



Plants as an alternative to the use of chemicals for crop protection against biotic threats: trends and future perspectives

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Abstract This review entails a critical appraisal on the potential of plants as alternatives to synthetic chemicals for crop protection, aligning with the global shift towards green-based approaches in agriculture. Utilising a defined set of inclusion and exclusion criteria, 235 papers were extracted from Scopus. These articles were analyzed to address specific

research questions related to plant-based biocontrol methods. Approximately 25% of the literature was published in journals such as "Industrial Crops and Products", "Journal of Agricultural and Food Chemistry", "Pest Management Science", and "Frontiers in Microbiology". Thematic analysis identified core focus areas, including the chemical properties of antifungal agents, bioactive compounds, environmental protection, and the use of fungicides. Italy and China emerged as countries with the most represented authors, while China, India, and USA led in scientific production, corresponding authors' publications, and citation impact. We identified 91 plant species from 28 families, notably from the Lamiaceae, with strong potential as biocontrol agents. The most promising plants were *Platycladus orientalis* (L.) Franco, *Mentha piperita* L., *Foeniculum vulgare* L., *Coriandrum sativum* L., and *Allium ascalonicum* L. This study offers valuable insights and practical applications in the field of plant-based biocontrol, thereby

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underscoring the relevance and efficacy of green-based approaches in contemporary agricultural practices. There is an increasing scientific interest in sustainable crop protection strategies and the potential of plant-based biocontrol agents in addressing biotic stresses in crops. Overall, this review contributes to the understanding of plant-based biocontrol for crop protection, providing a foundation for further research and application in sustainable agriculture.

Keywords Antifungal · Biodiversity · Biotic stress · Botanicals · Food security · Sustainability · UN SDGs

Introduction

Addressing the global challenge of meeting the escalating food demands of an increasing population remains a pivotal concern (Hall et al., 2017; Willett et al., 2019). While increasing crop yields is vital, protecting the current agricultural outputs is equally crucial toward alleviating prevalent food insecurity (Nxumalo et al., 2021; Ogunnupebi et al., 2020). To combat crop losses for food sustainability and security, their protection against plant pathogens and shelf-life extension remains pertinent (Nxumalo et al., 2021). Pests are estimated to cause a reduction in global crop production by 20 to 40%, leading to losses in food production worth hundreds of billions of dollars (Flood, 2010; Hollis, 2022; Rizzo et al., 2021). In addition, the Consultative Group on International Agricultural Research (CGIAR, 2018) alluded to the predictions from the Intergovernmental Panel on Climate Change (IPCC) that suggest a projected decrease in the yields of major crops by 2% per decade until 2050. The prevalent reliance of the agricultural sector on synthetic agro-chemicals (e.g. fungicides, synthetic coatings and preservatives) raises increasing concerns about their toxicological impact on human health, environmental sustainability, and the emergence of microbial resistance (Dayan et al., 2009; Katz & Baltz, 2016; Nxumalo et al., 2021; Ogunnupebi et al., 2020). Particularly in developing countries, the affordability and adherence to proper application protocols exacerbates these issues (Carlini & Grossi-de-Sá, 2002; Gozzo, 2003; Katz & Baltz, 2016). In response to these concerns, several green alternatives, including plant extracts and associated products, are

increasingly being explored for the control and protection of plants against pests and pathogens (Catani et al., 2022; Nxumalo et al., 2021; Ogunnupebi et al., 2020; Pilkington, 2022).

Historically, the use of local floras, underpinned by indigenous knowledge, has played a pivotal role in addressing agricultural challenges (Mwinga et al., 2023). The diverse local floras hold great potential as a new environmentally friendly and sustainable entity for protecting crops. Inherently, the diverse secondary metabolites/phytochemicals are relevant for their survival and protection against naturally occurring pests and pathogens (Dayan et al., 2009). The biological effects of plants used as biocontrol agents against pests and pathogens are often attributed to the diverse classes of phytochemicals such as alkaloids, coumarins, flavonoids, phenolics, and terpenoids (Gebashe et al., 2022; Ogunnupebi et al., 2020; Pilkington, 2022). Researchers have recognised the importance of unlocking the potential in plants as sustainable biocontrol agents (Copping & Duke, 2007; Dayan et al., 2009; Isman et al., 2011; Pilkington, 2022). In recent years, innovative technological approaches, such as nano-based techniques, have gained interest in leveraging plant materials for crop protection in the agricultural sector to meet food demands (du Plooy et al., 2009; Mohammadi et al., 2015; Ogunnupebi et al., 2020; Palou et al., 2015; Sekhon, 2014).

With the increasing global interest in the potential of plants as sustainable agents for crop protection, there is an increase in the number of publications (review and research articles) that are generated annually. In addition, a few appraisals on the potential of plants for crop protection and preservation and related aspects currently exist (Nxumalo et al., 2021; Ogunnupebi et al., 2020). Even though these existing reviews generally provide a broad perspective on a topic, their objectivity with respect to the selection and inclusion of existing literature is debatable (Manoj Kumar et al., 2023; Vargas et al., 2022). A comprehensive and unbiased assessment of contemporary developments and emerging trends is imperative for a holistic approach toward utilising plants in crop protection. A robust understanding of the value of plants as an alternative to agro-chemicals for crop protection against pathogens is essential, especially with bibliometry. The application of bibliometric tools offers a robust means to comprehensively

analyze the existing knowledge domain objectively and systematically (Aria & Cuccurullo, 2017; Manoj Kumar et al., 2023; Vargas et al., 2022). The popularity of this approach is evident in diverse fields such as natural science (Vargas et al., 2022), medicine (Kokol et al., 2021; Manoj Kumar et al., 2023), and humanity/business (Donthu et al., 2021) as well as in general research evaluation (Szomszor et al., 2021). Given the increasing importance of plants for the protection of crops against pests and pathogens, we applied bibliometric tools to analyze existing peer-reviewed studies on this subject quantitatively. This was important to gain a better understanding of the advancements and track the evolution of knowledge on the trends and patterns associated with the use of plants for the protection of crops. In addition, mapping the evolution of a particular field is crucial for academics and organizations and assessing its underlying knowledge framework is necessary to understand its dynamics and progress. This review critically assessed the potential of plant-based alternatives to synthetic agro-chemicals (pesticides, fungicides, bactericides, and insecticides) in crop protection, guided by the following research questions.

What is the current state and progression trend of research regarding the utilisation of plants for biocontrol in crop protection?

Based on empirical evidence, which plant species emerge as the most promising candidates for biocontrol applications?

How can we harness the full potential associated with plant-based biocontrol?

Methodology

To meet the scope of this review study, relevant academic publications on plant-based crop protection were retrieved from an online dataset. The Scopus database, renowned for its comprehensive coverage and high-quality content, was selected as the primary source for this review. A best-evidence methodology was also used.

Literature search strategy: bibliographic method

The data for this study, from the bibliometric search conducted on Scopus database, was gathered on

March 29, 2023, at approximately 3 p.m. The data spans a period of 53 years, from 1970 to 2023. Scopus incorporate numerous publications from reputable publishers such as Springer, Elsevier, Multidisciplinary Digital Publishing Institute (MDPI), Taylor & Francis, and EmeraldInsight (Fadiji et al., 2023; Ghalib et al., 2022). The search strategy applied Boolean operators ('OR', 'AND') in a structured search string to identify literature on biocontrol strategies against phytopathogens. The specific search string were as follows: TITLE-ABS-KEY (("plants" OR "plant extract*" OR "essential oil*") AND ("crop protect*" OR "crop quality*" OR "crop deteriorat*" OR "fruit* quality*" OR "fruit* preserv*") AND ("natural product*" OR "synthetic chemical*" OR "fungicide*")) AND (LIMIT-TO (LANGUAGE, "English")) AND (EXCLUDE (DOCTYPE, "ed") OR EXCLUDE (DOCTYPE, "bk") OR EXCLUDE (DOCTYPE, "er") OR EXCLUDE (DOCTYPE, "no") OR EXCLUDE (DOCTYPE, "tb")). The result brought about 797 documents from the Scopus search, of which the raw data of only 235 papers were saved in BibTeX and CSV formats for further analyses.

Network models: scientometric analysis

Scientometric method uses bibliometric data to generate a network model and identify research subjects. Bibliometric software including VosViewer and the 'Bibliometrix' package software was utilised to analyse the data (Aria & Cuccurullo, 2017; Sganzerla et al., 2021; Van Eck & Waltman, 2010). Network models generated from the scientometric analysis were utilised to visualize the intellectual landscape of plant-based biocontrol, aiding in the resolution of research questions and objectives of this review. The following analysis was conducted to reveal the research pattern: Keyword co-occurrence analysis, thematic evolution and mapping, influence network analysis, and forecasting via the 4Q analysis. In the keyword selection and analysis, both singular and plural forms of certain keywords, such as 'essential oil' vs. 'essential oils' and 'fungicide' vs. 'fungicides' were included. The singular form implies a specific type, while the plural form denotes multiple types or the general concept. This approach allowed for a comprehensive capture of the varied contexts in the literature. These scientometric methods provide

a comprehensive view of the research field, helping researchers to understand the past and present landscape, identify trends, predict future developments, and make informed decisions about their research strategy (Adetunji et al., 2022; Ghaleb et al., 2022).

Best-evidence review selection: inclusion and exclusion criteria

In a bid to address two of the research questions (What is the current state and progression trend of research regarding the utilisation of plants for biocontrol in crop protection? Which plant species emerge as the most promising candidates for biocontrol applications?), the papers from the bibliometric data were accessed and assessed. The titles and abstracts of the papers were manually reviewed to eliminate those irrelevant to the subject matter. Any papers discussing bio-nanocomposites, plant ingredients (isolated or fractionated) other than natural compounds, plant mixtures (binary or polyherbal), or natural products for anti-phytopathogenic crop protection were excluded. Studies that exclusively investigated the effect of plant on the preservation quality of crop without considering specific pathogens were also excluded in this review.

Moreover, we scrutinized pertinent articles to verify their alignment with the selection criteria of this study. The specific criteria for inclusion encompass the evaluation of percentage inhibition of crop pathogens in *in vitro*, *in vivo*, or/and *in planta* experiment(s). Papers that investigated plant-based coatings, extracts, and essential oils (either distilled or purchased) that could be traced to a specific or identified plant material were considered. Ultimately, we selected empirical studies pertaining to certain crop spoilage or diseases caused by identified pathogens, including fungi, bacteria, nematodes, and insects.

Data extraction

The process of data extraction from selected studies for the best-evidence review was conducted over the course of 9 weeks. Specific data were grouped into several main themes. Anti-phytopathogenic plants were extracted from each study based on their superior effects. We targeted plants with the least concentration that elicited the greatest effect amid varying concentrations as determined by the most effective

extraction solvent or/and plant material(s) amid other itemised ones. Only plants that exhibited $\geq 50\%$ effect were retrieved. Additionally, the most effective plant samples against a pathogen among several other pathogens was considered for extraction in each study, while plant sample efficacy against pesticide-resistant pathogens was prioritised over conventional pathogens. All botanical names were verified using the World Flora Online (www.worldfloraonline.org).

Data analysis

This dataset was compiled in Microsoft (MS) Excel, analysed with tables (conditional formatting) and appropriate charts, and narratively summarized. This empirical analysis was conducted to determine the most important plants utilised as biocontrol agents in crop protection against pathogens.

Results and discussion

Identification of research hotspots: Relevant terms and knowledge structure in the research field of plant-based crop protection

Co-occurrence network of keywords

Keyword co-occurrence network analysis is a valuable tool for researchers to identify the core content of literature and visualize the structure of knowledge. It identifies “keywords” that appear together in at least two publications within a certain period, playing a crucial role in information retrieval and research. This scientometric method forms clusters that provide a comprehensive view of various research focuses within a specific knowledge domain (Adetunji et al., 2022; Fadiji et al., 2023; Sabe et al., 2023; Zhou et al., 2023). Each cluster represents a group of keywords that frequently appear together in the same research context. This visualization helps identify frequently used keywords, their relationships, and underrepresented research areas. In a co-occurrence network, nodes represent keywords, and links represent co-occurrence relationships. The proximity of nodes indicates the frequency of co-occurrence, while the node colour and size represent different clusters and keyword frequencies, respectively. A high total

link strength represents the strength of the co-occurrence relationship among keywords in the same studies (Lozano et al., 2019).

We identified various types of co-occurrence networks in the research area, focusing on plant application for biocontrol (Fig. 1). Each type provides a different perspective on research trends and hotspots in this field. Co-occurrence of all keywords provides an overview of all-keywords used in a field, while co-occurrence of author-keywords focuses on the keywords chosen by authors to describe their research. Co-occurrence of index-keywords provides insight into how a field is indexed and categorized by databases and indexing services.

Co-occurrence network of all-keywords The keyword co-occurrence network provided a comprehensive overview of all-keywords used in the field of plant-based crop protection, including those appearing in titles, abstracts, and author keyword lists of a set of publications (Fig. 1A). In this study, we used VosViewer to analyze all keywords (using the full counting method), setting the minimum number of keyword occurrences as 5. Out of 2511 keywords, 180 met this threshold, resulting in five distinct word clusters (Fig. 1A). In the keyword co-occurrence network analysis, we noted an interesting pattern related to the use of singular and plural forms of certain keywords. For example, 'fungicide' was often used when a specific fungicide was the focus, while 'fungicides' when the discussion involved multiple types of fungicides, including essential oils, or the concept in general. The red cluster indicated a group of keywords in a research context of "pest control" or "pesticides", with "crop protection" being the most frequent keyword. The yellow cluster suggested a research focus on nanotechnology engaged in crops. "Nonhuman" and "chemistry" had the highest incidence of keywords in the blue and purple clusters, respectively. The proximity of some keywords could indicate a significant overlap in the research contexts of these keywords, potentially highlighting a common theme or trend in the literature.

Supplementary Table S1 compares the frequency of occurrence and total link strength of the top 10 keywords. The most frequently occurring keywords from each cluster (Fig. 1A) were included in this top 10 list. The total link strength signifies the degree of co-occurrence of each keyword with others in the

same publications. The keyword "fungicide" had the highest occurrence (54), followed by "crop protection" (52) and "nonhuman" (50). The term "article", potentially referring to the publication type, occurs 39 times. "Essential oil" was noted 37 times, while "anti-fungal activity" and "fungi" both occurred 36 times. The keywords "chemistry", "essential oils", and "unclassified drug" had frequencies of 32, 31, and 26 occurrences, respectively. Despite having a lower occurrence frequency than "fungicide", the keyword "nonhuman" (possibly referring to non-human subjects or models such as crops or plants) exhibited the highest total link strength. This indicates that occurrence frequency and total link strength are independent metrics, each providing unique insights into the data.

Co-occurrence network of author-keywords

Figure 1B illustrates the co-occurrence network of author-keywords in the field of plant-based crop protection. The nodes represent keywords that appear in a set of publications provided by the original authors, with a minimum occurrence of 5. Out of 792 keywords, 22 met this criterion, and the network comprised 5 clusters, each displaying a few keywords. The most frequent keywords in the red and green clusters were "crop protection" and "essential oil", respectively. In the yellow, blue, and purple clusters, the most frequent keywords were "plant extract", "anti-fungal activity" and "natural products", respectively. The overlap of keywords across different clusters suggests interconnected or bridging topics among various research themes in the field.

The top 10 author-keywords based on occurrence frequency and total link strength are shown in Supplementary Table S2, these contained the key trends in the clusters represented in Fig. 1B. "Essential oils" was the most frequent keyword (21 occurrences) and had the highest link strength (20). However, these metrics are independent, as shown by "fungicides", which, despite fewer occurrences, demonstrated higher interconnectedness than "fruit quality".

Co-occurrence network of index-keywords In terms of the co-occurrence network, the nodes represent index-keywords assigned to a set of publications by Scopus, a database that uses standardized vocabularies derived from thesauri owned or licensed by Elsevier. Unlike author-keywords, index-keywords



consider synonyms, alternate spellings, and plurals, enhancing the precision and breadth of article retrieval (Fadji et al., 2023; Golub et al., 2020; Soto, 2017). A minimum occurrence of 5 was selected for the index-keyword analysis, and out of the 2003 keywords, 155 met this criterion, which yielded a network comprising five clusters (Fig. 1C). The green and yellow clusters suggest research contexts of pesticides and plant oils, with “fungicide” and “chemistry” being the most prevalent keywords. The red cluster portrays a context of experimental activity in line with pest control, while the purple cluster shows keywords in the research context of “chemical structure” and “experimental effect”. Notably, the blue cluster has “nonhuman” as its most frequent keyword.

Based on their frequency of occurrence and total link strength, a comparative analysis of the top 10 index-keywords is shown in Supplementary Table S3. The four most frequent keywords, similar to Supplementary Table S1, are “fungicide” (51 occurrences), “nonhuman” (50), “article” (39), and “crop protection” (37). Other notable keywords include “chemistry” (32 occurrences), “fungi” (32), “essential oil” (31), “unclassified drug” (26), “plant extract” (24), and “fungicides” (22). It is important to note that occurrence frequency and total link strength are independent metrics.

Key research themes and trends of topics in the field of crop protection

The treemap depicts the distribution of keywords across different categories (Supplementary Figure S1). The categories were represented by various square sizes, which reflect the percentage frequency of each keyword used in the research literature. Among 50 categories, “fungicide,” “nonhuman,” “crop protection,” “article,” “fungi,” and “essential oil” had the largest distribution, with relative frequencies of occurrence at 6, 5, 5, 4, 4, and 3%, respectively (Supplementary Table S3). The keyword usage trends and patterns varied from 1999 to 2023 (Supplementary Figure S2). All keywords, including “article”, “crop protection”, “fungicide”, and “nonhuman” maintained minimal usage until around 2011. The occurrence of terms such as “essential oil”, “fruit”,

“fungicides”, “chemistry” and “unclassified drugs” only increased significantly around 2015, possibly reflecting the times when research on these topics became more prevalent.

A diverse pattern of the distribution of topics over time in research investigating the use of plants for biocontrol in crop protection was evident (Fig. 2). It represents various terms related to agriculture, such as “sustainable agriculture”, “crop protection”, “pest control” and “biological product” as well as keywords associated with experimental/scientific topics, such as “gas chromatography-mass spectrometry”, “chemistry”, “antifungal agents”, “microbiology”, and “nanoparticle” from 2000 to 2022. The horizontal lines represent the progressive occurrence of each term within a given time, with the starting and ending points of each line signifying the first quartile (the year when a quarter of the incidences of a topic have been recorded) and third quartile (the year by which 75% of the occurrences of a topic have appeared), respectively. The position and size of the dots or bubbles within a given time represent the median quartile (the year marking the point at which 50% of the topic occurrences have taken place) and occurrence frequency of the term, respectively. This increasing trend reflects the growing emphasis on developing more effective and environmentally sustainable fungicides. Recent advancements in this area have led to the development of bio-based fungicides, which are derived from natural sources and offer a more eco-friendly alternative to traditional synthetic fungicides. Furthermore, this indicates a rising interest in exploring essential oils as natural biopesticides. Recent studies have demonstrated the potential of essential oils in controlling a range of crop pathogens, offering a promising alternative to chemical pesticides due to their biodegradability and lower toxicity.

Bacillus thuringiensis is the earliest term, with 50% of its occurrence frequency already in 2000, while nanotechnology is the latest term in the field of research on the use of plants as an alternative control against crop pathogens, with its starting incidence in 2022 and 50% occurrence frequency in the same year. This visualisation provides a clear and informative representation of the trends in crop protection research, gaining insights into how different terms have evolved and identifying emerging trends and patterns.

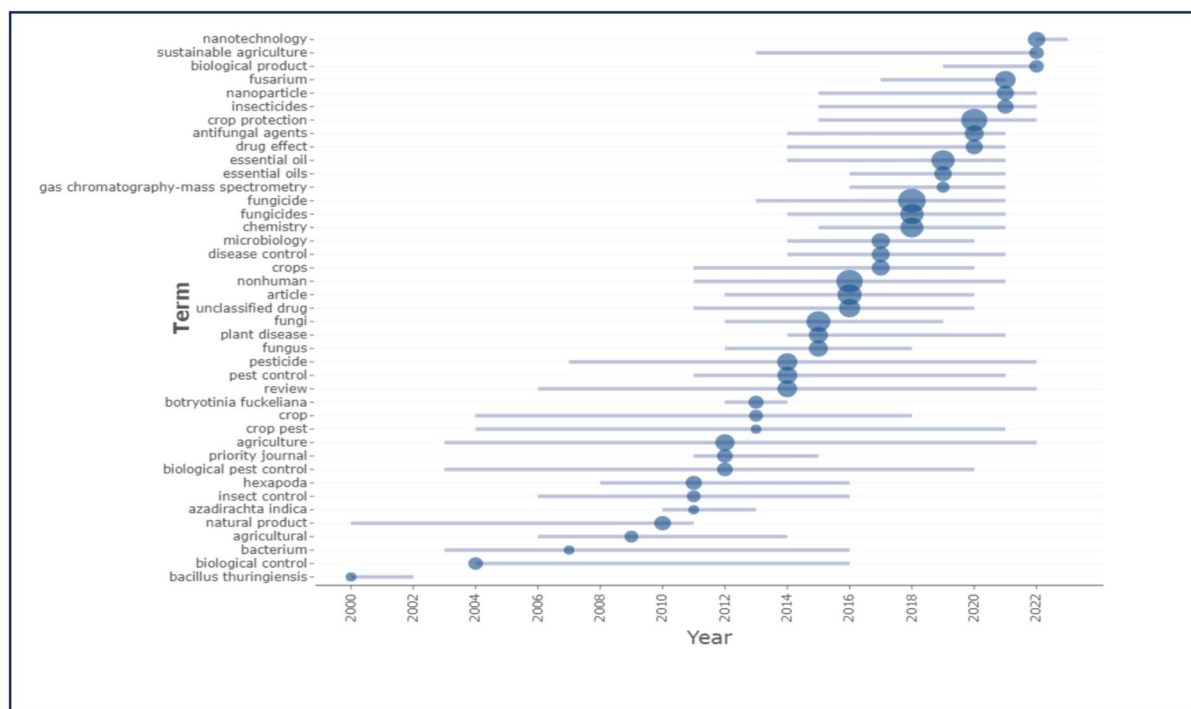


Fig. 2 The trend of topics over time in the research area focusing on the application of plants for biocontrol in crop protection

A thematic map plotting the development degree (density) against the relevance degree (centrality) of Keyword Plus (index keywords) revealed the Niche Themes, Emerging or Declining Themes, Basic Themes, and Motor Themes (Fig. 3). Each four-quadrant displayed different coloured ovoids representing various themes or topics within this field. Niche Themes are specialized areas of research important within their specific context. Keywords in this quadrant, such as “antifungal agents”, “drug effect”, and “chemical structure” suggest a focus on the chemical properties and effects of certain antifungal agents. The keyword “microbial sensitivity tests” overlapping into the Emerging Themes quadrant revealed that this area is gaining more attention. Emerging Themes represent areas of research currently gaining prominence. The keywords suggest a focus on bioactive compounds, health risks, antioxidant activities, essential oils, certain plants and fungi, and specific plants such as clove and garlic used for crop protection. The relatively small size of some themes in the quadrant suggests that they are still in the early stages of emergence.

