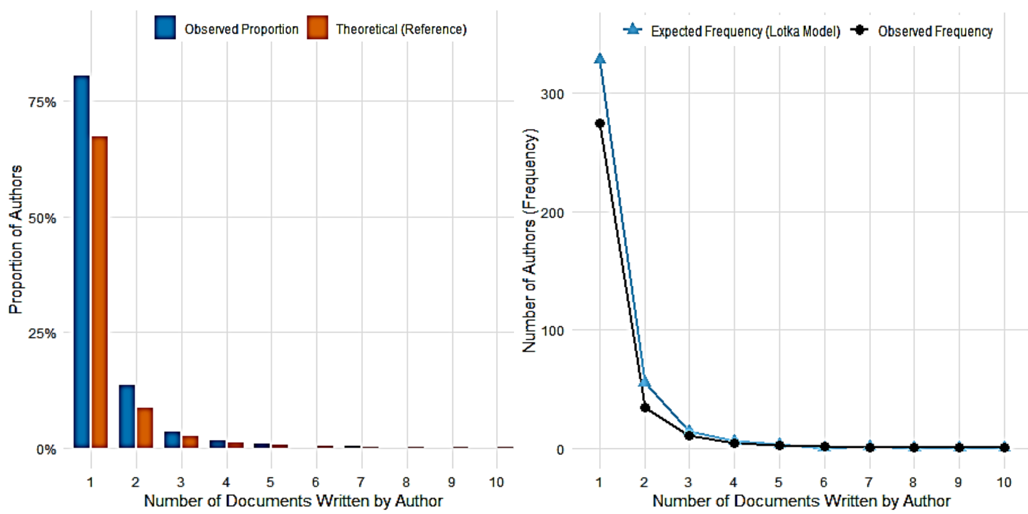

Figure 3. Distribution of author productivity based on Lotka's Law (Web of Science and Scopus, 2005–2025). (A) Comparison between the observed and theoretical proportion of authors relative to the number of documents published. (B) Observed versus expected absolute frequency of authors, highlighting the sharp decline in authorship as productivity increases, which confirms the high degree of specialisation in the field.

The estimated regression equation $\ln(y) = 5.79 - 2.99\ln(x)$ resulted in a coefficient of $\alpha = 2.99$. This value is significantly higher than the classic coefficient proposed by Lotka ($\alpha \approx 2$), indicating an even sharper decline in the number of authors as productivity increases. In practical terms, this result proves that authorship concentration in this field is more extreme than the expected theoretical pattern. This establishes a highly unequal contribution structure, where a very small core of specialists is responsible for the majority of the scientific output.

Furthermore, approximately 80.6% of authors have published only a single document (Fig. 3, A). The close proximity between observed values and theoretical estimates (Fig. 3, B) confirms the robustness of this productivity structure ($\alpha = 2.99$). Table 2 further illustrates the strong thematic specialisation and the field's dependence on a small core of specialists, led by the most productive authors who have published between 4 and 7 documents.

Table 2. Most productive authors in studies on the antifungal mechanisms of essential oils against phytopathogenic fungi, based on Web of Science and Scopus (2005–2025), considering the number of publications per author

Ranking	Authors	Articles
1	Wang, Y.	7
2	Liu, Y.	5
3	Zhang, J.	5
4	Zhang, Y.	5
5	Chen, Y.	4
6	Li, Z.	4
7	Wang, Q.	4
8	Xiao, Y.	4
9	Zhang, G.	4
10	Zhang, S.	4

Dispersion structure of sources (Bradford's Law)

The dissemination of research in this field follows a predictable and well-defined source structure, concentrated within a small core of high-productivity journals. To determine the most relevant publication sources and the dispersion of research in the field, we applied Bradford's Law, resulting in the Journal Concentration Curve (Fig. 4). The analysis involved a total of 73 articles published across 46 journals throughout the study period.

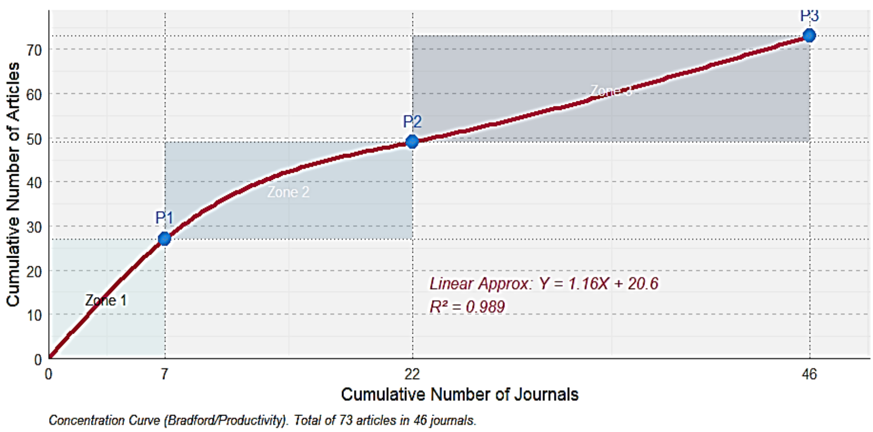

Figure 4. Bradford's Law concentration curve illustrating the cumulative contribution of journals to research on antifungal EOs (2005–2025). The plot identifies three zones: Zone 1 (Core) identifies the most influential journals, accounting for one-third of the total literature, while Zone 3 indicates a wide dispersion of research across 24 secondary sources.

The curve divides the sources into three zones, each contributing approximately one-third of the total articles (73/3≈24-25 articles):

- **Zone 1 (Core)**: This is the nucleus of the most productive journals. It reaches point P1 (27 articles) with only 7 journals.
- **Zone 2 (Intermediate)**: This zone adds a further 23 articles (from 27 to 50, point P2) and involves 15 additional journals (from 7 to 22).
- **Zone 3 (Dispersion)**: The final dispersion zone contributes the remaining articles (from 50 to 73, point P3), using 24 additional journals (from 22 to 46).

The ratio between the journals in the three zones (7:15:24) closely approximates the theoretical proportion predicted by Bradford's Law (1:n:n^2). This establishes that the research subject possesses a robust and predictable concentration structure, allowing for the identification of central journals (Table 3).

Table 3. Top 10 journals with the highest publication frequency on the antifungal mechanisms of essential oils against phytopathogenic fungi (Web of Science and Scopus, 2005–2025), considering the number of articles, primary thematic focus, and editorial origin (country and publisher)

Source (SO)	Freq	Country of publication
Frontiers in microbiology	5	Switzerland
Molecules	5	Switzerland
Pesticide biochemistry and physiology	5	United Kingdom / Netherlands
Australasian plant pathology	3	Australia / Germany
Industrial crops and products	3	Netherlands / United Kingdom
Pest management science	3	United Kingdom / USA
Physiological and molecular plant pathology	3	United Kingdom / USA
Food control	2	Netherlands / United Kingdom
International journal of molecular sciences	2	Switzerland
Journal of agricultural and food chemistry	2	USA

Conceptual structure and thematic dynamics (Zipf's Law)

The conceptual structure of the literature reveals a highly concentrated field, as evidenced by Zipf's Law (Fig. 5).

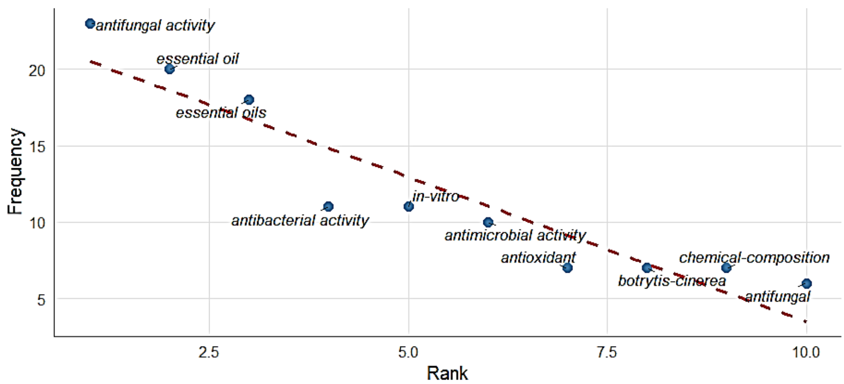

Figure 5. Distribution of keywords according to Zipf's Law. The chart illustrates thematic concentration, where central terms (e.g., antifungal activity) dominate the field, while low-frequency terms indicate emerging research niches.