Motor Themes are fundamental areas of study that drive the research in this field. The associated keywords suggest a focus on environmental protection, sustainable agriculture, nanotechnology, and the impact of crop protection methods; antifungal activity; and a review of pesticides and insecticides used for pest control. The keyword “fungicide” from the Basic Themes extrapolating into this quadrant could indicate its increasing importance in driving research in this field. Basic Themes form the foundation of the field, with keywords focusing on fungicides that may include the use of essential oils and their chemistry.

Research and influence networks: Drivers of scientific progress in the field of crop protection

Research and influence networks are pivotal in scientometric analysis, visually depicting relationships and collaborations among various entities. They facilitate the identification of key publications, their origins, authors, and associated countries within a specific research field (Akwu et al., 2023; Ghaleb et al., 2022; Sabe et al., 2023; Schäfermeier et al., 2023).

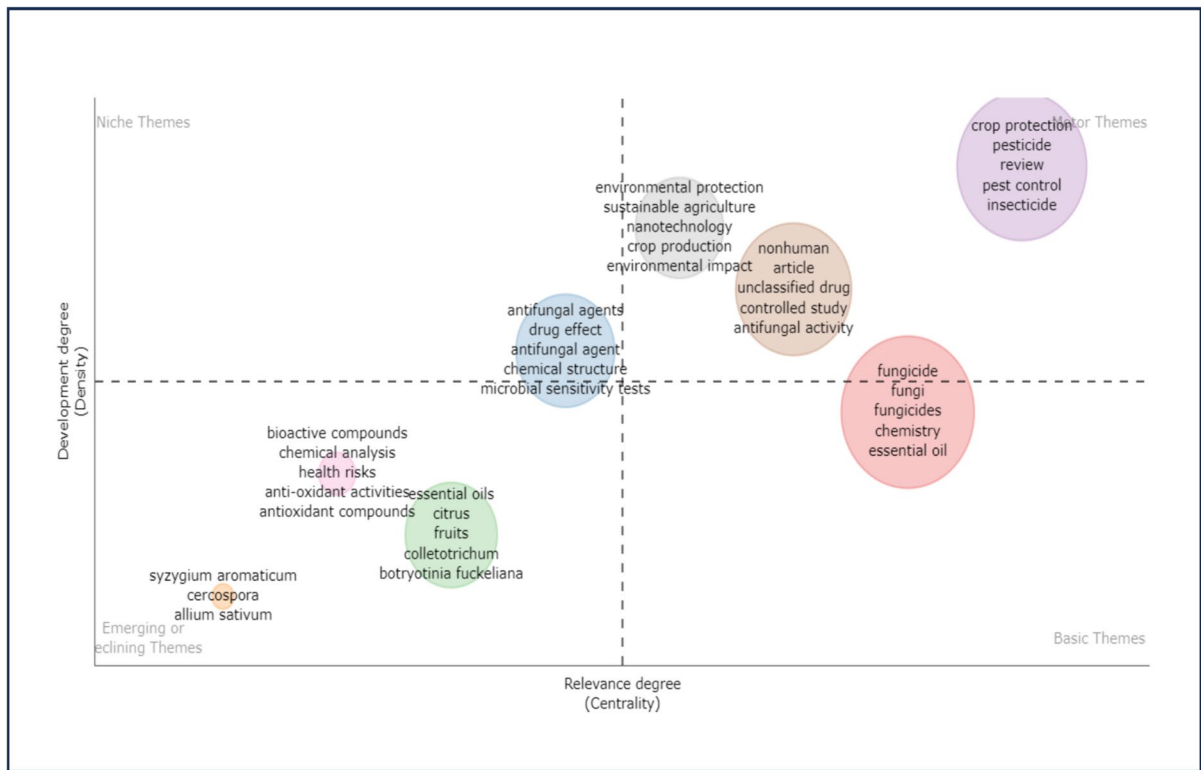


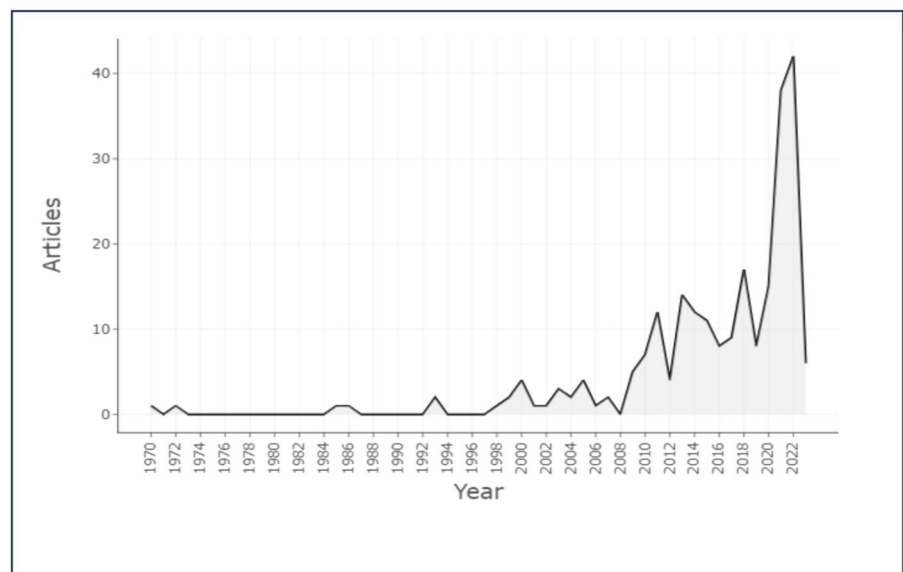
Fig. 3 Thematic map of Keyword Plus in the field of crop protection

Trends in publications and citation metrics: Scientific track over-time

The temporal analysis of publications in the field of plant-based biocontrol for crop protection, with

235 articles from 1970 to 2022, reveals significant insights into the evolution and current trends in this research area (Fig. 4). From 1970 to 2009, the field experienced modest activity, indicating that while the concept of plant-based biocontrol was recognised, it

Fig. 4 Annual scientific publications from 1970 to 2023 in the field of study focusing on plant-based crop protection



was not the primary focus in crop protection research. The average annual growth rate of 4.1% during this period reflects an early stage of development in this field. The cumulative total of 32 papers by 2009 suggests initial exploratory research efforts, possibly laying the groundwork for future advancements. The notable increase in publication volume from 2009 onwards, particularly the surge from 2019 to 2022 with a growth rate of 51%, signifies an increasing interest and recognition of the importance of plant-based methods in crop protection. This increase in research activity can be attributed to several factors, including growing environmental concerns, the push for sustainable agricultural practices, and advancements in understanding plant-pathogen interactions. The peak of 42 articles in 2022 suggests the field's dynamic nature and its alignment with global sustainability goals.

The distribution of publications across seven distinct periods, from 1970 to 2023 (Supplementary Table S4) further illustrated the evolving nature of this research field. The paradigm shift observed in the fourth period (2015–2017) and the subsequent sharp increases in publication volume highlight a growing scientific consensus on the potential of plant-based biocontrol methods. These periods coincide with significant advancements in biotechnology, nanotechnology, and the identification of new bioactive compounds, reflecting a more integrated and innovative approach to crop protection.

The citation metrics, particularly the high citation rates in 1999, 2007, 2009, and 2016, with a peak index in 2002 (Supplementary Figure S3), indicate the important contributions and lasting impact of research conducted during these years. High citation rates often suggest that the research has either introduced novel concepts, methodologies, or has significantly influenced the direction of future studies in the field.

Relevance of publication sources and their dynamics in the field of research on plant-derived biocontrol

Journals The selection of the most relevant journals in the field of research on the use of plants as biocontrol for crop protection is based on the number of published articles (Supplementary Figure S4). These journals have collectively published 58 articles, constituting approximately 25% of the

total 235 publications related to the scope of the current review. The journal "Industrial Crops and Products" leads with 9 articles, followed by "Journal of Agricultural and Food Chemistry" and "Pest Management Science", each with 7 articles. "Frontiers in Microbiology" has contributed 6 articles. The relevance of the top three journals to this field is likely due to their agriculture- or crop-related names. The common theme across most of these journals is a focus on scientific research related to agriculture and biology. More specifically, they cover topics such as the industrial use of crops, the chemistry of agricultural products, pest management strategies, and microbiological research. These journals contribute significantly to understanding and improving agricultural practices and products.

We highlighted the trends in cumulative publication occurrence over time in the top journals with ≥ 5 published articles within the research field of plant-based crop protection (Fig. 5; Supplementary Figure S4). Despite the establishment of sources such as "Journal of the Science of Food and Agriculture", "Journal of Agricultural and Food Chemistry", and "Pest Management Science" in 1950, 1953, and 1973, respectively, none of these journals disseminated any articles in this field until 2000. This is consistent with the observation that only 13 articles were published in this field prior to the millennium (Fig. 5). The reasons for the absence of publications within this period are unclear. Perhaps the research field centred on plant-derived biocontrol for crop protection against pathogens was not well established or recognized at that time. Other potential factors include technological, theoretical, and practical considerations. Furthermore, most of the journals that published papers in this field before the year 2000 had a relatively low impact factor, which was often < 3 (Anaya, 1999; Firman & Hoskin, 1970; Foy, 1993; Ingham, 1972; Jespers & Waard, 1993; Williams, 1985). Among the top recognised journals (Fig. 5), "Pest Management Science" was the first to publish papers (3) in this research field in 2000. This was followed by "Journal of Agricultural and Food Chemistry" with one paper in 2003. About nine years later (2012), articles within the scope of this review were published in "Acta Horticulturae" and "Industrial Crops and Products".

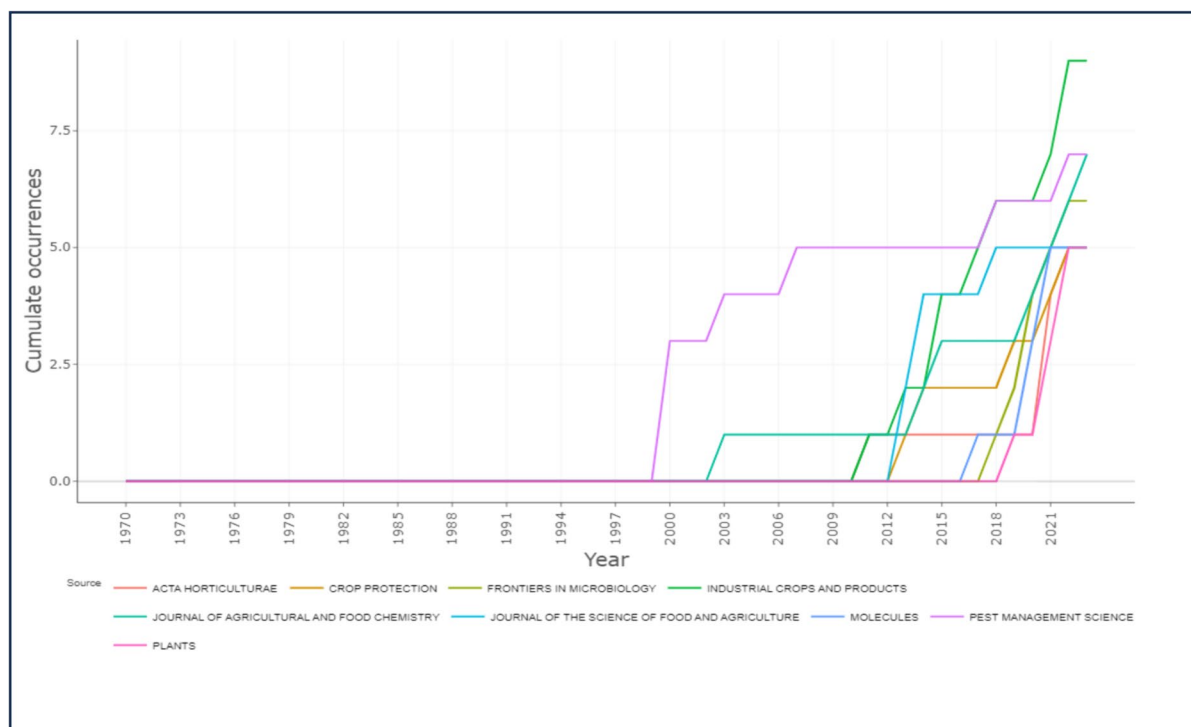


Fig. 5 Dynamics of journal publication occurrences over time in the research area focusing on the application of plants for biocontrol in crop protection

In terms of the impact (H-Index) of relevant sources in the field of plant-based crop protection against pathogens, the value of the journal ranged from 2–7 (Supplementary Figure S5). The leading journals in terms of publication count (≥ 5 , Supplementary Figure S4), such as “Industrial Crops and Products”, “Journal of Agricultural and Food Chemistry”, “Pest Management Science”, “Frontiers in Microbiology”, and “Journal of the Science of Food and Agriculture”, which also ranked highly in terms of impact, with H-indices of 7, 5, 5, 5, and 5, respectively.

Academic institutions In this study, the top 20 academic affiliations were identified on the basis of their relevance to the research field and their contributions to published articles in this field (Supplementary Figure S6). All affiliations from each of the 235 research literature data generated by the bibliometric analysis were considered, resulting in a total of 505 affiliation occurrences. These top 20 affiliations have contributed to 90 articles, accounting for 17.8% of the total 505 incidence of academic institutions in all research

literature in this field. Tshwane University of Technology in South Africa leads with 9 publications. Federal University of Paraíba in Brazil contributed to 6 publications. Cyprus University of Technology, Virginia State University in the United States, Northwest A&F University in China, Instituto Politécnico Nacional in Mexico, and Ferdowsi University of Mashhad in Iran follow with 5 publications each. It is noteworthy that among the top 20 affiliations, 50% are located in Asia (China, Iran, and Thailand); 20% are based in Europe (Cyprus, Serbia, Germany, and Romania); while Africa (Egypt and South Africa), North America (USA and Mexico), and South America (Brazil) each account for 10%.

Over time, the various universities had diverse research outputs (Fig. 6). It specifically highlights the trends in articles produced by the top academic institutions with ≥ 5 research outputs (Supplementary Figure S6). Interestingly, none of these affiliations contributed any articles in this field until 2009. This observation underscores the intermittent contribution of certain affiliations to earlier publications in this field (Adejumo, 2005; Almada-Ruiz

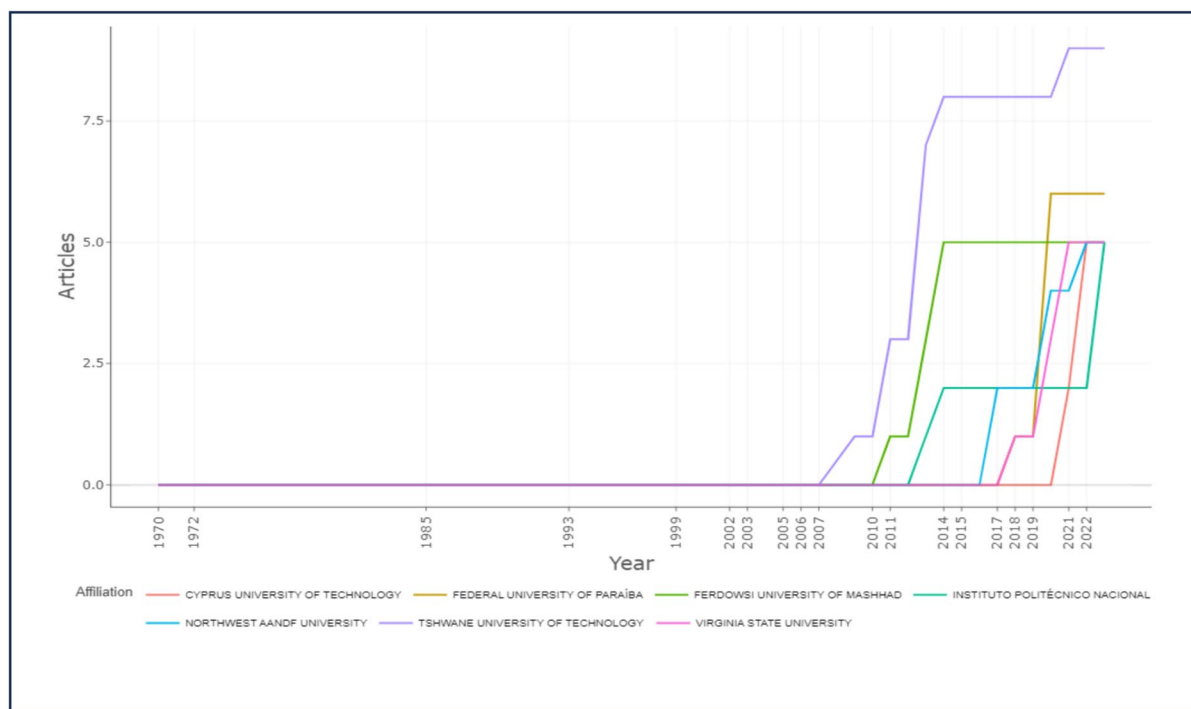


Fig. 6 Dynamics of affiliation contribution over time in the field of study focusing on plant-based crop protection

et al., 2003; Anaya, 1999; Carlini & Grossi-de-Sá, 2002; Chu et al., 2001; Firman & Hoskin, 1970; Foy, 1993; Gozzo, 2003; Ingham, 1972; Jespers & Waard, 1993; Jourand et al., 2004; Kiran et al., 2007; Korsten, 2004; Santino et al., 2005; Sturz et al., 2006; Williams, 1985). Among the universities that top the affiliation chart (Fig. 6), Tshwane University of Technology was the first to contribute a paper in this field in 2009. Ferdowsi University of Mashhad made its initial contribution of one paper in 2011, followed by Instituto Politécnico Nacional in 2013 and Virginia State University in 2018. The first contributions from Cyprus University of Technology and Northwest A&F University were made in 2021 and 2017, respectively. Each institution contributed two papers to the field.

Authors' contributions: Productivity, influence, and collaborations

Authors' productivity and impact Analysing the research outputs of leading authors in the field provides valuable insights into the intellectual landscape

and the evolving focus areas within plant-based bio-control (Fig. 7). The prolific publication record of authors such as Sivakumar D. and Zhang Y. highlights the dynamic nature of research in this field. Sivakumar D.'s highest publication count in a single year (2013) and the consistent output by Zhang Y., Chrysargyris A., Tzortzakis N., and Xylia P. in recent years (2021 and 2022) indicate an intensifying research interest in plant-based methods for crop protection. This productivity pattern reflects a growing scientific community's engagement with the challenges and opportunities in this domain. The high citation counts of articles including those published in 2009 on natural products in crop protection by Duke S.O. (Dayan et al., 2009) and those published in 2014 on essential oils for postharvest decay control by Bautista-Baños S. and Sivakumar S. (Sivakumar & Bautista-Baños, 2014) illustrate the significant impact these works have had on the field. This is an indication that these topics are highly interesting, relevant, and applicable to crop protection strategies.

The application of Lotka's law and the observation of authors' productivity patterns following this inverse power law distribution (Supplementary

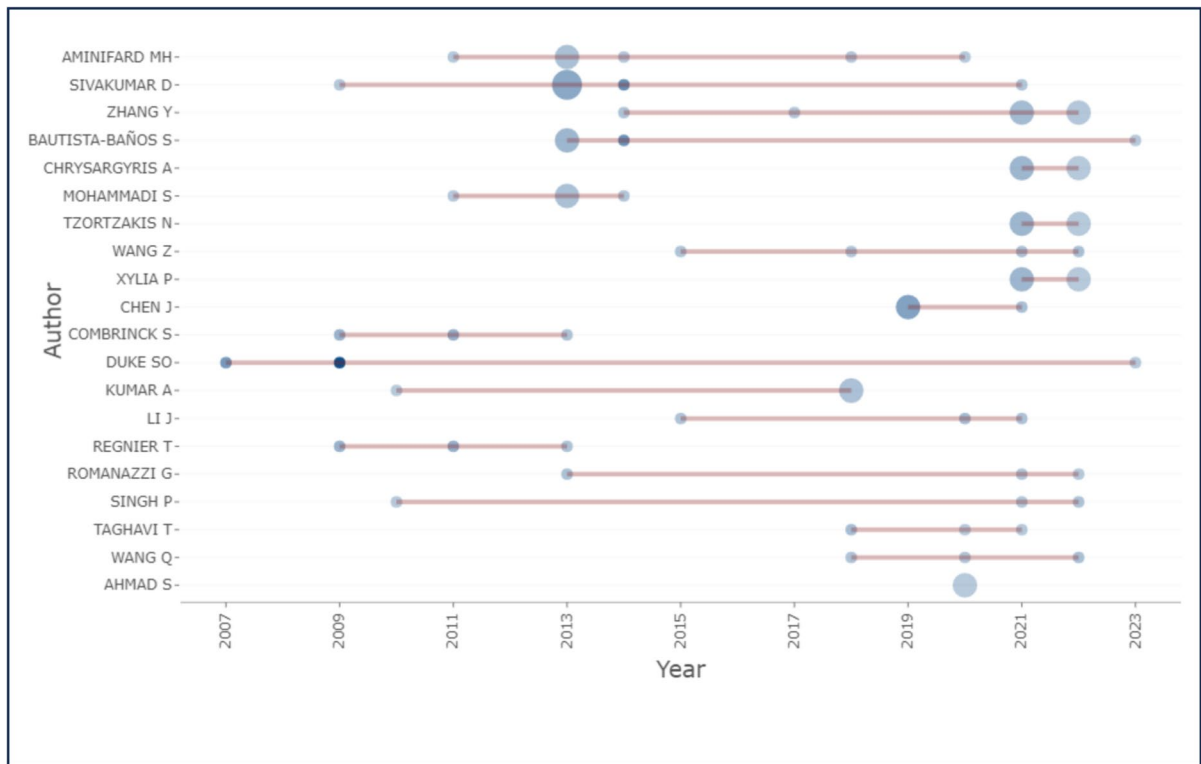


Fig. 7 Authors' productivity and research impact over time from 2007 to 2023 in the research field centred on utilising plants as a biocontrol method for crop protection

Figure S7), signify a typical academic productivity trend in this specialized field. The steep decline in the percentage of authors with increasing publication count suggests that while many researchers contribute to the field, fewer authors are highly prolific, driving significant advancements in plant-based crop protection.

The H-index data (Supplementary Figure S8) further suggested the influence of these key researchers, with an H-index of 5 for Sivakumar D., along with Aminifard M. H., Wang Z., and Zhang Y., each with an H-index of 4, indicating that their research is prolific and also impactful. This metric reflects their sustained contributions to advancing knowledge and practical applications in the field.

Co-authorship networks: Researchers' collaborations and countries The collaborative and fractionalized contributions of top authors with high publication counts (≥ 3) in the research field investigating the use of plants for biocontrol in crop protection is

shown in Table 1. The fractionalized count system, as reported by Mutz and Daniel (2019), considers each article by multiple authors as 'one unit' of work, and the count for that article is divided among them. This approach results in an average co-authorship count for Aminifard M. H., Sivakumar D., Zhang Y., Bautista-Baños S., Chrysargyris A., and Mohammadi S. of 2.45, 3.37, 6, 3.57, 4.21, and 2.35, respectively. On the other hand, fractionalized contribution refers to the allocation of authorship credit, which could be influenced by the order of authors in the byline or the type of contribution such as research design, data analysis, writing, and critical review (Hagen, 2008; Sundling, 2023). This approach provides a more equitable representation of authorship in scientific publications, acknowledging the varied roles and contributions of authors in research articles (Sivertsen et al., 2019). Aminifard M. H. contributed six articles, but their contribution to these articles was fractionalized in such a way that it is equivalent to 2.45 articles (Table 1). This suggests that they played a substantial

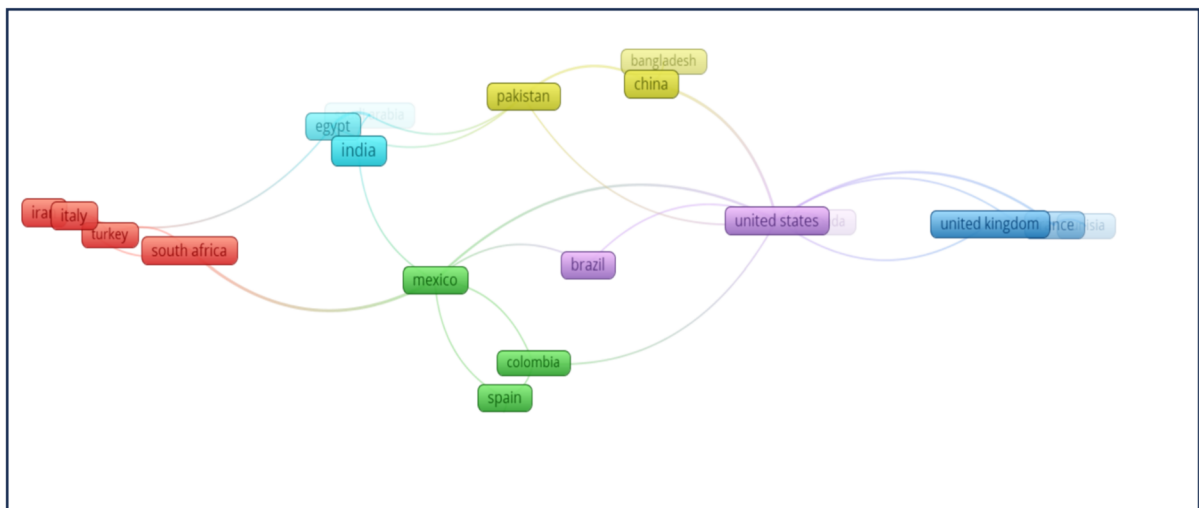
Table 1 Collaborative and fractionalized contributions of researchers with ≥ 3 publications

Authors	Articles	Articles fractionalized
Aminifard M.H	6	2.45
Sivakumar D	6	1.78
Zhang Y	6	1.00
Bautista-Baños S	4	1.12
Chrysargyris A	4	0.95
Mohammadi S	4	1.70
Tzortzakis N	4	0.95
Wang Z	4	0.61
Xylia P	4	0.95
Chen J	3	0.54
Combrinck S	3	0.92
Duke S.O	3	1.17
Kumar A	3	0.67
Li J	3	0.39
Regnier T	3	0.92
Romanazzi G	3	1.03
Singh P	3	1.03
Taghavi T	3	0.67
Wang Q	3	0.54

role in more than two articles. Similarly, Sivakumar D. contributed to six articles, but their contribution was split into portions equivalent to 1.78 articles,

indicating that their role was significant but not as extensive as the research outputs by Aminifard M.H. Zhang Y., who also contributed to six articles, had their contribution fractionalized to an equivalent of 1.00 article, suggesting that their contributions were more evenly distributed among these articles.

The Sankey diagram provides a visual representation of the relationships among authors, their affiliated countries, and frequently used keywords in the field of crop protection (Supplementary Figure S9). This visualisation offers insights into the interconnectedness of research in the field based on authors' contributions and their countries' affiliations to relevant keywords. The diagram shows that Italy (with authors Sivakumar D., Tzortzakis M., Xylia P., and Chrysargyris A.) and China (with authors Wang Z., Zhang Y., and Chen J.) are the countries with the most represented authors. The keywords “nonhuman” and “unclassified drugs” appear to be less popular among authors. However, keywords such as “fruit”, “fungicide”, “fungi”, “essential oil”, and “crop protection” are common among authors affiliated with Italy, South Africa, and Mexico. This suggests that these authors focus on research related to the potential use of essential oils as fungicides for crop protection. Authors connected to China, Iran, and USA (represented by only one author) cover all the keywords in this visualisation. This implies that these authors' research interests align with investigating the

**Fig. 8** Co-authorship network of countries in the research field centered on utilising plants as a biocontrol method for crop protection

efficacy of essential oils as antifungal agents, from a chemistry perspective to actual crop protection.

A network of co-authorship across different countries was evident in the current review (Fig. 8). According to López-Pernas et al. (2023), collaboration among authors and research institutions in various countries are explored through co-authorship network of countries. The minimum criterion for inclusion was a 3-publication contribution (documents) per country. Out of 51 countries, 29 met the threshold. The size of the nodes indicates the number of publications from each country, while the thickness of the links represents the strength of the co-authorship relationship between two countries, i.e., the number of co-authored publications. India, China, Italy, USA, and South Africa are identified as the countries with the most papers (Fig. 8; Supplementary Table S5). The network is divided into six clusters, each representing groups of countries that frequently collaborate with one another. The United Kingdom, Italy, and Mexico are the most prevalent in terms of publications within their respective clusters (blue, red, and green). Similarly, USA, China, and India led in terms of publication frequency within their respective clusters (purple, yellow, and turquoise).

The publication contribution and impact of the top 10 countries are compared with their total link strength in Supplementary Table S5. The ‘Documents’ column indicates the number of research papers contributed by the authors from each country. The ‘Citations’ column shows the total number of times these documents have been cited by other researchers, indicating their impact on the field. The ‘Total Link Strength’ column represents the strength of the co-authorship network within each country, indicating the interconnectivity of the authors from each country. It is noteworthy that USA maintains a central link with China, France, Mexico, and South Africa. This suggests strong co-authorship relationships between researchers from these countries (Supplementary Table S5; Figure S9). For example, with 23 documents, 2588 citations, and a total link strength of 10, USA was the major contributor to this field of research. Moreover, the publication contribution and impact of countries are independent of their co-authorship network. For example, China contributes high number of documents (25) but has fewer citations (494) and a lower total link strength (5) compared to USA and Mexico; while India contributed

the most documents among these countries (30) and had a high number of citations (956) as well as among the countries with the least strength of co-authorship network (2).

Country-wise publication output and citation impact

The analysis of global research output in plant-based crop protection reveals significant geographic trends and disparities (Fig. 9). A comprehensive geographic heat map covering 51 countries highlights the intensity of scientific production across these nations, with China, Italy, USA, Brazil, and South Africa leading in publication counts of 60, 38, 35, 34, and 28, respectively. The predominance of high-income and upper-middle-income countries in this productivity category, as observed in most of these leading nations, aligns with broader patterns in global scientific output (Hamadeh et al., 2022). This observation aligns with several bibliometric reviews of various fields that have also identified China as a leading country in terms of scientific productivity (Akwu et al., 2023; Fadji et al., 2023; Oyewola & Dada, 2022). However, India (47), Iran (39), Egypt (13), and Pakistan (11) were prominent as the only low-middle-income countries within the higher productivity category. Conversely, about 60% of the countries with lower publication count (<10) fall within the lower-middle-income and low-income levels (Fig. 9). These insights offer a valuable perspective on global research productivity in this field (Hamadeh et al., 2022).

The analysis of the research outputs from the top 5 countries revealed that USA, Italy, India, Iran, and China have significantly contributed to the knowledge generation in the field over time (Supplementary Figure S10). The late start of China in this research area (first publications in 2014) yet leading in total publications by 2023, illustrates a rapid acceleration in scientific productivity. The USA was the first to contribute to this research field with two papers in 1986, which increased to 35 by 2023. Italy followed with its first paper in 2003 and had contributed 38 by 2023. India's contributions began with two papers in 2007 and increased to 47 by 2023. The contributions from Iran started with five papers in 2010 and reached 39 by 2023. Despite being a leading contributor (by 2023) with a total of 60 papers, China only started

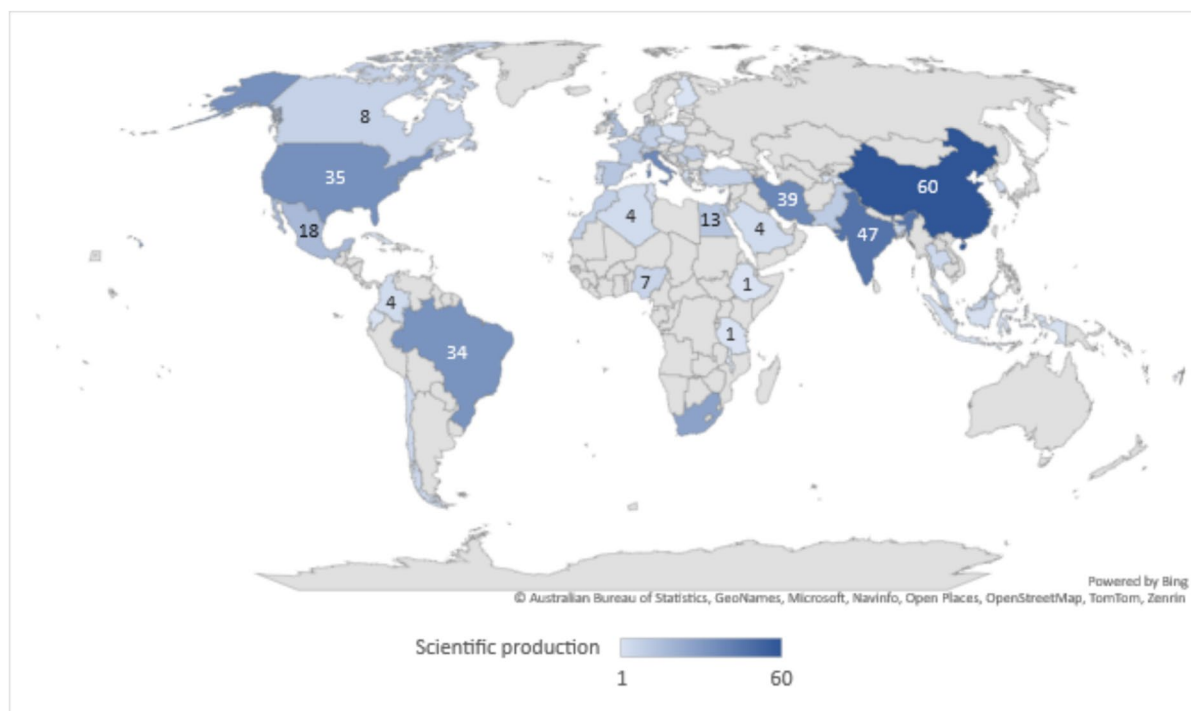


Fig. 9 Geographic heat map of scientific production across different countries in the research area focusing on the application of plants for biocontrol in crop protection

contributing to this field in 2014 with its first set of 10 publications.

The analysis based on the corresponding authors' publications provides insights into international collaborations (Supplementary Figure S11). Each bar in the visualisation represents a country, with the bar length indicating the number of publications by corresponding authors from that country. The red bar, labelled as MCP (multiple country publications), represents inter-country publications of corresponding authors, while the blue bar, labelled SCP (single country publications), represents intra-country publications. Corresponding authors play a significant role in facilitating correspondence between the co-authors of a manuscript and the target journal during the publication process and with readers after publication (Helgesson, 2021). India had the highest corresponding authors' publications (26) in this field. Generally, for all the selected countries with a mix of SCP and MCP, SCP was higher than MCP when considering the nationality of the corresponding author. The highest MCP is seen in China (5), Italy (5), and France (4), suggesting that these countries have relatively

high levels of international collaboration in this research area. In contrast, Brazil, Nigeria, Serbia, and Germany had only SCPs, indicating a focus on domestic research collaborations.

Supplementary Table S6 covers a comprehensive view of the top 20 countries based on their total citation count of publications attributable to them in the field of crop protection. The USA leads with the highest number of citations (1710), followed by India (906), South Africa (776), and the United Kingdom (752). This indicates that these countries have a high level of research impact in this field. Despite having fewer total citations than these four countries, Germany stands out with the highest average number of citations per article (213.67). This suggests that, on average, articles from Germany are more influential in this field. Hence, there is no direct correlation between a country's total citation count and the average citation count per article. Nigeria, despite having a relatively low total number of citations (38), had the lowest average number of citations per article (7.60). This indicated that Nigeria's research output in this field is relatively recent and with limited citations

thus far. Countries such as Brazil, Italy, and Iran, despite having a moderate number of total citations, have relatively low average citation counts. This suggests a need for authors associated with these countries to focus on improving the impact and reach of their research.

Research advances on the use of plants as an alternative to synthetic agro-chemicals for crop protection

Top 25 most cited papers

In identifying the 25 most cited documents in the field of plant-based crop protection against pathogens (Table 2), we uncover crucial research that has significantly influenced the trajectory of this field. These papers, spanning from 1972 to 2019 and accruing citations ranging from 67 to 862, represent foundational works and key advancements in the use of plants for crop protection. The output by Dayan et al. (2009) on natural products in weed, insect, and fungal management, had the highest citation count of 862, illustrating the profound impact and relevance of comprehensive studies in this area. Similarly, the substantial citations accrued by authors such as Sekhon (2014), Henkel et al. (1999), and Katz and Baltz (2016) indicated that their research has become important in the field, shaping on-going discussions and future research directions. The top-cited papers are predominantly published in journals such as "Bioorganic & Medicinal Chemistry", "Journal of Industrial Microbiology and Biotechnology", "Angewandte Chemie International Edition", "Nanotechnology, Science and Applications" and "Toxicon".

Research overview of the most-cited papers

The critical evaluation of the top 25 most-cited documents reveals significant trends and advancements in the field of plant-based crop protection. These trends encompass a broad spectrum of research directions, reflecting the evolution in the field over time and its current focus on sustainable and innovative solutions.

Historical trends and advancements in crop protection Russell (2005) provided a historical perspective on pest control, highlighting the initial reliance on inorganic compounds such as sulphur and

copper sulphate. The era marked the beginning of systematic approaches to crop protection, laying the groundwork for future advancements. The development of homemade fungicides and the better understanding of plant pathology and epidemiology during this period demonstrate an early interest in integrating plant science with pest control methods.

The mid-twentieth century witnessed a shift towards chemical solutions, with the introduction of systemic fungicides including blasticidin S and thia-bendazole. This period signifies a transition to more sophisticated and targeted approaches to crop protection. The rapid expansion of the crop protection market and the establishment of the Fungicide Resistance Action Committee (FRAC) reflect the growing complexity and challenges of managing crop diseases.

From the 1970s onwards, the increasing regulatory requirements and development of widespread resistance led to a search for new pesticide sources. Olson (2015) highlighted the increasing significance of biopesticides, including microbial, biochemical, and plant-incorporated protectants (PIPs). The projection that biopesticides would constitute a significant portion of the crop protection market by 2023 underscores a major shift towards more sustainable and environmentally friendly alternatives to synthetic pesticides.

Katz and Baltz (2016) described the evolution of natural product discovery from phenotypic screening to genome mining and the activation of silent genes. This evolution represents a cutting-edge approach to discovering new biopesticides, leveraging advances in genetics and biotechnology. The shift towards genetic engineering and the exploration of unexplored sources and biosynthetic pathways indicate a forward-looking, innovative approach for crop protection.

Natural products in pest management The utilisation of natural products in crop protection represents a critical area of innovation and development within the field. These products, known for their efficacy against human pathogens, are equally vital in managing agricultural pests and diseases, owing to their rich diversity of biologically active compounds (Balakumbahan et al., 2010; Henkel et al., 1999). Natural products have been integral to organic and conventional agriculture, showcasing their versatility across various applications. Their role in managing a broad spectrum of agricultural threats, including

Table 2 Top 25 most cited papers in plant-based crop protection research

Paper (Author)	Title	Journal	Total citation
Dayan et al. (2009)	Natural products in crop protection	Bioorganic & Medicinal Chemistry	862
Katz and Baltz (2016)	Natural product discovery: past, present, and future	Journal of Industrial Microbiology and Biotechnology	587
Henkel et al. (1999)	Statistical investigation into the structural complementarity of natural products and synthetic compounds	Angewandte Chemie International Edition	540
Sekhon (2014)	Nanotechnology in agri-food production: An overview	Nanotechnology, Science and Applications	529
Carlini and Grossi-de-Sá (2002)	Plant toxic proteins with insecticidal properties: A review on their potentialities as bioinsecticides	Toxicon	399
Copping and Duke (2007)	Natural products that have been used commercially as crop protection agents	Pest Management Science	377
Isman et al. (2011)	Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products	Phytochemistry Reviews	350
Sivakumar and Bautista-Baños (2014)	A review on the use of essential oils for postharvest decay control and maintenance of fruit quality during storage	Crop Protection	263
Gozzo (2003)	Systemic acquired resistance in crop protection: From nature to a chemical approach	Journal of Agricultural and Food Chemistry	230
Russell (2005)	A century of fungicide evolution	Journal of Agricultural Science	199
Anaya (1999)	Allelopathy as a tool in the management of biotic resources in agroecosystems	Critical Reviews in Plant Sciences	155
du Plooy et al. (2009)	Essential oil amended coatings as alternatives to synthetic fungicides in citrus postharvest management	Postharvest Biology and Technology	154
Mohammadi et al. (2015)	Nanoencapsulation of <i>Zataria multiflora</i> essential oil preparation and characterization with enhanced antifungal activity for controlling <i>Botrytis cinerea</i> , the causal agent of gray mould disease	Innovative Food Science and Emerging Technologies	150
Combrinck et al. (2011)	<i>In vitro</i> activity of eighteen essential oils and some major components against common postharvest fungal pathogens of fruit	Industrial Crops and Products	144
Olson (2015)	An analysis of the biopesticide market now and where it is going	Outlooks on Pest Management	118
Palou et al. (2015)	Antifungal edible coatings for fresh citrus fruit: A review	Coatings	104
Stetter and Lieb (2000)	Innovation in crop protection: Trends in research	Angewandte Chemie International Edition	86
Kenyon et al. (2014)	Virus diseases of peppers (<i>Capsicum</i> spp.) and their control	Advances in Virus Research	85

Table 2 (continued)

Paper (Author)	Title	Journal	Total citation
Ingham (1972)	Phytoalexins and other natural products as factors in plant disease resistance	Botanical Review	79
Balakumbahan et al. (2010)	<i>Acorus calamus</i> : An overview	Journal of Medicinal Plants Research	76
Marpudi et al. (2011)	Enhancement of storage life and quality maintenance of papaya fruits using <i>Aloe vera</i> -based antimicrobial coating	Indian Journal of Biotechnology	75
Sellamuthu et al. (2013)	Thyme oil vapour and modified atmosphere packaging reduce anthracnose incidence and maintain fruit quality in avocado	Journal of the Science of Food and Agriculture	75
Chen et al. (2019)	Inhibition of key citrus postharvest fungal strains by plant extracts <i>in vitro</i> and <i>in vivo</i> : A review	Plants	73
Bautista-Baños et al. (2013)	A review of the management alternatives for controlling fungi on papaya fruit during the postharvest supply chain	Crop Protection	70
Tembo et al. (2018)	Pesticidal plant extracts improve yield and reduce insect pests on legume crops without harming beneficial arthropods	Frontiers in Plant Science	67

weeds, insects, roundworms, nematodes, and fungi, is well-documented (Copping & Duke, 2007; Dayan et al., 2009). This broad-spectrum utility highlights the potential of natural products to address diverse challenges in crop protection. Some natural products have inspired the development of synthetic fungicides and herbicides. The transition from natural lead compounds to synthetic variants underscores the importance of natural products as a source of innovation in crop protection (Dayan et al., 2009). Products such as corn gluten meal, acetic acid, fatty acids, essential oils, and allelopathic compounds have been employed for weed control, demonstrating their effectiveness in non-chemical weed management. Insect control strategies have leveraged natural products such as pyrethrum, rotenone, spinosad, avermectins, milbemycins, ryania, and sabadilla, as well as neem, garlic, and essential oils as insect repellents or antifeedants. Additionally, products such as chitin, harpin, and essential oils are utilised for fungal control, enhancing disease resistance in crops (Dayan et al., 2009). Ingham (1972) proposed the significant role of post-infectious antifungal compounds and phytoalexins in plant disease resistance, suggesting the possibility of

developing their synthetic analogues for crop protection. This foresight points to the ongoing potential for natural products to inspire new, more effective, and environmentally friendly crop protection solutions.