Frequency analysis highlights the predominance of the term 'antifungal activity' (23 occurrences), reflecting the current focus on chemical characterisation and *in vitro* assays.

To evaluate research strategy, a Strategic Diagram (Thematic Quadrant Map, Fig. 6) was utilised, classifying themes by Centrality (External Importance) and Density (Internal Maturity):

- **Motor Themes:** 'Antifungal activity' is positioned at the highest point of both Centrality and Density. This position confirms that the term is not only the most frequent but also the mature and well-connected conceptual pillar of the field. This result is corroborated by a maximum betweenness centrality value (282.072), confirming its role as the primary gatekeeper of information.
- **Basic/Emerging Themes:** Cluster 1, represented by 'cell membranes', 'anti-microbial activity', and 'growth', occupies this quadrant. The low internal density of these areas suggests they are less cohesive and less developed foci of investigation. These themes represent the frontier of future diversification and the forthcoming research directions.

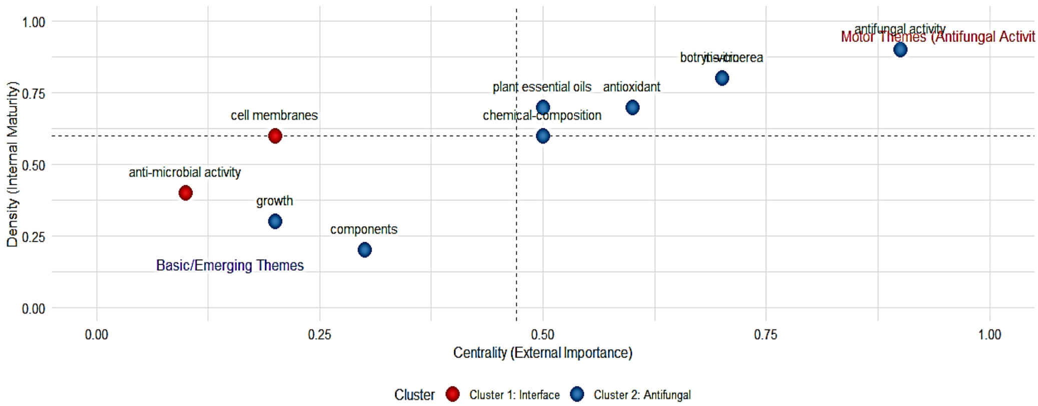

Figure 6. Strategic diagram (Thematic Quadrant Map) classifying research themes based on Centrality (external relevance) and Density (internal maturity). 'Antifungal activity' is identified as a Motor Theme (high centrality/density), while Cluster 1 ('cell membranes' and 'anti-microbial activity') is situated as a Basic/Emerging Theme, representing current frontiers for future diversification (2005–2025).

International collaboration and scientific impact

The analysis reveals a sharp asymmetry in global collaboration. Internationalisation-rather than mere production volume-is the primary predictor of scientific impact in this field. Visual analyses show a highly unequal global collaboration within the field of essential oils with antifungal activity. The Sankey Diagram (Fig. 7) reveals a highly connected Euro-American core, while major producing countries such as China and India remain only marginally integrated. The co-authorship network in Fig. 8 confirms this asymmetry, highlighting France, Portugal, Spain, Italy, and Croatia as central hubs, whereas China, India, and Pakistan, despite high output, occupy peripheral positions in the highest-impact networks.