Plant defense mechanisms and crop protection

The general reaction of plants to infection has been explained in the concept of oxidative burst which produces high levels of reactive oxygen species and leads to hypersensitive cell death around the sites of attempted invasion (Gozzo, 2003). The author further described Systemic Acquired Resistance (SAR) as a coordinated action of several gene products that are induced by salicylic acid (an organic compound found in natural products) or synthetic inducers and provide resistance against a broad spectrum of pathogens. The involvement of jasmonic acid and ethylene in plant defences, especially in response to wounding and insect feeding as well as the signal transduction pathway between sensitization by inducers and pathogenesis-related protein expression are also discussed. Despite research gaps in the prospects and costs of using SAR as a nonbiocidal alternative to pesticides in crop protection, virus co-infection resistance and

transgenic crop development are potential areas of applicability. Kenyon et al. (2014) noted that vector management is crucial as aphids, whiteflies, and thrips, which transmit the main virus groups infecting peppers, can quickly develop resistance to commonly used insecticides, thereby instigating virus co-infection, resulting in increased symptom severity and potential genetic recombination, and enhancing virus aggressiveness and virulence. Hence, the authors proposed the integration of various measures for future crop protection such as making judicious use of bio-control agents to induce plant resistance and developing polygenic resistances against virus sources to mitigate vector spread.

Allelopathy, a defence mechanism in plants, involves the release of bioactive compounds (allelochemicals) that can inhibit or promote the growth and development of neighbouring organisms, and has potential benefits in natural resource management despite the challenges with bioassays in allelopathy research and the fate of allelochemicals in soils (Anaya, 1999). On the other hand, Carlini and Grossi-de-Sá (2002) noted that various plant proteins involved in defence mechanisms against insect pests, including lectins, arcelins, canatoxin, ureases, proteases, and ribosome-inactivating proteins (RIPs), offer potential for developing new bioinsecticides or transgenic crops with enhanced resistance. Proteases play a role in plant defence against insects by reducing their starch digestion, while arcelins, a family of seed storage proteins derived from wild beans, confer resistance to bruchid beetles in postharvest storage.

Postharvest handling and preservation Bautista-Baños et al. (2013) compared the advantages and disadvantages of traditional methods such as fungicides, waxes, heat treatments, and irradiation. This comparison highlights the need to balance efficacy with safety and environmental considerations. Chen et al. (2019) evaluated innovative applications of plant extracts on citrus fruits, including coatings, fumigations, dips, and sprays. Their work emphasised the efficacy and stability of these methods and factors such as cost and consumer acceptance, which are crucial for the practical implementation of these techniques.

Research findings suggest the potential of natural products, including plant extracts and edible films, in preserving fresh fruits and mitigating major post-harvest losses (Marpudi et al., 2011; Palou et al.,

2015; Tembo et al., 2018). The successful use of plant extracts in field trials, which showed efficacy in reducing pest count without harming beneficial arthropods and even increasing crop yields, is particularly noteworthy (Tembo et al., 2018). The concept of integrated technologies combining biological, natural, and modified atmosphere methods represents a promising direction for crop protection and preservation. Bautista-Baños et al. (2013) explored the potential of combining antagonists, plant extracts, essential oils, chitosan, organic salts, ozone, and volatiles. Sellamuthu et al. (2013) provided a practical example of this approach by studying the effects of modified atmosphere packaging (MAP) combined with plant essential oil on fruit preservation. Their findings on various parameters, including disease incidence, fruit quality, and antioxidant activity, validate the effectiveness of such integrated approaches in maintaining fruit quality. Despite these advancements, challenges such as the lack of standardization of plant extracts and the need for more *in vivo* trials persist. Chen et al. (2019) recommended that future research should focus on developing strategies for managing crop postharvest diseases more effectively, improving extraction techniques, and understanding the molecular mechanisms of extracts derived from medicinal plants, edible plants, and essential oils.

Essential oils in crop protection Essential oils offer a multifaceted approach to crop protection with their rich composition of terpenes, sesquiterpenes, aldehydes, ketones, and phenolic compounds. These components disrupt cell membranes, inhibit spore germination, alter enzyme activity, and induce oxidative stress in fungal pathogens while also affecting insect nervous systems and behaviour (Isman et al., 2011; Sivakumar & Bautista-Baños, 2014). The use of essential oils in crop protection brings several advantages, such as low mammalian toxicity, environmental non-persistence, compatibility with biological control agents, and, in some cases, exemption from regulatory approval. However, they also face drawbacks such as limited persistence, phytotoxicity, and reduced efficacy against larger chewing insects. This dichotomy highlighted the need for a balanced approach in their application and further research into enhancing their efficacy and stability (Isman et al., 2011). Research have demonstrated the effectiveness of essential oils from various sources in completely inhibiting the

growth of pathogens including *Alternaria citrii*, *Botrytis cinerea*, *Colletotrichum gloeosporioides*, *Lasioidiplodia theobromae*, and *Penicillium digitatum* at minimal concentrations (Combrinck et al., 2011; du Plooy et al., 2009). This indicates the high efficacy of essential oils against a broad spectrum of fungal pathogens. The stability and activity of essential oils can be significantly enhanced through innovative techniques such as nanoencapsulation, particularly in chitosan nanoparticles (Mohammadi et al., 2015). This advancement opens up new possibilities for effectively applying essential oils in crop protection.

Innovations in crop protection The challenges in crop protection, including the need for increased food production and pest resistance, have catalysed various innovative solutions. These include precision agriculture techniques, the discovery of novel compounds, the integration of biotechnology with natural products, and biocontrol agents (Stetter & Lieb, 2000). A key innovation in this arena is the application of nanotechnology. The development of nano-sized particles and delivery systems for agrochemicals represents a significant advancement in crop protection and food processing (Sekhon, 2014). Nanofoods, nanoemulsions, nanocoatings, and nanoencapsulation are examples of how nanotechnology is being leveraged to enhance food products, focusing on efficiency, safety, specificity, and potential environmental impacts (Sekhon, 2014).

Empirical studies on plant-based biocontrol in the field of crop protection

Plants utilised in crop protection experiments We recorded 91 plant species from 28 families used as biocontrol agents against decay pathogens in crop protection experiments (Table 3). These plants were selected based on their outstanding effect against certain crop pathogens at minimal concentrations. The plants were sub-categorised into three groups: *in vitro* experiment (84 plants from 25 families), *in vivo* experiment (22 plants from 11 families), and *in planta* experiment (10 plants from 7 families). Families with the most representation were Lamiaceae (16 plants, 17.6%), Solanaceae (11 plants, 12.1%), and Apiaceae (7 plants, 7.7%). Even though some authors failed to specify the plant parts utilised (13%), the leaves (31%), aerial parts (23%), seeds

(9%), flowers (4%), and bulbs (4%) were the most frequently used plant materials for controlling crop pathogens in these experiments. The frequent use of aerial parts could be due to their inclusion of multiple plant components, potentially translating to a higher concentration of beneficial bioactive compounds. However, it should be noted that the specific plant materials used for the extraction of essential oils were not detailed in some source papers (Table 3). Many of these plants fall into categories such as grasses, herbs, or subshrubs, including plant species such as *Thymus* spp., *Cymbopogon* spp., *Ocimum* spp., *Mentha* spp., and *Origanum onites* being commonly studied.

Dominant pests and pathogens in the field of research on crop protection Based on the eligible studies included in this review, the distribution was fungi (93.9%), insects (4.5%), nematodes (0.6%), oomycete (0.6%) and bacteria (0.4%). This aligns with Anand and Rajeshkumar (2022), who identified fungi as a significant challenge to global food security and agricultural sustainability, causing up to 14% of annual crop yield losses. As shown in Fig. 10 and Table 3, *B. cinerea*, found colonizing various fruits, is the most common pathogen (16.3% frequency), followed by *Mycosphaerella fijiensis* (15.6%), *P. digitatum* (11.3%), and *Fusarium culmorum* (6.3%). These pathogens represent about 70% of those evaluated in this review. *Monilinia fructigena*, *Monilinia laxa*, *Alternaria alternata*, and *C. gloeosporioides* are other common crop pathogens evaluated in this study for their susceptibility to plant extracts. These pathogens account for approximately 70% of the total crop pathogens involved in the anti-phytopathogenic evaluation in this review. *B. cinerea*, a significant necrotrophic plant pathogen, causes devastating diseases on more than 500 plant species, particularly on fresh fruits and vegetables. Globally, this results in economic losses ranging from \$10 – \$100 billion (Hua et al., 2018). Black sigatoka, caused by *M. fijiensis*, is considered the most destructive foliar disease. It has the potential to cause a 50% yield reduction and a 100% loss of production in banana crops due to quality degradation (Arango Isaza et al., 2016).

The most promising anti-phytopathogenic plants in crop protection experiments Based on the assessment of the recorded plants (Table 3), 12 plants demonstrated exceptional biocontrol effects against

Table 3 Selected plants used for controlling pathogens in crop protection studies. PDA = Potato dextrose agar

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>In vitro</i> experiment			
<i>Ageratum conyzoides</i> L. "Goatweed"	Asteraceae	The hexane extract derived from leaves, when incubated at 26 °C for 30 days with <i>Leucoagaricus gongylophorus</i> (a fungal pathogen), at a concentration of 100 mg/mL resulted in a reduction of symbiotic fungal biomass by 100% (Morais et al., 2015)	
<i>Allium ampeloprasum</i> L.; Synonym: <i>Allium porum</i> L. "Leek"	Amaryllidaceae	Essential oil derived from the bulb, when coated with Hydroxypropyl- β -cyclodextrin and incubated at 20 °C for 7 days with <i>Fusarium culmorum</i> (a fungal pathogen isolated from wheat heads), exhibited an IC ₅₀ value of 0.6 mg/mL for mycelial growth inhibition. In contrast, when the same oil was incubated in PDA medium under similar conditions, it demonstrated an IC ₅₀ value of 1.2 mg/mL. For comparison, the synthetic fungicide Aviator Xpro showed an IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	The bulb oil inhibited seedling germination against lettuce and rye-grass at IC ₅₀ values of 1.6 and 1.8 mg/mL, respectively, and exhibited a phytotoxic effect against the same plants at IC ₅₀ values of 2.1 and 3.7 mg/mL (El-Alam et al., 2020)
<i>Allium ascalonicum</i> L. "Shallot"	Amaryllidaceae	Essential oil derived from the bulb, when coated with Hydroxypropyl- β -cyclodextrin and incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> (a fungal pathogen isolated from wheat heads), exhibited an IC ₅₀ value of 0.03 mg/mL for mycelial growth inhibition. In contrast, when the same oil was incubated in PDA medium under similar conditions, it demonstrated an IC ₅₀ value of 0.01 mg/mL. For comparison, the synthetic fungicide Aviator Xpro showed an IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	The bulb oil inhibited seedling germination against lettuce and rye-grass at IC ₅₀ values of 0.1 and 1.3 mg/mL, respectively, and a phytotoxic effect against the same plants at IC ₅₀ values of 0.2 and 0.7 mg/mL (El-Alam et al., 2020)
<i>Allium cepa</i> L. "Onion"	Amaryllidaceae	Essential oil derived from the bulb, when coated with Hydroxypropyl- β -cyclodextrin and incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> (a fungal pathogen isolated from wheat heads), exhibited an IC ₅₀ value of 0.2 mg/mL for mycelial growth inhibition. In contrast, when the same oil was incubated in PDA medium under similar conditions, it demonstrated an IC ₅₀ value of 0.1 mg/mL. For comparison, the synthetic fungicide Aviator Xpro showed an IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	The bulb oil inhibited seedling germination against lettuce and rye-grass at IC ₅₀ values of 0.08 and 0.4 mg/mL, respectively, and exhibited phytotoxicity against the same plants at IC ₅₀ values of 0.2 and 1.7 mg/mL (El-Alam et al., 2020)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Allium sativum</i> L. "Garlic"	Amaryllidaceae	Essential oil derived from the bulb, when coated with Hydroxypropyl- β -cyclodextrin and incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> (a fungal pathogen isolated from wheat heads), exhibited an IC ₅₀ value of 0.4 mg/mL for mycelial growth inhibition. In contrast, when the same oil was incubated in PDA medium under similar conditions, it demonstrated an IC ₅₀ value of 1.6 mg/mL (El-Alam et al., 2020). Additionally, when essential oil extracted from the clove was incubated in PDA medium at 25 °C for 3 days with <i>Alternaria alternata</i> (a fungal pathogen isolated from grapefruit), it exhibited a mycelial growth inhibition of 52% at a dose of 1 μ L/mL (Ghuffar et al., 2022). For comparison, the synthetic fungicide Benzimidazole (benomyl) – 5% demonstrated a complete (100%) mycelial growth inhibition (Ghuffar et al., 2022)	The bulb oil inhibited seedling germination against lettuce and rye-grass at IC ₅₀ values of 5.4 and 0.4 mg/mL, respectively (El-Alam et al., 2020), and exhibited phytotoxicity against the same plants at IC ₅₀ values of 0.08 and 0.4 mg/mL (El-Alam et al., 2020)
<i>Allium schoenoprasum</i> L. "Chive"	Amaryllidaceae	Essential oil derived from the bulb, exhibited an IC ₅₀ (mycelial growth inhibition) value of 0.3 mg/mL when coated with Hydroxypropyl- β -cyclodextrin and incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> , a fungal pathogen isolated from wheat heads. However, when the same oil was incubated in PDA medium under similar conditions, it demonstrated an IC ₅₀ value of 0.9 mg/mL. In comparison, the synthetic fungicide Aviator Xpro demonstrated a significantly lower IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	The bulb oil demonstrated phytotoxic effects against lettuce and rye-grass, inhibiting seedling germination at IC ₅₀ values of 0.9 and 3.9 mg/mL, respectively, and affecting their growth at IC ₅₀ values of 0.8 and 1.2 mg/mL, respectively (El-Alam et al., 2020)
<i>Angelica archangelica</i> L. "Angelica"	Apiaceae	Essential oil derived from the roots and seeds, when coated with Hydroxypropyl- β -cyclodextrin and incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> , exhibited IC ₅₀ values of 5.8 mg/mL and 0.2 mg/mL, respectively. When extracted without coating, the root and seed oils had IC ₅₀ values of 4.2 mg/mL and 0.3 mg/mL, respectively. In comparison, the synthetic fungicide Aviator Xpro demonstrated an IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	El-Alam et al. (2020) reported that the root oil exhibited phytotoxicity against lettuce at an IC ₅₀ value of 1.1 mg/mL and inhibited seedling germination at an IC ₅₀ value of 4.9 mg/mL. The seed oil showed phytotoxicity against rye-grass at an IC ₅₀ value of 0.5 mg/mL and inhibited seedling germination of lettuce and rye-grass at IC ₅₀ values of 0.01 and 0.6 mg/mL, respectively
<i>Annona squamosa</i> L. "Sweet sop"	Annonaceae	The hexane/40 EC seeds extract at a concentration of 35 mg/mL, when incubated at 27 °C for 3 days with <i>Brevicoryne brassicae</i> (an insect pathogen isolated from cabbage leaf), exhibited an insecticidal effect of 90%. In comparison, the synthetic insecticide Dimethoate (30 EC) at 0.1% dose demonstrated a complete (100%) insecticidal effect (Purkait et al., 2019)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Anthriscus cerefolium</i> Hoffm "Chervil"	Apiaceae	When incubated in PDA medium at 20 °C for 7 days with <i>F. culmorum</i> , essential oil extracted from the leaves and flowers (aerial parts) exhibited an IC ₅₀ value of 3.1 mg/mL. Essential oil derived from the aerial parts, when coated with Hydroxypropyl-β-cyclodextrin, exhibited an IC ₅₀ value of 1.9 mg/mL. In comparison, the synthetic fungicide Aviator Xpro demonstrated an IC ₅₀ value of 0.001 mg/mL (El-Alam et al., 2020)	El-Alam et al. (2020) reported that the aerial part oil inhibited seedling germination against lettuce and rye-grass at IC ₅₀ values of 0.3 and 1.7 mg/mL, respectively. Similarly, the oil from the leaves and flowers inhibited seedling germination of lettuce and rye-grass at IC ₅₀ values of 1.7 and 1.4 mg/mL, respectively
<i>Brassica juncea</i> (L.) Czern "Oriental mustard"	Brassicaceae	Drakopoulos et al. (2020) reported that the seed husk extract exhibited 96% mycelial growth inhibition against <i>Fusarium graminearum</i> isolated from wheat at a concentration of 20 mg/mL in PDA medium. The seeds extract derived from the same plant elicited a complete mycelial growth inhibition under similar conditions. In comparison, the synthetic fungicide Proline® at a dose of 2% demonstrated a complete mycelial growth inhibition	The seed powder performed better than Proline® at 1% concentration (Drakopoulos et al., 2020)
<i>Browallia speciosa</i> Hook "Bush violet"	Solanaceae	The methanolic aerial parts extract, when incubated at 25 °C for 1 day with <i>Mycosphaerella fijiensis</i> (a fungal pathogen isolated from plantain/banana leaf), exhibited an IC ₅₀ (mycelial growth inhibition) value of 1 mg/mL (Niño et al., 2011)	
<i>Carum carvi</i> L. "Black caraway"	Apiaceae	Essential oil extracted from seeds exhibited varying degrees of mycelial growth inhibition and spore germination inhibition when incubated with different fungal pathogens in PDA medium/Tween-80 (5%) at different temperatures. Specifically, it showed 75% mycelial growth inhibition against <i>Botrytis cinerea</i> isolated from plum fruit at a concentration of 0.4 µL/mL (Aminifard & Mohammadi, 2012), 100% spore germination inhibition against <i>B. cinerea</i> isolated from sweet cherry fruit at a concentration of ≥0.6 µL/mL (Aminifard & Mohammadi, 2013), complete mycelial growth inhibition against <i>Penicillium digitatum</i> isolated from blood orange fruit at a concentration of ≥0.6 µL/mL (Aminifard & Bayat, 2017), and 95% mycelial growth inhibition along with complete spore germination inhibition against <i>Rhizopus stolonifer</i> isolated from strawberry fruit at a concentration of 0.8 µL/mL (Mohammadi et al., 2013). In comparison, the synthetic fungicide Aviator Xpro demonstrated an IC ₅₀ value of 0.001 mg/mL	The seed oil at a dose of ≥0.4 µL/mL inhibited the mycelial growth of grey mould by 74.9% and also reduced disease symptoms on fruits as well as increased their storage life (Aminifard & Mohammadi, 2012, 2013). The oil, at a concentration of 0.8 µL/mL, also inhibited spore germination completely (Aminifard & Bayat, 2017; Mohammadi et al., 2013)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Cestrum humboldtii</i> Francey "Jessamine"	Solanaceae	The dichloromethane aerial parts extract at a concentration of 1 mg/mL, when incubated at 27 °C for 2 days with <i>M. fijiensis</i> (a fungal pathogen isolated from plantain/banana leaf), exhibited 60% mycelial growth inhibition (Niño et al., 2011)	
<i>Cinchona pubescens</i> Vahl "Red cinchona"	Rubiaceae	The methanolic aerial parts extract at a concentration of 1 mg/mL, when incubated at 25 °C for 1 day with <i>M. fijiensis</i> (a fungal pathogen isolated from plantain/banana leaf), exhibited 70% mycelial growth inhibition (Niño et al., 2011)	
<i>Cinnamomum verum</i> J.Presl "Cinnamon"	Lauraceae	The essential oil at a concentration of 0.5 µL/mL exhibited complete (100%) mycelial growth inhibition when incubated in PDA medium/Triton-X 100 at 23 °C for 7 days with various fungal pathogens. Specifically, it demonstrated complete inhibition against <i>B. cinerea</i> isolated from grapefruit, <i>Colletotrichum gloeosporioides</i> isolated from avocado fruit, and <i>Lasiodiplodia theobromae</i> isolated from mango fruit (Combrinck et al., 2011)	
<i>Cistus ladanifer</i> L. "Rockrose"	Cistaceae	Essential oil extracted from the aerial parts, when used in the vapour phase and incubated at 25 °C for 7 days with various fungal and oomycete pathogens, exhibited varying degrees of mycelial growth inhibition. Specifically, it demonstrated complete mycelial growth inhibition against <i>Cryphonectria parasitica</i> isolated from chestnut trees at concentrations of 250 µL/mL and 0.13 µL/mL, against <i>Fusarium oxysporum</i> isolated from tomato fruit at concentrations of 0.33 µL/mL and 500 µL/mL (with an estimated inhibition of 87%), against <i>P. stolonifer</i> isolated from holm oak at a concentration of 0.09 µL/mL, and against <i>Rhizoctonia solani</i> isolated from artichoke at a concentration of 0.13 µL/mL. The aerial parts hydrolate also exhibited complete mycelial growth inhibition against <i>P. stolonifer</i> and <i>R. solani</i> at a concentration of 250 µL/mL (Pérez-Izquierdo et al., 2022)	Pérez-Izquierdo et al. (2022) reported that the aerial part hydrolate exhibited a dose-dependent phytotoxic effect on the germination index and seedling length of radish seeds, which were more sensitive than lupin to the hydrolate treatment. The phytotoxic effect of the aerial part oil at a dose of 1 µL drastically decreased the seed germination index of radish, reaching a near-zero value. Lupin seeds revealed the highest germination index with a 4 µL dose, reducing with increasing doses. The aerial part hydrolate at high doses (250 and 500 µL/mL) also affected the growth and development of lupin seedlings in a pathosystem with <i>P. stolonifer</i>

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Citrus aurantium</i> L.; Synonyms: <i>Citrus sinensis</i> (L.), <i>Citrus aurantium</i> L. ssp. <i>Amara</i> "Seville orange"	Rutaceae	Essential oil extracted from flowers and fruit peels, when incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days with <i>Monilinia fructigena</i> and <i>Monilinia laxa</i> (fungal pathogens isolated from apple fruit), exhibited varying degrees of mycelial growth inhibition and conidial germination inhibition at a concentration of 100 µL/mL. Specifically, the flower oil showed 91% mycelial growth inhibition against <i>M. fructigena</i> and 92% mycelial growth inhibition against <i>M. laxa</i> , along with 96% inhibition of conidial germination. The fruit peel oil demonstrated 93% mycelial growth inhibition against <i>M. fructigena</i> and 92% mycelial growth inhibition against <i>M. laxa</i> , along with 96% inhibition of conidial germination (El Khetabi et al., 2021)	The flower oil and fruit peel oil, both at a concentration of 100 µL/mL, caused varying degrees of conidial germination inhibition against <i>M. fructigena</i> and <i>M. laxa</i> . Specifically, the flower oil caused 97% inhibition of <i>M. fructigena</i> conidial germination and 96% inhibition of <i>M. laxa</i> conidial germination. The fruit peel oil caused 96% inhibition of <i>M. fructigena</i> conidial germination and 100% inhibition of <i>M. laxa</i> conidial germination (El Khetabi et al., 2021)
<i>Coriandrum sativum</i> L. "Coriander"	Apiaceae	Essential oil extracted from the aerial parts exhibited a 50% insecticidal effect against <i>Bemisia tabaci</i> isolated from tomato at a concentration of 0.023 µL/mL when incubated at 25 °C for 1 day. The same oil, in its vapour phase, exhibited a 50% insecticidal effect against <i>Ephesia kuehniella</i> isolated from wheat flour and a 90% insecticidal effect against <i>Rhyzopertha dominica</i> isolated from whole wheat, both at a concentration of 0.057 µL/mL. Essential oil extracted from seeds exhibited an IC ₅₀ (mycelial growth inhibition) value of 0.46 mg/mL against <i>F. culmorum</i> isolated from cereals and an IC ₅₀ value of 0.001 mg/mL against <i>Zymoseptoria tritici</i> isolated from cereals when incubated in PDA medium at 20 °C for 7 days (Raveau et al., 2022). Moreover, Morais et al. (2015) reported that the hexane leaves extract exhibited a symbiotic fungal biomass reduction of 100% at a concentration of 100 mg/mL against <i>L. gongylophorus</i> when incubated at 26 °C for 30 days	The aerial part oil inhibited seed germination and stifled seedling growth in <i>Lactuca sativa</i> L. (lettuce) and <i>Lolium perenne</i> L. (rye-grass) with varying IC ₅₀ values (Raveau et al., 2022). Specifically, it inhibited seed germination with IC ₅₀ values of 0.05 mg/mL for lettuce and 0.15 mg/mL for rye-grass, and stifled seedling growth with IC ₅₀ values of 0.017 mg/mL for lettuce and 0.05 mg/mL for rye-grass. It also inhibited seed germination with IC ₅₀ values of 0.56 mg/mL for lettuce and 0.6 mg/mL for rye-grass, and mitigated seedling growth with IC ₅₀ values of 0.28 mg/mL for lettuce and 0.25 mg/mL for rye-grass. The effect of the seed oil was found to be fungistatic
<i>Crotalaria virgulata</i> subsp. <i>grati-ana</i> (Harv.) Polhill	Fabaceae	The aqueous seeds extract, when incubated with the nematode <i>Meloidogyne incognita</i> (second-stage juveniles isolated from tomato root) at 25 °C for 2 days, exhibited a nematostatic effect of 100% at a concentration of ≥ 1 mg/mL (Jourand et al., 2004) (Jourand, 2004 #331)	The effect of the seed extract was reversible after 21 days submersion of extract-treated (1 mg/mL) nematodes in water (Jourand et al., 2004)
<i>Curcuma longa</i> L. "Turmeric"	Zingiberaceae	The ethanolic rhizome extract, when incubated with the fungal pathogen <i>P. digitatum</i> (isolated from tangerine fruit) at 25 °C for 1 day, demonstrated a mycelial growth inhibition of 79% at a concentration of 20 mg/mL (Sukorini et al., 2013)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Cymbopogon citratus</i> (DC.) Stapf "Lemon grass"	Poaceae	Essential oil of the plant in its vapour phase demonstrated varying degrees of mycelial growth inhibition when incubated with different fungal pathogens. Specifically, it exhibited a mycelial growth inhibition of 100% against <i>B. cinerea</i> isolated from strawberry fruit at a concentration of ≥ 0.1 μ L/mL after 7 days of incubation at 25 °C (Yan et al., 2021). The same oil demonstrated a mycelial growth inhibition of 60% against <i>C. gloeosporioides</i> after incubation (Mpho et al., 2013). The ethanol extract from the stem exhibited a mycelial growth inhibition of 54% against <i>P. digitatum</i> isolated from tangerine fruit at a concentration of 20 mg/mL after 1 day of incubation at 25 °C (Sukorini et al., 2013)	
<i>Cymbopogon khasianus</i> (Hack.) Stapf ex Bor	Poaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, demonstrated a mycelial growth inhibition of 73% at a concentration of 0.15 μ L/mL (Yan et al., 2021)	
<i>Cymbopogon martini</i> (Roxb.) Will. Watson "Palmarosa"	Poaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 100% at a concentration of 0.15 μ L/mL (Yan et al., 2021)	
<i>Cymbopogon nardus</i> (L.) Rendle "Citronella grass"	Poaceae	Essential oil in PDA medium/Tween-20 (0.5%), when incubated with the fungal pathogen <i>A. alternata</i> (isolated from cherry tomato fruit) at 25 °C for 7 days, demonstrated a mycelial growth inhibition of 100% at a concentration of 1 μ L/mL (Chen et al., 2019)	The oil (1.5 μ L/mL) also caused 87% inhibition of conidial germination (Chen et al., 2019)
<i>Deprea glabra</i> (Standl.) Hunz	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, exhibited a mycelial growth inhibition of 50% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Eucalyptus radiata</i> Sieber ex DC "Narrow-leaved Peppermint"	Myrtaceae	Essential oil extracted from the flowers demonstrated a mycelial growth inhibition of 64% against <i>M. fructigena</i> and 72% against <i>M. laxa</i> , both isolated from apple fruit and incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 μ L/mL (El Khetabi et al., 2021)	El Khetabi et al. (2021) reported that the flower oil (100 μ L/mL) caused 58% and 59% inhibition of conidial germination in <i>M. fructigena</i> and <i>M. laxa</i> , respectively

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Foeniculum vulgare</i> Mill "Fennel"	Apiaceae	Essential oil extracted from various parts exhibited varying degrees of mycelial growth inhibition and spore germination inhibition when incubated with different fungal pathogens. Specifically, Essential oil from the aerial parts exhibited a mycelial growth inhibition of 100% against <i>B. cinerea</i> isolated from strawberry fruit at a concentration of ≥ 0.3 $\mu\text{L/mL}$ (Abdolahi et al., 2010). Essential oil extracted from the seeds demonstrated a mycelial growth inhibition of 83% against <i>A. alternata</i> isolated from grapefruit at a concentration of 1 $\mu\text{L/mL}$ (Ghuffar et al., 2022), and a spore germination inhibition of 100% against <i>B. cinerea</i> isolated from sweet cherry fruit at a concentration of 0.8 $\mu\text{L/mL}$ (Aminifard & Mohammadi, 2013). The same oil exhibited a mycelial growth inhibition of 95% against <i>R. stolonifer</i> isolated from strawberry fruit at a concentration of 0.6 $\mu\text{L/mL}$, and also completely inhibited spore germination (Mohammadi et al., 2013)	Abdolahi et al. (2010) reported that the inhibitory effect of the fruit oil was fungistatic, not fungicidal. Ghuffar et al. (2022) found that the seed oil (0.1%) performed better than the synthetic fungicide benomyl at fungal growth inhibition. The seed oil also completely inhibited spore germination (Mohammadi et al., 2013)
<i>Humulus lupulus</i> L. "Hop"	Cannabaceae	Bocquet et al. (2018) reported that essential oil from cones demonstrated a mycelial growth inhibition of 100% against <i>Z. tritici</i> isolated from wheat leaf at a concentration of 0.63 mg/mL when incubated in PDA medium/methanol at 21 °C for 10 days. The hydroethanolic cones extract exhibited a mycelial growth inhibition of 85% at a concentration of 1.25 mg/mL under similar conditions	
<i>Lavandula angustifolia</i> Mill "English lavender"	Lamiaceae	Essential oil extracted from the aerial parts demonstrated varying degrees of mycelial growth inhibition when incubated with different fungal pathogens. Specifically, it demonstrated a mycelial growth inhibition of 71% against <i>M. fructigena</i> and 67% against <i>M. laxa</i> , both isolated from apple fruit and incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 $\mu\text{L/mL}$ (El Khetabi et al., 2021). The same oil exhibited a mycelial growth inhibition of 100% against <i>P. digitatum</i> isolated from Verna lemon fruit at a concentration of ≥ 40 $\mu\text{L/mL}$ when incubated in its vapour phase at room temperature for 5 days (Sumalan et al., 2020). The oil also demonstrated a mycelial growth inhibition of 82% against <i>B. cinerea</i> isolated from strawberry fruit at a concentration of 0.15 $\mu\text{L/mL}$ when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021)	El Khetabi et al. (2021) reported that the aerial part oil (100 $\mu\text{L/mL}$) caused 65% and 59% inhibition of conidial germination in <i>M. fructigena</i> and <i>M. laxa</i> , respectively. Sumalan et al. (2020) found that the same oil (≥ 200 μL) exhibited a fungistatic effect and caused a fungicidal effect on <i>P. digitatum</i> with a ≥ 350 μL dose

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Lavandula latifolia</i> Medik "Spike lavender"	Lamiaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 86% at a concentration of 150 µL/L (Yan et al., 2021)	The effect of the aerial part oil was observed on ascospores (Niño et al., 2011)
<i>Lycianthes acutifolia</i> (Ruiz & Pav.) Bitter	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, demonstrated a spore germination inhibition of 100% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Lycianthes radiata</i> (Sendtn.) Bitter	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, exhibited a mycelial growth inhibition of 60% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Melaleuca ericifolia</i> Sm "Swamp paperbark"	Myrtaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, demonstrated a mycelial growth inhibition of 100% at a concentration of 0.15 µL/mL (Yan et al., 2021)	
<i>Melaleuca leucadendra</i> (L.) L "Long-leaved paperbark"	Myrtaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 71% at a concentration of 0.15 µL/mL (Yan et al., 2021)	
<i>Melaleuca viridiflora</i> Sol. Ex Gaertn	Myrtaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, demonstrated a mycelial growth inhibition of 64% at a concentration of 0.15 µL/mL (Yan et al., 2021)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Mentha piperita</i> L. "Peppermint"	Lamiaceae	Essential oil extracted from the aerial parts exhibited varying degrees of mycelial growth inhibition and spore germination inhibition when incubated with different fungal pathogens. Specifically, it exhibited nearly complete (99%) spore germination inhibition against <i>B. cinerea</i> isolated from sweet cherry fruit at a concentration of 0.8 µL/mL in PDA medium/Tween-80 (5%) at 28 °C for 1 day (Aminifard & Mohammadi, 2013). The same oil demonstrated a mycelial growth inhibition of 100% against <i>P. digitatum</i> isolated from Verna lemon fruit at a concentration of ≥ 6 µL/mL when incubated in its vapour phase for 5 days (Sumalan et al., 2020), and a mycelial growth inhibition of 95% against <i>R. stolonifer</i> isolated from strawberry fruit at a concentration of 0.8 µL/mL when incubated in PDA medium at 28 °C for 3 days (Mohammadi et al., 2013). The oil also exhibited a mycelial growth inhibition of 100% against <i>B. cinerea</i> at a concentration of 0.15 µL/mL when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021). Moreover, Morais et al. (2015) reported that the hexane leaves extract demonstrated a symbiotic fungal biomass reduction of 100% against <i>L. gongylophorus</i> at a concentration of 100 mg/mL when incubated at 26 °C for 30 days	The aerial part oil elicited only a fungistatic effect against <i>P. digitatum</i> at concentrations of ≥ 300 µL (Sumalan et al., 2020) and inhibited <i>R. stolonifer</i> spore germination by approximately 95% (Mohammadi et al., 2013)
<i>Mentha pulegium</i> L. "Pennyroyal"	Lamiaceae	Essential oil extracted from the aerial parts demonstrated a mycelial growth inhibition of 80% against <i>M. fructigena</i> and <i>M. laxa</i> , both isolated from apple fruit and incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 µL/mL (El Khetabi et al., 2021)	The aerial part oil (100 µL/mL) caused 72% and 73% inhibition of conidial germination in <i>M. fructigena</i> and <i>M. laxa</i> , respectively (El Khetabi et al., 2021)
<i>Mentha spicata</i> L. "Spearment"	Lamiaceae	The reported that Essential oil, when used in its vapour phase and incubated at 25 °C for 7 days with <i>B. cinerea</i> isolated from strawberry fruit, demonstrated a mycelial growth inhibition of 97% at a concentration of 0.15 µL/mL (Yan et al., 2021). Furthermore, Combrinck et al. (2011) found that the same oil exhibited a mycelial growth inhibition of 100% against <i>P. digitatum</i> isolated from cactus pear fruit at a concentration of 1 µL/mL when incubated in PDA medium/Triton-X 100 at 23 °C for 7 days	The experimented phytopathogen (<i>P. digitatum</i>) is resistant to guazatine (Combrinck et al., 2011)
<i>Momordica charantia</i> L. "Bitter squash"	Cucurbitaceae	The ethanol extract from fruit, when incubated with the fungal pathogen <i>P. digitatum</i> (isolated from tangerine fruit) at 25 °C for 1 day, demonstrated a mycelial growth inhibition of 64% at a concentration of 20 mg/mL (Sukorini et al., 2013)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Nectandra acutifolia</i> (Ruiz & Pav.) Mez	Lauraceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, exhibited a complete (100%) spore germination inhibition at a concentration of 1 mg/mL (Niño et al., 2011)	The dichloromethane extract also caused 98% mycelial growth inhibition of the ascomycetes (Niño et al., 2011)
<i>Nectandra lineatifolia</i> (Ruiz & Pav.) Mez	Lauraceae	The extract from aerial parts, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated a mycelial growth inhibition of 65% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Neolitsea cassia</i> (L.) Kosterm.; Synonym: <i>Cinnamomum cassia</i> "Shore laurel"	Lauraceae	The extract from stem bark, when incubated with the fungal pathogen <i>P. digitatum</i> (isolated from tangerine fruit) at 25 °C for 1 day, exhibited a mycelial growth inhibition of 75% at a concentration of 20 mg/mL (Sukorini et al., 2013)	
<i>Ocimum basilicum</i> L. "Basil"	Lamiaceae	Essential oil extracted from the aerial parts demonstrated varying degrees of mycelial growth inhibition when incubated with different fungal pathogens. Specifically, it demonstrated a mycelial growth inhibition of 100% against <i>P. digitatum</i> isolated from Vernia lemon fruit at a concentration of $\geq 3 \mu\text{L/mL}$ when incubated in its vapour phase for 5 days (Sumalan et al., 2020). The same oil exhibited a mycelial growth inhibition of 90% against <i>Phytophthora stolonii</i> , <i>Phytophthora drechsleri</i> , and <i>Phytophthora melonis</i> at a concentration of 0.4 $\mu\text{L/mL}$ when incubated in CMA medium/Tween-80 (0.1%) at 26 °C for 2 days (Farhang et al., 2014). The oil also demonstrated a mycelial growth inhibition of 83% against <i>B. cinerea</i> at a concentration of 0.15 $\mu\text{L/mL}$ when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021)	The aerial part oil ($\geq 150 \mu\text{L}$) elicited fungistatic effect and caused fungicidal effect with $\geq 300 \mu\text{L}$ dose (Sumalan et al., 2020)
<i>Ocimum tenuiflorum</i> L.; Synonym: <i>Ocimum sanctum</i> L. "Tulsi"	Lamiaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 82% at a concentration of 0.15 $\mu\text{L/mL}$ (Yan et al., 2021)	
<i>Ocotea atirrensis</i> Mez & Donn. Sm.; Synonym: <i>Ocotea paulii</i> C.K.Allen	Lauraceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated a complete (100%) spore germination at a concentration of 1 mg/mL (Niño et al., 2011)	The effect of the dichloromethane extract was observed on ascospores (Niño et al., 2011)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Origanum compactum</i> Benth "Compact oregano"	Lamiaceae	Essential oil extracted from the aerial parts demonstrated a mycelial growth inhibition of 69% against <i>M. fructigena</i> and <i>M. laxa</i> , both isolated from apple fruit and incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 µL/mL (El Khetabi et al., 2021)	The aerial part oil (100 µL/mL) caused 60% inhibition of conidial germination in <i>M. fructigena</i> and 57% inhibition in <i>M. laxa</i> (El Khetabi et al., 2021)
<i>Origanum onites</i> L. "Turkish oregano"	Lamiaceae	Essential oil extracted from the aerial parts exhibited varying degrees of mycelial growth inhibition when incubated with <i>B. cinerea</i> isolated from strawberry fruit. Specifically, it demonstrated a mycelial growth inhibition of 94% at a concentration of 0.5 µL/mL in PDA medium/Ethanol at 25 °C for 7 days (Kahramanoğlu et al., 2022), and a complete mycelial growth inhibition in its vapour phase at a concentration of ≥ 0.1 µL/mL (Yan et al., 2021)	The phytopathogen (<i>B. cinerea</i>) is specifically referred to as M2-1 isolate in the experiment (Kahramanoğlu et al., 2022)
<i>Pachyrhizus erosus</i> (L.) Urb "Mexican turnip"	Fabaceae	The hexane/40 EC seeds extract, when incubated with the insect <i>B. brassicae</i> (aphid isolated from cabbage leaf) at 27 °C for 3 days, exhibited an insecticidal effect of 90% at a concentration of 1034 mg/mL (Purkait et al., 2019)	The effect of the hexane/40 EC was observed on aphids (Purkait et al., 2019)
<i>Palicourea andaluciana</i> Standl "Andalusian palicourea"	Rubiaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, demonstrated a mycelial growth inhibition of 65% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Palicourea petiolaris</i> Kunth "Cordoncillo"	Rubiaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, exhibited a mycelial growth inhibition of 55% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Palicourea thyrsoiflora</i> (Ruiz & Pav.) DC "Balsamroot"	Rubiaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, demonstrated a mycelial growth inhibition of 60% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Passiflora foetida</i> L. "Stinking passion"	Passifloraceae	The aqueous leaves extract, when incubated with the fungal pathogen <i>C. gloeosporioides</i> (isolated from Egusi melon seed) at 28 °C for 5 days, exhibited a spore germination inhibition of nearly complete (96%) at a concentration of 7500 mg/mL (Ogunsola & Ogunsola, 2023)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Peltargonium graveolens</i> L'Hér "Rose-scented geranium"	Geraniaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, demonstrated a mycelial growth inhibition of 100% at a concentration of 0.15 µL/mL (Yan et al., 2021)	
<i>Peperomia acuminata</i> Ruiz & Pav "Sweet scented geranium"	Piperaceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for both one and two days, demonstrated both spore germination and mycelial growth inhibitions of nearly complete (100%) and significant (70%), respectively, at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Persicaria odorata</i> (Lour.) Soják "Vietnamese coriander"	Polygonaceae	The acetone aerial parts extract demonstrated a spore germination inhibition of 100% against <i>Colletotrichum stolonii</i> isolated from chili fruit at a concentration of 20 mg/mL and against <i>C. gloeosporioides</i> isolated from mango fruit at a concentration of 10 mg/mL when incubated at 25 °C for 3 days (Yanpirat & Vajrodaya, 2015)	
<i>Pimpinella anisum</i> L. "Anise"	Apiaceae	Essential oil extracted from the seeds in PDA medium/Tween-80 (5%), when incubated with the fungal pathogen <i>P. digitatum</i> (isolated from blood orange fruit) at 24 °C for 5 days, demonstrated a mycelial growth inhibition of 100% at a concentration of ≥ 0.4 µL/mL (Aminifard & Bayat, 2017)	The seed oil (≥ 600 µL/L) also elicited 100% spore germination (Aminifard & Bayat, 2017)
<i>Pinus nigra</i> J.F.Arnold "Austrian pine"	Pinaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 61% at a concentration of 0.15 µL/mL (Yan et al., 2021)	
<i>Piper crassinervium</i> Kunth	Piperaceae	The aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated a mycelial growth inhibition of 55% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Piper eriopodon</i> C.DC "Woolly-footed piper"	Piperaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, exhibited a spore germination inhibition of 55% at a concentration of 1 mg/mL (Niño et al., 2011)	The effect of the methanol extract was observed on ascospores (Niño et al., 2011)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Piper glanduligerum</i> C.DC	Piperaceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated a mycelial growth inhibition of 55% at a concentration of 1 mg/mL (Niño et al., 2011)	
<i>Piper lacunosum</i> Kunth; Synonym: <i>Piper pesaresanum</i>	Piperaceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, exhibited mycelial growth inhibitions of 100% at a concentration of 1 mg/mL (Niño et al., 2011)	The methanolic and dichloromethane extracts also elicited 96% ascospore germination inhibition and 78% mycelial growth inhibition, respectively (Niño et al., 2011)
<i>Piper</i> sp.	Piperaceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated an IC ₅₀ (mycelial growth inhibitions) value of 1 mg/mL (Niño et al., 2011)	
<i>Pongamia pinnata</i> (L.) Pierre "Indian beech Tree"	Fabaceae	The hexane/40 EC seeds extract, when incubated with the insect <i>B. brassicae</i> (aphid isolated from cabbage leaf) at 27 °C for 3 days, exhibited an insecticidal effect of 90% at a concentration of 63.8 mg/mL (Purkait et al., 2019)	The effect of the hexane/40 EC extract was observed on aphids (Purkait et al., 2019)
<i>Punica granatum</i> L. "Pomegranate"	Lythraceae	The methanolic fruit peels extract demonstrated a mycelial growth inhibition of 100% when incubated at 28 °C for 2 days with various fungal pathogens at different concentrations. Specifically, it exhibited complete inhibition against <i>Aspergillus flavus</i> , <i>Aspergillus fumigatus</i> , and <i>Aspergillus parasiticus</i> at a concentration of 2.5 mg/mL, and against <i>Fusarium proliferatum</i> and <i>Fusarium verticillioides</i> at a concentration of 5 mg/mL (Sadhasivam et al., 2019)	
<i>Rhodostemonodaphne</i> sp.	Lauraceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, exhibited mycelial growth inhibition of 100% at a concentration of 1 mg/mL (Niño et al., 2011)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Rosmarinus officinalis</i> L. "Rosemary"	Lamiaceae	Essential oil extracted from the aerial parts demonstrated varying degrees of mycelial growth inhibition when incubated with different fungal pathogens. Specifically, it demonstrated a mycelial growth inhibition of 64% against <i>M. fructigena</i> and <i>M. laxa</i> , both isolated from apple fruit and incubated in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 µL/mL (El Khetabi et al., 2021). The same oil exhibited a mycelial growth inhibition of nearly complete (72%) against <i>B. cinerea</i> at a concentration of ≥ 0.15 µL/mL when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021)	The aerial part oil (100 µL/mL) caused 68% inhibition of conidial germination in <i>M. fructigena</i> and 65% inhibition in <i>M. laxa</i> (El Khetabi et al., 2021)
<i>Salvia sclarea</i> L. "Clary sage"	Lamiaceae	Essential oil extracted from flowers exhibited varying degrees of mycelial growth inhibition and insecticidal effect when incubated with different organisms. Specifically, it exhibited a 50% insecticidal effect against <i>E. kuehniella</i> (Mediterranean flour moth) isolated from wheat flour at a concentration of ≥ 0.057 µL/mL in its vapour phase at room temperature for one day (Raveau et al., 2022). The same oil demonstrated a mycelial growth inhibition of 50% against <i>F. culmorum</i> at a concentration of 2.08 mg/mL and against <i>Z. tritici</i> at a concentration of 0.08 mg/mL when incubated in PDA medium at 20 °C for 7 days	Raveau et al. (2022) reported that the oil inhibited lettuce (<i>L. sativa</i> L.) and rye-grass (<i>L. perenne</i> L.) seed germination with IC ₅₀ values of 6.2 and 2.6 mg/mL, respectively, and also mitigated seedling growth with IC ₅₀ values of 1.16 and 0.66 mg/mL, respectively. The effect of the flower oil was fungistatic against <i>F. culmorum</i> and <i>Z. tritici</i>
<i>Sinapis alba</i> L.; Synonym: <i>Brassica hirta</i> Moench "Yellow mustard"	Brassicaceae	The seeds extract in PDA medium, when incubated with the fungal pathogen <i>F. graminearum</i> at 20 °C for 2 days, demonstrated a mycelial growth inhibition of 100% at a concentration of 20 mg/mL (Drakopoulos et al., 2020)	The seed powder performed better than Proline® at 1% concentration (Drakopoulos et al., 2020)
<i>Solanum brevifolium</i> Dunal	Solanaceae	The dichloromethane aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, exhibited an IC ₅₀ (mycelial growth inhibition) of 1 mg/mL (Niño et al., 2011)	
<i>Solanum deflexiflorum</i> Bitter	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 25 °C for 1 day, demonstrated an IC ₅₀ (mycelial growth inhibition) value of 1 mg/mL (Niño et al., 2011)	
<i>Solanum ovalifolium</i> Dunal	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 1 day, exhibited spore germination inhibitions of 70% at a concentration of 1 mg/mL (Niño et al., 2011)	The methanolic and dichloromethane extracts also inhibited mycelial growth of the ascomycetes by approximately 60% each (Niño et al., 2011)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Solanum</i> sp.	Solanaceae	The dichloromethane extract from the aerial parts, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at 27 °C for 2 days, demonstrated a mycelial growth inhibition of 65% at a concentration of 1 mg/mL (Niño et al., 2011)	The dichloromethane extract also caused approximately 60% mycelial growth inhibition (El Khetabi et al., 2021)
<i>Syzygium aromaticum</i> (L.) Merr. & L.M.Perry "Clove"	Myrtaceae	Essential oil extracted from flowers demonstrated varying degrees of mycelial growth inhibition when incubated with different fungal pathogens. Specifically, it exhibited a nearly complete (95%) mycelial growth inhibition against <i>M. laxa</i> isolated from apple fruit in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days at a concentration of 100 µL/mL (El Khetabi et al., 2021). The same oil demonstrated a mycelial growth inhibition of 87% against <i>B. cinerea</i> at a concentration of ≥ 0.15 µL/mL when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021). The oil also exhibited a 50% insecticidal effect against <i>E. kuehniella</i> (Mediterranean flour moth) isolated from wheat flour at a concentration of ≥ 0.057 µL/mL in its vapour phase at room temperature for one day (Raveau et al., 2022). The ethanolic flower buds extract demonstrated a mycelial growth inhibition of 100% against <i>P. digitatum</i> at a concentration of 5 mg/mL when incubated at 25 °C for 1 day (Sukorini et al., 2013)	The flowers oil (100 µL/mL) caused 100% inhibition of conidial germination in both <i>B. cinerea</i> and <i>M. laxa</i> (El Khetabi et al., 2021; Yan et al., 2021)
<i>Thuja plicata</i> Donn ex. D.Don "Thuja"	Cupressaceae	Essential oil extracted from the leaves and twigs demonstrated IC ₅₀ (mycelial growth inhibition) values of 3.6 and 3.7 mg/mL against <i>F. culmorum</i> , when incubated in PDA medium uncoated and coated with Hydroxypropyl-B-cyclodextrin, respectively, at 20 °C for 7 days (El-Alam et al., 2020)	El-Alam et al. (2020) reported that the oil extracted from leaves and twigs inhibited lettuce (<i>L. sativa</i> L.) and rye-grass (<i>L. perenne</i> L.) seed germination with IC ₅₀ values of 2.3 and 2.1 mg/mL, respectively, and inhibited rye-grass seedling germination at an IC ₅₀ value of 4.8 mg/mL
<i>Thymus saturejoides</i> Coss. & Balansa "Savory-leaf thyme"	Lamiaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at 25 °C for 7 days, exhibited a mycelial growth inhibition of 100% at a concentration of ≥ 150 µL/mL (Yan et al., 2021)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Thymus vulgaris</i> L. "Common thyme"	Lamiaceae	<p>Essential oil extracted from the aerial parts demonstrated a mycelial growth inhibition of 100% against <i>Alternaria citri</i> at a concentration of ≥ 0.4 $\mu\text{L/mL}$ when incubated in PDA medium at 25 °C for 7 days (Ramezani et al., 2016). The same oil exhibited a nearly complete (93%) mycelial growth inhibition and up to 100% conidial germination inhibition against <i>M. fructigena</i> at a concentration of 100 $\mu\text{L/mL}$ in PDA medium/Tween-20 (0.05%) at 25 °C for 7 days (El Khetabi et al., 2021). The oil also demonstrated a nearly complete (95%) mycelial growth inhibition and up to 96% conidial germination inhibition against <i>M. laxa</i> similar conditions (El Khetabi et al., 2021). The oil exhibited a mycelial growth inhibition of 80% against <i>R. stolonifer</i> at a concentration of 0.8 $\mu\text{L/mL}$ when incubated in PDA medium at 28 °C for 3 days (Mohammadi et al., 2013). Essential oil extracted from leaves demonstrated a mycelial growth inhibition of 100% against <i>A. alternata</i> at a concentration of ≥ 10 $\mu\text{L/mL}$ when incubated in PDA medium at room temperature for one day (Ghuffar et al., 2022). The same oil exhibited a complete (100%) mycelial growth inhibition against <i>A. alternata</i> and <i>A. citri</i> at a concentration of ≥ 0.5 $\mu\text{L/mL}$ when incubated in PDA medium/Triton-X 100 at room temperature for one day (Combrinck et al., 2011). The oil also demonstrated a mycelial growth inhibition of 100% against <i>B. cinerea</i> at a concentration of ≥ 0.1 $\mu\text{L/mL}$ when incubated in its vapour phase at 25 °C for 7 days (Yan et al., 2021)</p> <p>Essential oil extracted from leaves and twigs demonstrated a mycelial growth inhibition of 100% against various fungal pathogens when incubated in PDA medium/Triton-X 100. Specifically, it exhibited complete inhibition against <i>C. gloeosporioides</i> isolated from both plantain/banana leaf and avocado fruit, <i>L. theobromae</i> isolated from both mango fruit and avocado fruit, and <i>P. digitatum</i> isolated from both cactus pear fruit and Valencia orange fruit, all at a concentration of 0.5, 0.5, and 1 $\mu\text{L/mL}$, respectively, and incubated at 23 °C for 7 days (Combrinck et al., 2011)</p>	<p>The aerial part oil (100 $\mu\text{L/mL}$) caused 100% inhibition of conidial germination in <i>M. fructigena</i> and 96% inhibition in <i>M. laxa</i> (El Khetabi et al., 2021). The same oil elicited <i>R. stolonifer</i> spore germination inhibition by approximately 70% (Mohammadi et al., 2013). The leaves oil at a concentration of 0.1% caused the inhibition of spore germination of <i>A. alternata</i> by more than 90%, and also performed better at fungal growth inhibition than the synthetic fungicides (Ghuffar et al., 2022)</p>