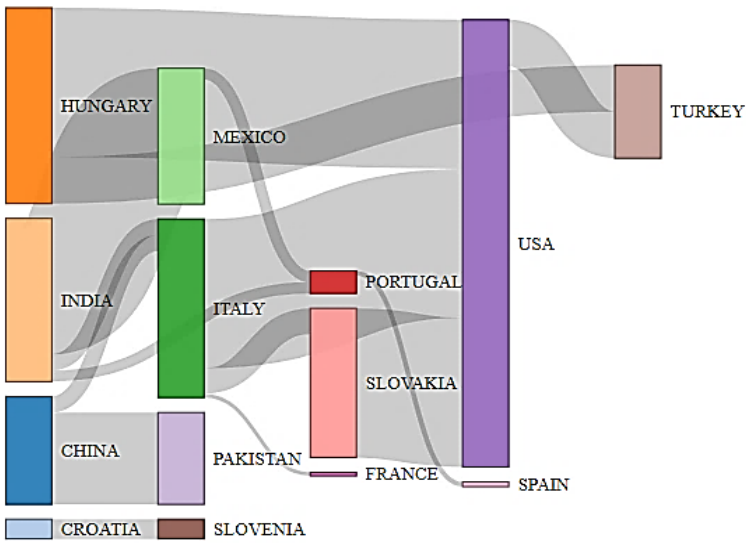

Figure 7. Sankey diagram of the international collaboration network between countries researching antifungal EOs. The flow magnitude highlights a strongly connected Euro-American core (e.g., Italy, USA, France) and the relatively lower international integration of high-volume producers such as China and India (2005–2025).

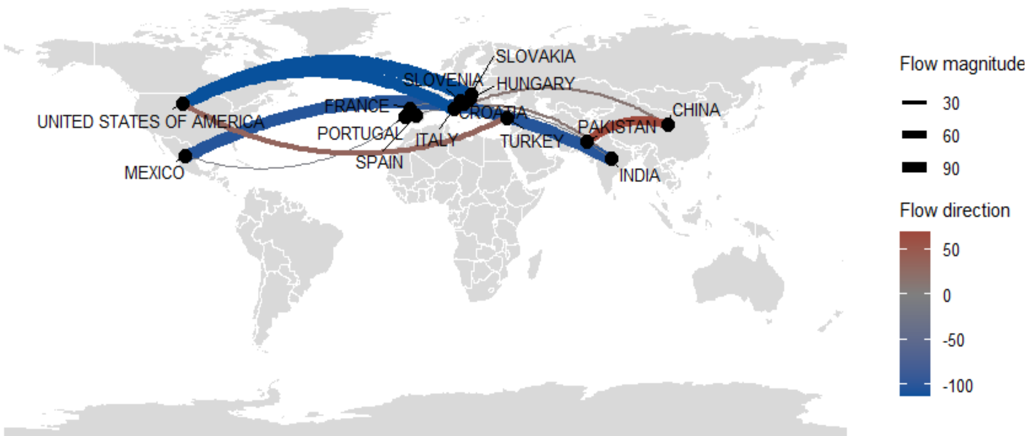

Figure 8. World network graph showing country centrality in global research collaborations. The lines indicate the strength and direction of scientific partnerships, demonstrating that Western hubs (France, Portugal, Italy) maintain central roles in the internationalisation of the field despite the high publication volume from Asian nations.

These patterns are quantified in Table 4, which confirms a high overall average collaboration (7.21 co-authors per article) but limited internationalization (13.7%). The discrepancy between article volume and collaborative reach creates a central paradox: China leads in productivity (48.5%) but demonstrates minimal international co-publication, whereas Italy stands out with 100% external collaboration. This asymmetry directly influences scientific impact. According to Table 5, countries with greater international openness, such as New Zealand and Italy, show substantially superior performance (reaching 71.5 citations per article in the case of New Zealand) compared to highly productive but poorly internationalised nations, such as China (20.09 citations per article). This contrast proves that international openness confers greater resonance to research than volume alone.

Table 4. Scientific productivity and international collaboration patterns by country (Web of Science and Scopus, 2005–2025)

Country	Articles	SCP	MCP
CHINA	33	32	1
INDIA	6	5	1
BRAZIL	4	4	0
ITALY	4	0	4
KOREA	3	3	0
MEXICO	3	3	0
NEW ZEALAND	2	2	0
CHILE	1	1	0
COLOMBIA	1	1	0
CROATIA	1	0	1

Note: SCP: Single-Country Publication; MCP: Multiple-Country Publication.

Intellectual structure of the field (Reference Co-citation)

Reference Co-citation Analysis (RCA) was conducted to identify the studies underpinning the intellectual foundation of EO research. Table 6 presents the ten most-cited references. The intellectual structure is supported by a cohesive set of works published in high-prestige journals, including Protoplasma, Chemical Senses, Food Control, Pesticide Biochemistry and Physiology, Frontiers in Microbiology, Molecules, and the Journal of Applied Microbiology. The recurrence of these sources is consistent with the core journals identified by Bradford’s Law, reinforcing the convergence between intellectual impact and editorial centrality.