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Thymus zygis</i> L. "Spanish thyme"	Lamiaceae	Essential oil of the plant in its vapour phase, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at room temperature for one day, exhibited a mycelial growth inhibition of nearly complete (100%) at a concentration of 0.15 µL/mL (Yan et al., 2021)	
<i>Tinospora crispa</i> (L.) Hook.f. & Thomson "Heart-leaved moonseed"	Menispermaceae	The ethanolic stem bark extract, when incubated with the fungal pathogen <i>P. digitatum</i> at 25 °C for 1 day, demonstrated a mycelial growth inhibition of 66% at a concentration of 20 mg/mL (Sukorini et al., 2013)	
<i>Trachyspermum ammi</i> Sprague; Synonym: <i>Carum copiticum</i> (L.) Benth. & Hook.f "Ajowan caraway"	Apiaceae	Essential oil extracted from the fruit demonstrated a mycelial growth inhibition of 100% against <i>A. alternata</i> at a concentration of ≥ 0.2 µL/mL and against <i>P. digitatum</i> at a concentration of ≥ 0.4 µL/mL when incubated in PDA medium/Tween-80 (0.01%) at 25 °C for 7 days (Abdollahi et al., 2010). Essential oil extracted from the seeds exhibited a mycelial growth inhibition of 72% against <i>A. alternata</i> at a concentration of 1 µL/mL when incubated in PDA medium at 25 °C for 3 days (Ghuffar et al., 2022)	Abdollahi et al. (2010) reported that the inhibitory effect of the fruit oil was fungistatic, not fungicidal against both <i>A. alternata</i> and <i>P. digitatum</i> . Ghuffar et al. (2022) found that the seed oil (0.1%) performed better than the synthetic fungicide benomyl at fungal growth inhibition
<i>Witheringia coccinloboides</i> (Damer) Hunz "Wild peppervine"	Solanaceae	The methanolic aerial parts extract, when incubated with the fungal pathogen <i>M. fijiensis</i> (isolated from plantain/banana leaf) at room temperature for 1 day, demonstrated a mycelial growth inhibition of 70% at a concentration of 1 mg/mL (Niño et al., 2011)	The dichloromethane aerial part extract also exhibited $\approx 50\%$ mycelial growth inhibition (Niño et al., 2011)
<i>Zataria multiflora</i> Boiss "Shirazi thyme"	Lamiaceae	Essential oil extracted from the aerial parts exhibited a mycelial growth inhibition of 100% against <i>A. citri</i> when incubated in PDA medium at room temperature for one day at a concentration of ≥ 0.3 µL/mL (Ramezani et al., 2016). The same oil demonstrated an IC ₅₀ (mycelial growth inhibition) of 1.5 µL/mL against <i>B. cinerea</i> isolated from strawberry fruit under similar conditions (Mohammadi et al., 2015)	
<i>Zingiber officinale</i> Roscoe "Ginger"	Zingiberaceae	Essential oil extracted from rhizome exhibited a mycelial growth inhibition of 59% against <i>A. alternata</i> isolated from grapefruit at a concentration of 1 µL/mL when incubated in PDA medium at room temperature for 1 day (Ghuffar et al., 2022). The ethanol extract from rhizome demonstrated a mycelial growth inhibition of 69% against <i>P. digitatum</i> isolated from tangerine fruit at a concentration of 20 mg/mL under similar conditions (Sukorini et al., 2013)	The rhizome oil (0.1%) appears to perform better than the synthetic fungicide (benomyl) at fungal growth inhibition (Ghuffar et al., 2022)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Ziziphora clinopodioides</i> Lam "Blue mint bush"	Lamiaceae	Essential oil extracted from the aerial parts in PDA medium/ ethanol, when incubated with the fungal pathogen <i>B. cinerea</i> (isolated from strawberry fruit) at room temperature for one day, exhibited a nearly complete (94%) mycelial growth inhibition at a concentration of 2 µL/mL (Kahramanoğlu et al., 2022)	The result for the M2-1 pathogen isolate showed consistency with other tested <i>B. cinerea</i> isolates (M1-5, M3-5), indicating that the aerial part oil efficacy for mycelial growth inhibition applies to different strains of the pathogens (Kahramanoğlu et al., 2022)
<i>In vivo</i> experiment			
<i>A. cepa</i> L. "Onion"	Amaryllidaceae	The ethanolic bulb extract from, when applied to apple fruit infected by the fungal pathogen <i>Penicillium expansum</i> , demonstrated an infection incidence inhibition of 50% at a concentration of 150 mg/mL after 14 days of storage at 28 °C (Mahmoud, 2016)	The bulb extract at 15% concentration significantly reduced weight loss and enhanced firmness in stored fruit (Mahmoud, 2016)
<i>A. sativum</i> L. "Garlic"	Amaryllidaceae	The ethanolic clove extract used to treat apple fruits infected with <i>P. expansum</i> resulted in a 70% infection incidence inhibition (IC ₅₀) at a concentration of 150 mg/mL after 14 days of incubation at 28 °C. The aqueous extract under similar conditions resulted in a slightly lower effect, with a 60% infection incidence inhibition (Mahmoud, 2016)	The clove extracts have been found to significantly reduce weight loss and enhance firmness in stored fruit at a concentration of 15% (Mahmoud, 2016)
<i>C. carvi</i> L. "Black caraway"	Apiaceae	Essential oils extracted from seeds and fruit have also demonstrated significant antifungal activity. The oil from seeds inhibited the growth of <i>B. cinerea</i> on sweet cherry fruit by 80% at a concentration of ≥ 0.4 µL/mL after 40 days of incubation at 4 °C (Aminifard & Mohammadi, 2013). The same oil mixed with Tween-80 (5%) inhibited the growth of <i>P. digitatum</i> on Blood orange fruits by 100% at a concentration of 0.8 µL/mL after 60 days of incubation at 6 °C (Aminifard & Bayat, 2017). The oil from fruit sprayed on tomato fruit infected with <i>A. alternata</i> resulted in a 63% infection incidence inhibition at a concentration of 0.5 µL/mL after 10 days of incubation at 13 °C (Abdollahi et al., 2010)	The seed oil also improved the quality characteristics of the fruit (Aminifard & Mohammadi, 2013)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>C. aurantium</i> L.; Synonyms: <i>Citrus sinensis</i> (L.), <i>Citrus aurantium</i> L. ssp. <i>Anara</i> "Seville orange"	Rutaceae	Essential oils extracted from flowers and fruit peels have been found to inhibit the growth of various fungal pathogens. For instance, when mixed with a suspension of Tween-20 (0.05%) and used to treat apple fruits infected with <i>M. fructigena</i> and <i>M. laxa</i> , the oil from flowers led to a 60% and 93% infection incidence inhibition, respectively, at a concentration of 100 μ L/mL after 10 days of incubation at 20 °C. The oil from fruit peels led to a 58% infection incidence inhibition against <i>M. laxa</i> under similar conditions. In comparison, the synthetic fungicide Methylthiophanate resulted in a 65% and 73% effect against these pathogens, respectively (El Khetabi et al., 2021)	
<i>Citrus trifoliata</i> L. "Trifoliate orange"	Rutaceae	Essential oil extracted from fruit was used in an artificial diet to treat cotton leaves infested by the insect <i>Spodoptera littoralis</i> (2nd instar larvae). This treatment led to a larvicidal effect of 90% at a dose of 25 μ L/g after one day (Abdel-Kawy et al., 2021)	
<i>C. longa</i> L. "Turmeric"	Zingiberaceae	The ethanolic rhizome extract was used to treat tangerine fruit infected with the fungal pathogen <i>P. digitatum</i> . The treatment resulted in a 65% infection incidence inhibition (IC ₅₀) at a concentration of 30 mg/mL after 7 days of incubation at 25 °C (Sukorini et al., 2013)	
<i>C. citratus</i> (DC.) Stapf "Lemon grass"	Poaceae	The essential oil was used to treat avocado fruit infected with the fungal pathogen <i>C. gloeosporioides</i> . This treatment led to a 60% infection incidence inhibition (IC ₅₀) at a dose of 100 μ L after 14 days of incubation at 10 °C (Mpho et al., 2013)	The MAP-incorporated rhizome oil also elicited lower weight loss and delayed fruit ripening in the fruits, extending the shelf life (Mpho et al., 2013)
<i>Cymbopogon nardus</i> (L.) Rendle "Citronella grass"	Poaceae	The essential oil mixed with PDA medium/Tween-20 (at a concentration of 0.5%) was used to treat cherry tomato fruits infected with the fungal pathogen <i>A. alternata</i> . This treatment resulted in a 52% infection incidence inhibition at a concentration of 1.5 μ L/mL after 5 days of incubation at 25 °C (Chen et al., 2019)	The oil caused no negative effect on fruit quality (Chen et al., 2019)
<i>Foeniculum vulgare</i> Mill "Fennel"	Apiaceae	Essential oil extracted from the fruit sprayed on tomato fruit infected with <i>A. alternata</i> resulted in a 75% infection incidence inhibition at a concentration of 0.5 μ L/mL after 10 days of incubation at 13 °C (Abdollahi et al., 2010). Essential oil extracted from seeds led to an 80% infection incidence inhibition against <i>B. cinerea</i> on sweet cherry fruit at a concentration of ≥ 0.4 μ L/mL after 40 days of incubation at 4 °C (Aminifard & Mohammadi, 2013)	The seed oil also improved the quality characteristics of the fruit (Aminifard & Mohammadi, 2013)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>L. angustifolia</i> Mill "English lavender"	Lamiaceae	Essential oil extracted from the aerial parts and enclosed with a modified atmosphere in its vapour phase, when applied to Verna lemon fruit infected by the fungal pathogen <i>P. digitatum</i> , exhibited an infection incidence inhibition of 50% at a concentration of 0.086 µL/mL after 7 days of storage at 24 °C (Sumalan et al., 2020)	
<i>M. piperita</i> L. "Peppermint"	Lamiaceae	Essential oils extracted from the aerial parts and fruit have also shown promising results. The oil from aerial parts led to an infection incidence inhibition with an IC_{50} value of 0.18 µL/mL against <i>A. alternata</i> on Verna lemon fruits after 7 days of incubation at 24 °C in its vapour phase (Sumalan et al., 2020). Essential oil extracted from aerial parts led to an 80% infection incidence inhibition against <i>B. cinerea</i> on sweet cherry fruits at a concentration of ≥ 0.4 µL/mL after 40 days of incubation at 4 °C (Aminifard & Mohammadi, 2013)	
<i>Neolitsea cassia</i> (L.) Kosterm.; Synonym: <i>Cinnamomum cassia</i> "Shore laurel"	Lauraceae	Essential oils extracted from the stem bark and used in different forms have demonstrated significant antifungal activity. When encapsulated with Shellac or enriched with Shellac and applied to Thomson navel orange fruit infected by <i>P. digitatum</i> , the oil resulted in an infection incidence inhibition of 100% at a dose of 5 µL/mL after 28 days of storage at 5 °C. In its pure form, the oil led to an 89% infection incidence inhibition under similar conditions. For comparison, the synthetic fungicide Carbendazim (at a dose of 0.5%) resulted in a 100% effect (Khorram & Ramezani, 2020)	
<i>Nigella sativa</i> L. "Black seed"	Ranunculaceae	Essential oil extracted from seeds and mixed with ethanol was used to treat pomegranate fruits infected with the fungal pathogen <i>B. cinerea</i> . This treatment resulted in a decay/disease severity reduction of 59% at a concentration of 5 µL/mL after 150 days of incubation at 6.5 °C. For comparison, the synthetic fungicide Fludioxonil (at a dose of 0.06%) resulted in a reduction effect of 75% (Kahramanoğlu et al., 2022)	
<i>O. basilicum</i> L. "Basil"	Lamiaceae	Essential oil extracted from the aerial parts and enclosed in a modified atmosphere was used in the vapour phase to treat Verna lemon fruits infected with the fungal pathogen <i>P. digitatum</i> . This treatment led to a 50% infection incidence inhibition at a concentration of 0.046 µL/mL after 7 days of incubation at 24 °C (Sumalan et al., 2020)	