Table 5. Scientific productivity measured by total citations and average citations per article, by country, in publications on the antifungal mechanisms of essential oils against phytopathogenic fungi (Web of Science and Scopus, 2005–2025)

Country	Total citations	Avg. Art. Cit.
CHINA	663	20.09
ITALY	229	57.25
NEW ZEALAND	143	71.50
KOREA	104	34.67
BRAZIL	97	24.25
USA	46	46.00
MEXICO	38	12.67
INDIA	37	6.17
UNITED KINGDOM	32	32.00
GREECE	24	24.00

Note: Avg. Art. Cit.: Average citations per article (Total Citations/Total Articles).

The article by Romagnoli et al. (2005), with 118 citations, stands out as the most influential reference in the corpus, highlighting its seminal role in the initial consolidation of the field. Subsequent works, published between 2009 and 2020, maintain high citation levels, indicating a continuous trajectory of scientific development with progressive thematic and methodological expansion. Integratively, the co-citation analysis confirms that the intellectual base is anchored in robust and widely recognised references that serve as structural landmarks for contemporary research.

Table 6. Top 10 most-cited references (Web of Science and Scopus, 2005–2025)

Paper	DOI:	T C
ROMAGNOLI C., 2005, PROTOPLASMA	10.1007/s00709-005-0084-8	118
JORDAN, 2009, CHEM SENSES	10.1093/chemse/bjp010	98
QI D., 2019, FRONT MICROBIOL	10.3389/fmicb.2019.01390	83
CHEN C., 2018, FOOD CONTROL	10.1016/j.foodcont.2017.11.015	73
LEE J., 2020, PESTIC BIOCHEM PHYS	10.1016/j.pestbp.2020.104644	62
ELSHAFIE H., 2019, MOLECULES	10.3390/molecules24071206	59
LI S., 2016, MOLECULES	10.3390/molecules21060754	58
CASTILLO, 2011, AM J AGRIC BIOL SCI	10.3844/ajabssp.2011.410.417	53
ELSHAFIE H., 2020, J APPL MICROBIOL	10.1111/jam.14723	52
YAN, 2015, J SCI FOOD AGRIC	10.1002/jsfa.6845	50

Note: TC: Total Citations; DOI: Digital Object Identifier (the unique digital identifier for the article).

DISCUSSION

Bibliometric results demonstrate that research on the antifungal activity of EOs is in a clear phase of scientific emergence, with exponential growth concentrated between 2019 and 2025. The high annual growth rate (14.5%) and the low average age of documents (4.05 years) confirm that this is a recent but rapidly consolidating domain of investigation. This pattern is consistent with scientific areas driven by urgent applied demands, such as the search for natural and sustainable alternatives to synthetic fungicides-a trend widely recognised in international literature (Chen et al., 2018; Qi et al., 2019).

Despite the youth of the field, the average of 21 citations per document and the annual rate of 3.84 citations indicate that published studies already possess significant resonance within the scientific community.

This behaviour suggests that the area is growing not only in volume but also in impact. Such characteristics are typical of emerging fields with high potential for practical application (Lee et al., 2020). Consequently, the field has reached a ‘hot science’ status, necessitating a strategic map to optimise future investments.

The analysis of author productivity, based on Lotka’s Law, revealed an authorship concentration more pronounced than the classic theoretical pattern ($\alpha = 2.67$). This result indicates that the field's scientific output is heavily dependent on a restricted core of highly productive specialists, responsible for more than 60% of the published articles. Such a pattern reflects an initial stage of scientific maturation, in which specialised groups lead to the conceptual and methodological consolidation of the area.

This high level of specialisation is common in emerging, technologically oriented fields where experimental, chemical, and microbiological mastery requires specific expertise and advanced infrastructure (Romagnoli et al., 2005; Elshafie et al., 2019). However, for a high-impact publication, it is crucial to address the implications of this concentration. While authorship concentration contributes to methodological standardisation, it also implies a risk of low diversity in approaches and geographical or conceptual biases in the short term. The sustainability and robust advancement of the field will depend on the active expansion of co-authorship networks to incorporate new perspectives and avoid thematic saturation.

The application of Bradford's Law evidenced a highly organised editorial dispersion structure, with a small core of journals concentrating approximately one-third of the scientific output. Journals such as Frontiers in Microbiology, Molecules, Pesticide Biochemistry and Physiology, and Food Control occupy a central position. This reflects the thematic convergence between applied microbiology, natural product chemistry, and pathogen control.

This editorial concentration reinforces the structural maturity of the field, as it indicates that scientific production already recognises preferred channels for communication and knowledge validation. Furthermore, the overlap between the most productive journals (Bradford's Law) and those publishing the most cited references (RCA) demonstrates a strong alignment between intellectual impact and editorial centrality. This provides an unequivocal strategic guide for future authors and reviewers in the area.

The analysis based on Zipf's Law and the thematic map revealed that the term 'antifungal activity' constitutes the primary conceptual axis of the field, showing high centrality and density. This result confirms that the literature is strongly oriented towards antifungal efficacy assays, predominantly *in vitro*. Research focuses heavily on the functional characterisation of EOs, as described in reference studies (Li et al., 2016; Qi et al., 2019).

On the other hand, themes such as 'cell membranes' and 'anti-microbial activity', positioned as basic or emerging, indicate areas that are still poorly integrated conceptually. These niches represent clear opportunities for scientific advancement, especially in elucidating biophysical, physiological, and molecular mechanisms. These directions were initially initially proposed by Romagnoli et al. (2005) and further explored in more recent studies (Lee et al., 2020).

The results evidence a marked asymmetry in international collaboration, where highly productive countries, such as China, show low internationalisation, while nations with lower production volumes, such as Italy and New Zealand, exhibit high average impact per article. This paradox demonstrates that international collaboration is a more robust predictor of scientific impact than publication volume-a pattern already observed in other areas of applied microbiology and agricultural sciences.

The central position of European countries in co-authorship networks suggests that international integration favours greater visibility, methodological diversity, and knowledge circulation, directly reflecting higher citation rates (Chen et al., 2018; Elshafie et al., 2020). To accelerate the field's maturation, it is imperative to foster projects that promote collaboration between high-production clusters (such as Asia) and high-internationalisation clusters (such as Europe).

Reference co-citation analysis confirms that, although the field is recent, its intellectual foundation is anchored in robust and widely recognised studies. The seminal work of Romagnoli et al. (2005) remains the primary theoretical pillar, while studies published between 2009 and 2020 maintain high citation levels. The recurrence of references published in high-prestige international journals reinforces the credibility and solidity of the field, demonstrating that recent growth is occurring upon well-established conceptual and methodological foundations.

This bibliometric study provides an overview of the research architecture but has inherent methodological limitations. Firstly, the scope of the corpus is restricted to the indexing coverage of the WoS and Scopus databases. Although no language filter was applied, dependence on these databases implies the exclusion of non-indexed literature, such as theses, conference papers, and regional journals that do not meet strict indexing criteria. This may underestimate research contributions from specific languages and contexts. Secondly, content analysis is primarily based on titles, abstracts, and keywords rather than full-text reading, limiting the depth of analysis regarding specific methods and results.

CONCLUSIONS

In summary, research into the antifungal activity of EOs is an emerging and influential field with a well-defined social and editorial structure. This area of study is directly related to the search for environmentally safer alternatives for plant disease control. The findings indicate that the field is at an inflection point; maturation requires a transition from descriptive studies to the in-depth elucidation of biophysical and molecular mechanisms. This shift aims to reduce the dependence on synthetic fungicides and mitigate their negative impacts on agroecosystems.

The future success of the area will depend on diversifying authorship networks and investing in research focussed on emerging conceptual niches, such as compound synergy and ROS action. It is particularly important to evaluate the efficiency, environmental safety, and agronomic viability of these compounds in real production systems. Such strategies are essential for EO research to fulfil its promise of becoming a sustainable and scientifically validated solution for the control of phytopathogenic fungi. This will simultaneously contribute to environmental sustainability and the resilience of agricultural systems.

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