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>P. anisum</i> L. "Anise"	Apiaceae	Essential oil extracted from seeds in Tween 80 (5%) suspension, when applied to blood orange fruit infected by the fungal pathogen <i>P. digitatum</i> , exhibited an infection incidence inhibition of 100% at a concentration of 0.8 µL/mL after 60 days of storage at 6 °C (Aminifard & Bayat, 2017)	
<i>S. aromaticum</i> (L.) Merr. & L.M.Perry "Clove"	Myrtaceae	Essential oils extracted from flowers and fruit peels have been found to inhibit the growth of various fungal pathogens. For instance, when mixed with a suspension of Tween-20 (0.05%) and used to treat apple fruit infected with <i>M. fructigena</i> and <i>M. laxa</i> , the oil from flowers led to a 70% and 98% infection incidence inhibition, respectively, at a concentration of 100 µL/mL after 10 days of incubation at 20 °C. The ethanol extract derived from flower buds resulted in a 67% infection incidence inhibition against <i>P. digitatum</i> on tangerine fruits at a concentration of 15 mg/mL after 7 days of incubation at 25 °C (Sukorini et al., 2013)	
<i>T. vulgaris</i> L. "Common thyme"	Lamiaceae	Essential oils extracted from the aerial parts have demonstrated significant antifungal activity. The oil mixed with PDA medium was used to treat 'Washington Navel' orange fruit infected with <i>A. citri</i> , leading to a 100% infection incidence inhibition at a concentration of ≥ 0.5 µL/mL after 60 days of incubation at 5 °C (Ramezani et al., 2016). The same oil was used to treat sweet cherry fruit infected with <i>Monilinia fructicola</i> , resulting in a 57% infection incidence inhibition at a concentration of 0.6 µL/mL after 50 days of incubation at 0 °C (Hassani et al., 2012). When mixed with a suspension of Tween-20 (0.05%), the oil was used to treat apple fruits infected with <i>M. fructigena</i> and <i>M. laxa</i> , leading to a 98% infection incidence inhibition in both cases at a concentration of 100 µL/mL after 10 days of incubation at 20 °C. For comparison, the synthetic fungicide, Methylthiophanate resulted in a 65% and 73% effect against these pathogens, respectively (El Khetabi et al., 2021). Essential oil was also used to treat strawberry fruits infected with <i>B. cinerea</i> , leading to an infection incidence inhibition of 85% at a dose of 40 µL after 2.5 days of incubation at 25 °C (Yan et al., 2021)	The aerial part oil inhibited weight loss and also increased fruit quality in terms of firms (Ramezani et al., 2016)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Trachyspermum ammi</i> Sprague; Synonym: <i>Carum copiticum</i> (L.) Benth. & Hook.f "Ajowan caraway"	Apiaceae	Essential oil extracted from fruit was used as a spraying solution on tomato fruit infected with the fungal pathogen <i>A. alternata</i> . This treatment resulted in 70% infection incidence inhibition at a concentration of 0.5 µL/mL after 10 days of incubation at 13 °C (Abdollahi et al., 2010)	
<i>Vachellia seyal</i> (Delile) P.J.H.Hurter "Shittimwood"	Fabaceae	The methanolic leaves extract was used to treat sweet orange fruits infected with the fungal pathogen <i>P. digitatum</i> . The treatment resulted in a 50% infection incidence inhibition at a concentration of 50 mg/mL after 21 days of incubation at 7 °C (Mekbib et al., 2009)	
<i>Withania somnifera</i> (L.) Dunal "Indian ginseng"	Solanaceae	The methanolic leaves extract was used to treat sweet orange fruits infected with the fungal pathogen <i>P. digitatum</i> . The treatment resulted in a 56% infection incidence inhibition at a concentration of 50 mg/mL after 21 days of incubation at 7 °C (Mekbib et al., 2009)	
<i>Z. multiflora</i> Boiss "Shirazi thyme"	Lamiaceae	Essential oil extracted from the aerial parts and mixed with PDA medium was used to treat 'Washington Navel' orange fruits infected with the fungal pathogen <i>A. citri</i> . This treatment led to a 100% infection incidence inhibition at a concentration of ≥ 0.4 µL/mL after 60 days of incubation at 5 °C (Ramezani et al., 2016)	The aerial part oil inhibited weight loss and also increased fruit quality in terms of firms (Ramezani et al., 2016)
<i>Z. clinopodioides</i> Lam "Blue mint bush"	Lamiaceae	Essential oil derived from the aerial parts and used in the vapour phase was used to treat strawberry fruits infected with the fungal pathogen <i>B. cinerea</i> . This treatment resulted in a decay/disease severity reduction of 54% at a concentration of 2 µL/mL after 21 days of incubation at 3.5 °C (Kahramanoğlu et al., 2022)	The aerial part oil prevented the weight loss of the fruits and also delayed the onset of disease during storage. The experimented phytopathogen is M2-1 isolate (Kahramanoğlu et al., 2022)
<i>In planta</i> experiment			
<i>A. cepa</i> L. "Onion"	Amaryllidaceae	The aqueous bulb extract applied on Kinnow mandarin plant infected by bacterial pathogen (<i>Xanthomonas axonopodis</i> pv. <i>citri</i>) elicited 73% disease incidence inhibition at a concentration of 10 µL/mL after 1095 days of treatment (Rehman et al., 2020)	The bulb extract also inhibited disease incidence in the standing fruits by 95% as well as increased the fruit size and quality (Rehman et al., 2020)
<i>Annona squamosa</i> L. "Sweet sop"	Annonaceae	The hexane/40 EC seeds extract applied on cabbage leaf infested by insect (<i>A. gossypii</i> G.—aphids) resulted in 72% reduction of aphid population at a concentration of 10 mg/mL after 7 days of treatment. In comparison, the synthetic insecticide (λ -Cyhalothrin—5 EC at 0.05%) caused 92% effect (Purkait et al., 2019)	The seed oil, at same dose and time, also reduced <i>B. tabaci</i> G. (white-fly) population by 72% (Purkait et al., 2019)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>C. virgulata</i> subsp. <i>granitana</i> (Harv.) Polhill	Fabaceae	The aqueous seeds extract applied on tomato root infested by nematode (<i>M. incognita</i> —second-stage juveniles) resulted in 96% inhibition of root infestation at a concentration of 5 mg/mL after 42 days of treatment (Jourand et al., 2004)	The seed extract at both 1 and 5 mg/mL delayed nematode penetration by 10 days compared to the control or lower concentrations (≤ 1 mg/mL) of extract, thereby leading to improved plant growth compared to infested tomato plants (Jourand et al., 2004)
<i>Costus afer</i> Ker Gawl "Bush cane"	Costaceae	The aqueous leaves extract applied on egusi melon seed infected by the fungal pathogen <i>Colletotrichum truncatum</i> and <i>C. gloeosporioides</i> demonstrated 83% and 100% disease incidence inhibition, respectively at a concentration of 100 mg/mL after 42 days of treatment. In comparison, the synthetic fungicide Mancozeb (80% WP) caused an 83% and 100% effect, respectively (Ogunsola & Ogunsola, 2023)	The leaves extract significantly reduced the severity of leaf blight disease and showed enhanced growth parameters (% germination, vine length, number of leaves and vines) of plants from infected seeds
<i>Lycoris aurea</i> (L'Hér.) Herb "Golden spider-lily"	Amaryllidaceae	The ethanolic bulb extract elicited an insecticidal effect of 84% against <i>Plutella xylostella</i> (diamondback moth) at a concentration of 200 g ai/ha after 7 days of treatment (Hu et al., 2018)	
<i>P. erosus</i> (L.) Urb "Mexican turnip"	Fabaceae	The hexane/40 EC seeds extract applied on cabbage leaf infested by insect (<i>Aphis gossypii</i> G.—aphids) resulted in a reduction of aphid population by 50% at a concentration of 10 mg/mL after 10 days of treatment. In comparison, the synthetic insecticide (λ -Cyhalothrin—5 EC at 0.05%) caused an effect of 95% (Purkait et al., 2019)	
<i>P. foetida</i> L. "Stinking passion"	Passifloraceae	The aqueous leaves extract applied on egusi melon seed infected by <i>C. gloeosporioides</i> and <i>C. truncatum</i> , separately, elicited an effect of disease incidence inhibition by 80% at a concentration of 100 mg/mL after 42 days of treatment. In comparison, the synthetic fungicide Mancozeb—80% WP caused an effect of 100% and 83% on <i>C. gloeosporioides</i> and <i>C. truncatum</i> , respectively (Ogunsola & Ogunsola, 2023)	The leaves extract significantly reduced leaf blight disease severity caused by <i>C. gloeosporioides</i> and <i>C. truncatum</i> and increased growth parameters of plants from infected seeds (Ogunsola & Ogunsola, 2023)
<i>Phyllanthus amarus</i> Schumach. & Thonn "Seed on the leaf"	Phyllanthaceae	The aqueous leaves extract applied on egusi melon seed infected by <i>C. gloeosporioides</i> and <i>C. truncatum</i> resulted in an 83% and 100% disease incidence inhibition, respectively, at concentrations of 100 mg/mL and 500 mg/mL after 42 days of treatment. In comparison, the synthetic fungicide Mancozeb—80% WP caused 83.3% effect (Ogunsola & Ogunsola, 2023)	The leaves extract significantly reduced the severity of leaf blight disease caused by <i>C. gloeosporioides</i> and <i>C. truncatum</i> , and enhanced growth parameters of plants from infected seeds (Ogunsola & Ogunsola, 2023)

Table 3 (continued)

Scientific name "common name"	Family	Anti-phytopathogenic effect(s)	Phytotoxicity effect(s)/notable remark(s)
<i>Platykladus orientalis</i> (L.) Franco "Chinese arborvitae"	Cupressaceae	The hydro-methanolic leaves and stem extract applied on plantain/banana leaf infected by the fungal pathogen <i>Magnaporthe oryzae</i> resulted in a 90% disease incidence inhibition at a concentration of 3 mg/mL after 5 days of treatment. Similarly, when applied on wheat leaf infected by the fungal pathogen <i>Puccinia tritici</i> , the same treatment led to a 90% disease incidence inhibition. In comparison, the synthetic fungicides Blasticidin-S and Flusilazole caused a 100% effect (Bae et al., 2021)	
<i>Pongamia pinnata</i> (L.) Pierre "Indian beech Tree"	Fabaceae	The hexane/40 EC seeds extract applied on cabbage leaf infested by insect (<i>A. gossypii</i> G.—aphids) resulted in a reduction of aphid population by 69% at a concentration of 10 mg/mL after 7 days of treatment. In comparison, the synthetic insecticide (λ-Cyhalothrin—5 EC at 0.05%) caused an effect of 95% (Purkait et al., 2019)	The seed oil, at same dose and time, also reduced <i>B. tabaci</i> G. (whitefly) population by 69% (Purkait et al., 2019)

Fig. 10 The most occurring crop pathogens based on the number of plants (≥ 7) used for their control from the empirical data on crop protection

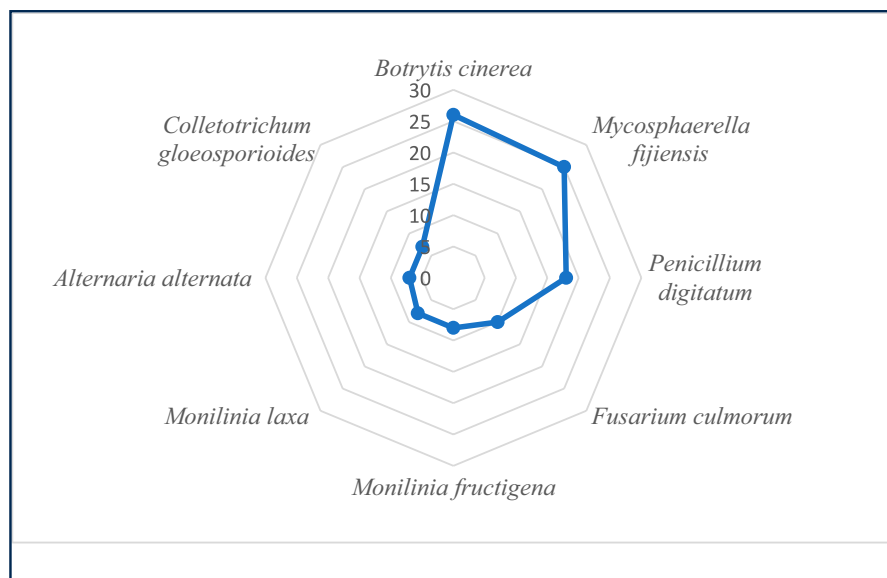
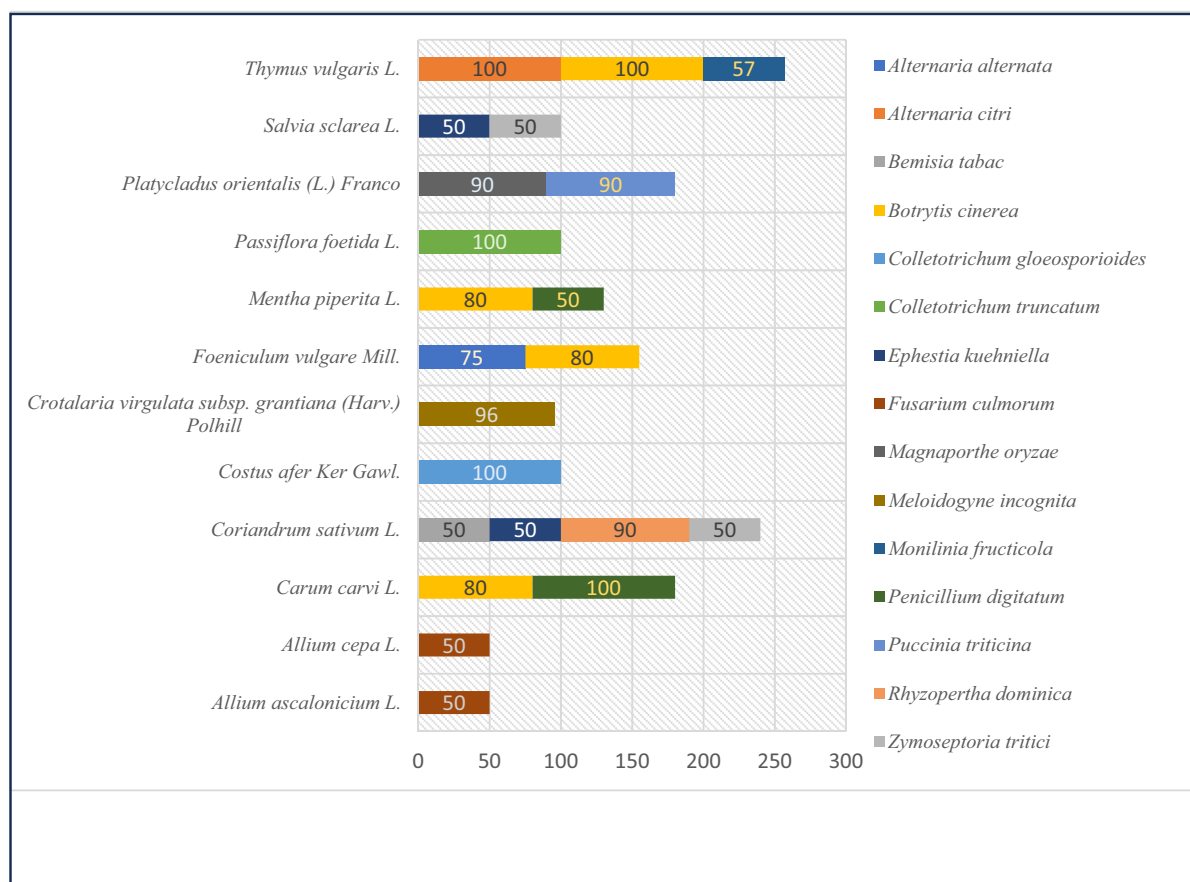


Fig. 11 The most promising plants for controlling decay pathogens in crop protection

certain crop pathogens at relatively minimal concentrations (Fig. 11). These plants were chosen due to their significant biological effects ($\geq 50\%$) at low concentrations ($\leq 0.01\%$, w/v or v/v *in vitro*; $\leq 1\%$, w/v or v/v *in vivo*).

In the *in vitro* experiments, four plants were chosen for the outstanding antifungal and insecticidal properties as their essential oils effectuate. Essential oil from the bulbs of *Allium ascalonicum* L. and *Allium cepa* L. exhibited IC_{50} values of 0.01 mg/mL and 0.1 mg/mL, respectively, against *F. culmorum* when incubated in PDA medium at 20 °C for 7 days (El-Alam et al., 2020). Essential oil from the aerial parts of *Coriandrum sativum* L. showed a 50% insecticidal effect against *Bemisia tabac* isolated from tomato at a concentration of 0.023 μ L/mL after 1 day at 25 °C. The same oil in its vapour phase demonstrated a 50% and 90% insecticidal effect against *Ephestia kuehniella* and *R. dominica*, respectively, both at a concentration of 0.057 μ L/mL. Additionally, the oil extracted from the seeds inhibited mycelial growth (IC_{50}) of *Zymoseptoria tritici* isolated from cereals by 0.001 mg/mL. Essential oil from *Salvia sclarea* L. flowers exhibited an IC_{50} value (insecticidal effect) of 0.057 μ L/mL against *E. kuehniella* and an IC_{50} value (mycelial growth inhibition) of 0.08 mg/mL against *Z. tritici* (Raveau et al., 2022). Lastly, essential oil from the aerial parts of *Thymus vulgaris* L. completely inhibited mycelial growth of *A. citri* at a concentration of ≥ 0.4 μ L/mL (Ramezani et al., 2016).

In the *in vivo* studies, four plants were selected due to the exceptional antifungal potential exhibited by their essential oils. Essential oil from *Carum carvi* L. seeds inhibited the growth of *B. cinerea* on sweet cherry fruits by 80% at a concentration of ≥ 0.4 μ L/mL after 40 days of incubation at 4 °C, and when mixed with Tween-80 (5%), it completely inhibited the growth of *P. digitatum* on Blood orange fruits at a concentration of 0.8 μ L/mL after 60 days of incubation at 6 °C (Aminifard & Bayat, 2017). Essential oil from *Foeniculum vulgare* L. fruit sprayed on tomato fruits infected with *A. alternata* resulted in a 75% infection incidence inhibition at a concentration of 0.5 μ L/mL after 10 days of incubation at 13 °C (Abdolahi et al., 2010), and the oil extracted from its seeds led to an 80% infection incidence inhibition against *B. cinerea* on sweet cherry fruits at a concentration of ≥ 0.4 μ L/mL after 40 days of incubation at 4 °C (Aminifard & Mohammadi, 2013).

Essential oil from *Mentha piperita* L. aerial parts led to an infection incidence inhibition with an IC_{50} value of 0.18 μ L/mL against *A. alternata* on Verna lemon fruits after 7 days of incubation at 24 °C in its vapour phase (Sumalan et al., 2020), and the same oil extract led to an 80% infection incidence inhibition against *B. cinerea* on sweet cherry fruits at a concentration of ≥ 0.4 μ L/mL after 40 days of incubation at 4 °C (Aminifard & Mohammadi, 2013). Essential oil extracted from the aerial parts of *T. vulgaris* L. mixed with PDA medium demonstrated complete infection incidence inhibition in ‘Washington Navel’ orange fruits infected with *A. citri*, at a concentration of ≥ 0.5 μ L/mL after 60 days of incubation at 5 °C (Ramezani et al., 2016), and the same oil was used to treat sweet cherry fruits infected with *Monilinia fructicola*, resulting in a 57% infection incidence inhibition at a concentration of 0.6 μ L/mL after 50 days of incubation at 0 °C (Hassani et al., 2012).

In the *in planta* experiments, four plants were chosen for the relatively substantial antifungal properties their various extracts elicit. The aqueous seeds extract of *Crotalaria virgulata* subsp. *grantiana* (Harv.) Polhill applied on tomato root infested by nematode (*Meloidogyne incognita* second-stage juveniles) resulted in 96% inhibition of root infestation at a concentration of 5 mg/mL after 42 days of treatment (Jourand et al., 2004). The aqueous leaf extracts of *Costus afer* Ker Gawl. and *Passiflora foetida* L. both demonstrated 100% disease incidence inhibition at a concentration of 100 mg/mL after 42 days of treatment on ‘egusi’ melon seed infected with *C. gloeosporioides* and *Colletotrichum truncatum*, respectively (Ogunsola & Ogunsola, 2023). The hydro-methanolic leaf and stem extracts of *Platycladus orientalis* (L.) Franco applied on plantain/banana leaf infected by the fungal pathogen *Magnaporthe oryzae* resulted in a 90% disease incidence inhibition at a concentration of 3 mg/mL after 5 days of treatment.

Potential trends for future research

As highlighted by Kastrin and Hristovski (2021), scientometric analysis is instrumental in deducing the most prominent and emerging research themes in a field. This approach provides a holistic perspective of the research landscape, thereby facilitating the identification of trends,

gaps, and potential future trajectories in a specific domain (Kastrin & Hristovski, 2021; López-Pernas et al., 2023; Oyewola & Dada, 2022; Schäfermeier et al., 2023).

As represented in Fig. 12, the thematic evolution of Keyword Plus (index keywords) in the research area focusing on the application of plants for biocontrol in crop protection offers valuable insights into the progression of research topics and themes over time (1970–2023). This visualisation categorizes index keywords obtained from Scopus into seven periods based on significant shifts in research themes and noticeable changes in publication volume. In the first period (1970–2000), the keyword is exclusively centred on “agriculture.” This aligns with trends observed in Fig. 2, which show a focus on plant-based crop protection themes beginning from the year 2000. It is evident that the research field focusing on plant-based crop protection was not distinctly defined until the turn of the millennium (Fig. 4). Moreover, the link between the keywords of the second and third periods suggests a transition in research

focus. Initially, research centred on studying diseases affecting crops including tomatoes (*Lycopersicon esculentum*), with an emphasis on enhancing their resistance to fungal pathogens including the genus *Penicillium*. However, the focus appears to have shifted towards the use of fungicides for crop protection, including fennel (*F. vulgare*), in subsequent periods. Based on keywords in the fourth period, it can be inferred that chemical evaluation of plant-derived fungicides commenced around 2015. The presence of keywords such as “concentration(composition)” and “chemistry” in the fifth period indicated the sustained interest in chemical analysis and experimental considerations within this field. The recurring appearance of “fungi/fungus” and “fungicide(s)” across various periods underscores the primary focus of experimental research on combating crop pathogens. Although there were limited publications in the seventh period at the time of bibliometric data extraction (March 29, 2023), the research in this field was already transitioning towards

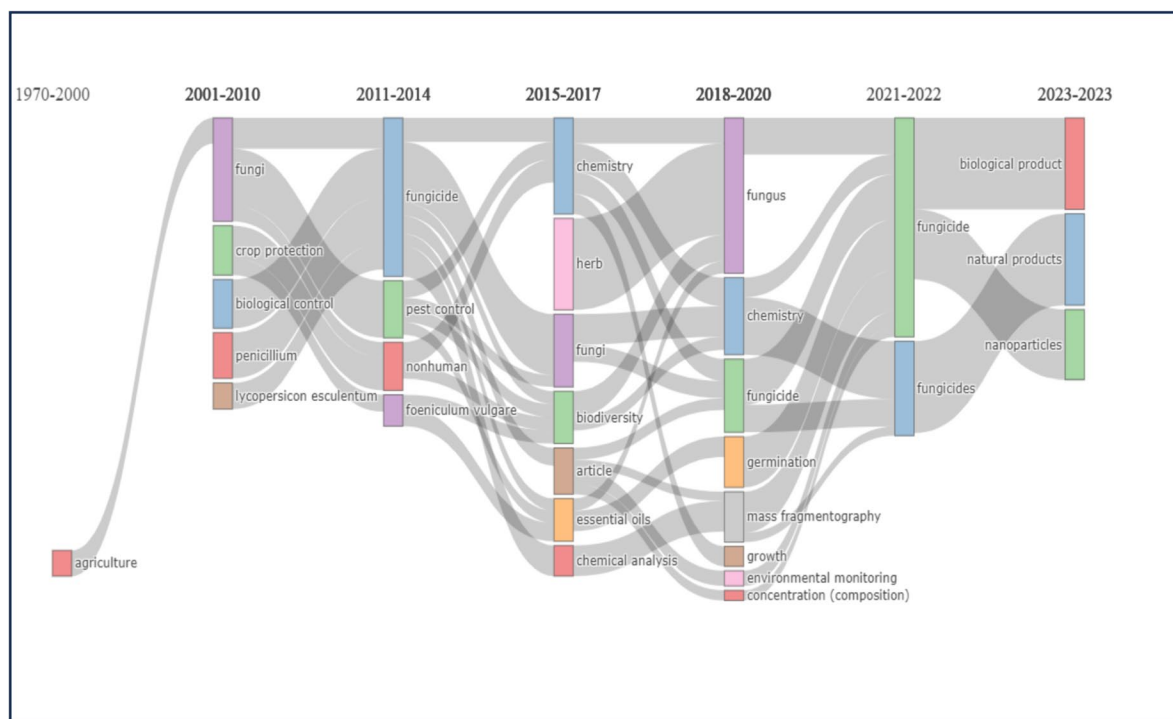


Fig. 12 Timeline chart of thematic evolution of Keyword Plus in the field of crop protection

incorporating nanoparticles/nanotechnology in biological products.

Future perspectives

The scientometric analysis of the research field focusing on the application of plants for biocontrol in crop protection revealed several promising trends and potential areas of future research (Fig. 12). These future perspectives highlight the dynamic and evolving nature of the research field. They provide a roadmap for future research and development efforts and set the stage for the next phase of innovation in plant-based crop protection. Some of the envisaged aspects worth pursuing are briefly highlighted below.

Nanotechnology in biological products One of the emerging trends is the incorporation of nanoparticles and nanotechnology in biological products. This advancement in technology is expected to enhance the effectiveness of plant-based biocontrol methods (Fig. 2).

Sustainable and environmentally friendly practices The future of pest control methods appears to be moving towards more sustainable and environmentally friendly practices (Fig. 2). This shift aligns with the global trend towards sustainability and the need to reduce the environmental impact of agricultural practices (United Nations, 2024; Green Journal, 2023; Nchu, 2024).

Integrated approach to crop protection An integrated approach to crop protection is expected to become more prevalent. This approach combines pest and pathogen control methods to provide a more effective and holistic solution to their management. It includes the use of plant-based biocontrol methods, chemical fungicides, and advancements in biotechnology (FAO, 2024; Franco, 2020).

Chemical evaluation of plant-derived fungicides The chemical evaluation of plant-derived fungicides is another area of potential future research. This includes the identification of new bioactive compounds and the study of their effectiveness in controlling crop pests and pathogens (Thind, 2021).

Limitations of the current review

Bibliometric review: Bibliographic coupling and co-citation of research literature in the field of crop protection

Although this review provides a comprehensive bibliometric analysis of the field of crop protection, it does not incorporate bibliographic coupling and co-citation analysis. These two key scientometric methods offer deeper insights into the relationships within the research community and the structure of the field. Bibliographic coupling occurs when two documents reference a common third document, indicating a topical similarity between them. This method is instrumental in uncovering the thematic connections and intellectual lineage within a field, as it reflects the shared knowledge base of the coupled documents. Conversely, co-citation happens when two documents are cited together by a third document, suggesting a relational link between them (Kleminski et al., 2020; Tan, 2022). This method is valuable in identifying emerging trends and networks of collaboration or influence within the research community. The absence of bibliographic coupling analysis in this review means potentially overlooking unique insights and nuanced relationships that go beyond direct citations or co-citations. Such analysis could reveal underlying thematic connections between studies that are not immediately apparent through direct citation analysis alone (Kleminski et al., 2020).

The exclusion of co-citation analysis limited our ability to map out the network of relationships and influences within the field. Co-citation can highlight clusters of related work and trace the evolution of ideas, identifying key papers or authors that have significantly shaped the research landscape. One way to address this limitation is by using category-based co-citation analysis, as suggested by Liu and Hsu (2019). This approach mitigates the primary limitation in bibliometric analysis, where two related articles might cite different references, by assuming that references can be related if cited within the same categories on specific topics. It offers a more nuanced view of the interconnections in the field.

Research database

Secondly, while Scopus is a comprehensive and widely used database for bibliometric and scientometric analyses, relying solely on it presents certain limitations. Other databases including Web of Science and Dimensions might offer additional relevant articles not indexed in Scopus, which could provide a broader view of the field of plant-based crop protection. The exclusive use of Scopus may limit the scope of the review, potentially overlooking significant studies and trends that are present in other databases. Furthermore, citation data can vary across different databases, and therefore, a citation analysis based solely on Scopus might not fully capture the citation impact of articles in this field. Future studies should consider incorporating data from multiple databases to achieve a more comprehensive and nuanced understanding of the field. A multi-database approach would enhance the robustness of bibliometric analyses, ensuring a wider coverage of relevant literature and citation data.

Research gap

The review identified a significant gap in the current literature regarding the detailed mechanisms and factors influencing the anti-phytopathogenic activity of plant-based biocontrol agents. There is an absence of comprehensive and critical investigation into the specific mechanisms through which plant-based agents exert their anti-phytopathogenic effects. This limits our ability to fully understand and optimize these biocontrol agents for more effective use in crop protection. Another potential gap that emerged during our review process was the omission of plant pathogenic viruses from our search criteria. Viruses, as a significant group of plant pathogens, can impact crop health, yield, and quality, including effects from sublethal infections on fruit quality and shelf-life (Krenz et al., 2024; Tatineni & Hein, 2023). Excluding viruses from our search criteria inherently limit the comprehensiveness of this review. Future reviews could enhance their scope by including plant pathogenic viruses in their search criteria for a more holistic overview of plant-based crop protection strategies.

Additionally, the potential risks and challenges associated with the use of plant-based biocontrol agents, such as impacts on non-target organisms and the development of resistance were insufficiently

discussed in the current literature. Regulatory considerations related to the use of these agents were not adequately addressed, which is crucial given the increasing interest in sustainable and environmentally friendly crop protection methods. There are several other underexplored areas in the current literature, which present opportunities for future research. These include the role of seed treatment in plant protection, the use of the liquid fraction of digestates for plant protection, and the phytoprotective properties of plant-based fertilizers. Future studies could focus on these areas to develop more effective plant protection strategies, thereby filling these inherent gaps in the literature.

Conclusion

This bibliometric and scientometric analysis, combined with a best-evidence literature review, has comprehensively addressed the research questions pertaining to plant-based crop protection. This study analysed 235 documents from the Scopus database, spanning from 1970 to 2023, and successfully identified significant research hotspots, trends, themes, influential publications, authors, institutions, and countries in the field. The analysis has pinpointed significant publications, sources, authors, institutions, and countries contributing to the scientific progress in plant-based crop protection. From the existing *in vitro*, *in vivo* and *in planta* experiments, we identified 91 plant species from 28 families highlighted for their potential as biocontrol agents and applications. The Lamiaceae as a plant family and aerial parts of plants were predominantly used in the eligible studies. Some of the most promising anti-phytopathogenic plants included *P. orientalis*, *M. piperita*, *F. vulgare*, *C. sativum*, and *A. ascalonicum*. The predominant keywords shaping the knowledge structure in this field were "fungicide", "nonhuman", and "crop protection", with a thematic focus on chemical properties of antifungal agents, bioactive compounds, and environmental protection. A paradigm shift was noted around 2015–2017, followed by a substantial increase in publication volume, signaling a growing scientific interest and commitment to this research area. An emerging focus on nanotechnology suggests an innovative trajectory for developing sustainable biocontrol methods.

Further research is necessary to elucidate the mechanisms and factors influencing the efficacy of plant-based biocontrol agents, thereby enhancing our understanding of their mode of action, safety, and environmental impact. Comparative studies are recommended to assess the effectiveness, cost-efficiency, and potential synergies of plant-based biocontrol agents in various crop protection scenarios. These future studies will be crucial in providing evidence-based recommendations for agricultural practices, informing policy decisions, and advancing the field of sustainable crop protection.

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The opinions, findings and conclusions or recommendations expressed are those of the authors alone, and the NRF accepts no liability whatsoever in this regard.

Data availability The datasets generated and/or analysed during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest We declare no conflict of interest with regards to this study.

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References

- Abdel-Kawy, M. A., Michel, C. G., Kirolos, F. N., Hussien, R. A. A., Al-Mahallawi, A. M., & Sedeek, M. S. (2021). Chemical composition and potentiation of insecticidal and fungicidal activities of *Citrus trifoliata* L. fruits essential oil against *S. littoralis*, *Fusarium. oxysporum* and *Fusarium solani* via nano-cubosomes. *Natural Product Research*, 35, 2438–2443. <https://doi.org/10.1080/14786419.2019.1675063>
- Abdolahi, A., Hassani, A., Ghosta, Y., Javadi, T., & Meshkatal-Sadat, M. H. (2010). Essential oils as control agents of postharvest *Alternaria* and *Penicillium* rots on tomato fruits. *Journal of Food Safety*, 30, 341–352. <https://doi.org/10.1111/j.1745-4565.2009.00211.x>
- Adejumo, T. O. (2005). Crop protection strategies for major diseases of cocoa, coffee and cashew in Nigeria. *African Journal of Biotechnology*, 4, 143–150.
- Adetunji, T. L., Olawale, F., Olisah, C., Adetunji, A. E., & Aremu, A. O. (2022). Capsaicin: A two-decade systematic review of global research output and recent advances against human cancer. *Frontiers in Oncology*, 12, 908487. <https://doi.org/10.3389/fonc.2022.908487>
- Akwu, N. A., Lekhooa, M., Deqiang, D., & Aremu, A. O. (2023). Antidepressant effects of coumarins and their derivatives: A critical analysis of research advances. *European Journal of Pharmacology*, 956, 175958. <https://doi.org/10.1016/j.ejphar.2023.175958>
- Almada-Ruiz, E., Martínez-Téllez, M. A., Hernandez-Álamos, M. M., Vallejo, S., Primo-Yúfera, E., & Vargas-Arispuro, I. (2003). Fungicidal potential of methoxylated flavones from citrus for in vitro control of *Colletotrichum gloeosporioides*, causal agent of anthracnose disease in tropical fruits. *Pest Management Science*, 59, 1245–1249. <https://doi.org/10.1002/ps.747>
- Aminifard, M. H., & Bayat, H. (2017). Antifungal activity of black caraway and anise essential oils against *Penicillium digitatum* on blood orange fruits. *International Journal of Fruit Science*. <https://doi.org/10.1080/1553362.2017.1409682>
- Aminifard, M. H., & Mohammadi, S. (2012). Essential oils to control *Botrytis cinerea* in vitro and in vivo on plum fruits. *Journal of the Science of Food and Agriculture*. <https://doi.org/10.1002/jsfa.5765>
- Aminifard, M. H., & Mohammadi, S. (2013). Efficacy of plant essential oils to control post-harvest decay of sweet cherry (*Prunus avium* L.) fruit. *The Journal of Horticultural Science and Biotechnology*, 88, 79–84. <https://doi.org/10.1080/14620316.2013.11512939>
- Anand, G., & Rajeshkumar, K. C. (2022). Challenges and threats posed by plant pathogenic fungi on agricultural productivity and economy. In V. R. Rajpal, I. Singh, & S. S. Navi (Eds.), *Fungal diversity, ecology and control management*. Singapore: Springer. https://doi.org/10.1007/978-981-16-8877-5_23

- Anaya, A. L. (1999). Allelopathy as a tool in the management of biotic resources in agroecosystems. *Critical Reviews in Plant Sciences*, 18, 697–739. <https://doi.org/10.1080/07352689991309450>
- Arango Isaza, R. E., Diaz-Trujillo, C., Dhillon, B., Aerts, A., Carlier, J., Crane, C. F., de Jong, T. V., de Vries, I., Dietrich, R., Farmer, A. D., Fortes Ferreira, C., Garcia, S., Guzman, M., Hamelin, R. C., Lindquist, E. A., Mehrabi, R., Quiros, O., Schmutz, J., Shapiro, H., ... Kema, G. H. J. (2016). Combating a global threat to a clonal crop: Banana black sigatoka pathogen *Pseudocercospora fijiensis* (Synonym *Mycosphaerella fijiensis*) genomes reveal clues for disease control. *PLOS Genetics*, 12, e1005876. <https://doi.org/10.1371/journal.pgen.1005876>
- Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11, 959–975. <https://doi.org/10.1016/j.joi.2017.08.007>
- Bae, S., Han, J. W., Dang, Q. L., Kim, H., & Choi, G. J. (2021). Plant disease control efficacy of *Platyedus orientalis* and its antifungal compounds. *Plants*, 10, 1496. <https://doi.org/10.3390/plants10081496>
- Balakumbahan, R., Rajamani, K., & Kumanan, K. (2010). *Acorus calamus*: An overview. *Journal of Medicinal Plants Research*, 4, 2740–2745.
- Bautista-Baños, S., Sivakumar, D., Bello-Pérez, A., Villanueva-Arce, R., & Hernández-López, M. (2013). A review of the management alternatives for controlling fungi on papaya fruit during the postharvest supply chain. *Crop Protection*, 49, 8–20. <https://doi.org/10.1016/j.cropro.2013.02.011>
- Bocquet, L., Rivi re, C., Dermont, C., Samaillie, J., Hilbert, J.-L., Halama, P., Siah, A., & Sahpaz, S. (2018). Antifungal activity of hop extracts and compounds against the wheat pathogen *Zymoseptoria tritici*. *Industrial Crops and Products*, 122, 290–297. <https://doi.org/10.1016/j.indcrop.2018.05.061>
- Carlini, C. R., & Grossi-de-S , M. F. (2002). Plant toxic proteins with insecticidal properties. A review on their potentialities as bioinsecticides. *Toxicon*, 40, 1515–1539. [https://doi.org/10.1016/S0041-0101\(02\)00240-4](https://doi.org/10.1016/S0041-0101(02)00240-4)
- Catani, L., Grassi, E., Coccozza di Montanara, A., Guidi, L., Sandulli, R., Manachini, B., & Semprucci, F. (2022). Essential oils and their applications in agriculture and agricultural products: A literature analysis through VOSviewer. *Biocatalysis and Agricultural Biotechnology*, 45, 102502. <https://doi.org/10.1016/j.cbab.2022.102502>
- Chen, J., Shen, Y., Chen, C., & Wan, C. (2019). Inhibition of key citrus postharvest fungal strains by plant extracts *in vitro* and *in vivo*: A review. *Plants*, 8, 26. <https://doi.org/10.3390/plants8020026>
- Chu, C.-L., Liu, W.-T., & Zhou, T. (2001). Fumigation of sweet cherries with thymol and acetic acid to reduce postharvest brown rot and blue mold rot. *Fruits*, 56, 123–130. <https://doi.org/10.1051/fruits:2001113>
- Combrinck, S., Regnier, T., & Kamatou, G. P. P. (2011). *In vitro* activity of eighteen essential oils and some major components against common postharvest fungal pathogens of fruit. *Industrial Crops and Products*, 33, 344–349. <https://doi.org/10.1016/j.indcrop.2010.11.011>
- Consultative Group on International Agricultural Research. (2018). Which are the right crops to enable food security under future climates? <https://www.cgiar.org/news-events/news/right-crops-enable-food-security-future-climates>. Accessed 24/04/2024.
- Copping, L. G., & Duke, S. O. (2007). Natural products that have been used commercially as crop protection agents. *Pest Management Science*, 63, 524–554. <https://doi.org/10.1002/ps.1378>
- Dayan, F. E., Cantrell, C. L., & Duke, S. O. (2009). Natural products in crop protection. *Bioorganic & Medicinal Chemistry*, 17, 4022–4034. <https://doi.org/10.1016/j.bmc.2009.01.046>
- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285–296. <https://doi.org/10.1016/j.jbusres.2021.04.070>
- Drakopoulos, D., Meca, G., Torrijos, R., Marty, A., K gi, A., Jenny, E., Forrer, H.-R., Six, J., & Vogelgsang, S. (2020). Control of *Fusarium graminearum* in wheat with mustard-based botanicals: From *in vitro* to *in planta*. *Frontiers in Microbiology*, 11, 1595. <https://doi.org/10.3389/fmicb.2020.01595>
- du Plooy, W., Regnier, T., & Combrinck, S. (2009). Essential oil amended coatings as alternatives to synthetic fungicides in citrus postharvest management. *Postharvest Biology and Technology*, 53, 117–122. <https://doi.org/10.1016/j.postharvbio.2009.04.005>
- El Khetabi, A., Ezrari, S., El Ghadraoui, L., Tahiri, A., Ait Haddou, L., Belabess, Z., Merah, O., & Lahlali, R. (2021). *In vitro* and *in vivo* antifungal activities of nine commercial essential oils against brown rot in apples. *Horticulturae*, 7, 545. <https://doi.org/10.3390/horticulturae7120545>
- El-Alam, I., Raveau, R., Fontaine, J., Verdin, A., Laruelle, F., Fourmentin, S., Chahine, R., Makhlof, H., & Loun s-Hadj Sahraoui, A. (2020). Antifungal and phytotoxic activities of essential oils: *In vitro* assays and their potential use in crop protection. *Agronomy*, 10, 825. <https://doi.org/10.3390/agronomy10060825>
- Fadiji, T., Bokaba, T., Fawole, O. A., & Twinomurinzi, H. (2023). Artificial intelligence in postharvest agriculture: Mapping a research agenda. *Frontiers in Sustainable Food Systems*, 7, 1226583. <https://doi.org/10.3389/fsufs.2023.1226583>
- Farhang, V., Amini, J., Ebadollahi, A., & Sadeghi, G. R. (2014). *Ocimum basilicum* L. essential oil cultivated in Iran: Chemical composition and antifungal activity against three *Phytophthora* species. *Archives of Phytopathology and Plant Protection*, 47, 1696–1703. <https://doi.org/10.1080/03235408.2013.855022>
- Firman, I. D., & Hoskin, P. (1970). Spraying bananas in Fiji to control black leaf streak disease. *Annals of Applied Biology*, 66, 293–300.
- Flood, J. (2010). The importance of plant health to food security. *Food Security*, 2, 215–231. <https://doi.org/10.1007/s12571-010-0072-5>

- Food and Agriculture Organization of the United Nations. (2024). Integrated pest management. Food and Agriculture Organization of the United Nations (FAO). Retrieved April 23, 2024 from <https://www.fao.org/agriculture/crops/thematic-sitemap/theme/compendium/scpi-practices/integrated-pest-management/en/>. Accessed 24 Apr 2024.
- Foy, C. L. (1993). Progress and developments in adjuvant use. *Pesticide Science*, 38, 65–76.
- Franco, J. C. (2020). Integrated pest management: Sustainable approach to crop protection. In W. Leal Filho, A. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Life on land: Encyclopedia of the UN Sustainable Development Goals*. Cham: Springer. https://doi.org/10.1007/978-3-319-71065-5_84-1
- Gebashe, F. C., Aremu, A. O., & Amoo, S. O. (2022). Therapeutic properties of bioactive secondary metabolites in essential oil crops. In S. Sabiu (Ed.), *Therapeutic use of plant secondary metabolites* (pp. 50–83). Singapore: Bentham Science Publishers Pte. Ltd.
- Ghaleb, H., Alhajlah, H. H., Bin Abdullah, A. A., Kassem, M. A., Al-Sharafi, M. A. (2022). A scientometric analysis and systematic literature review for construction project complexity. *Buildings*, 12. <https://doi.org/10.3390/buildings12040482>
- Ghuffar, S., Irshad, G., Naz, F., Khan, M. A., Ahmed, M. Z., & Gleason, M. L. (2022). Efficacy of plant essential oils against *Alternaria alternata* causing bunch rot of grapes in Pakistan. *Journal of Animal & Plant Sciences*, 32, 150–162. <https://doi.org/10.36899/JAPS.2022.1.0411>
- Golub, K., Tyrkkö, J., Hansson, J., & Ahlström, I. (2020). Subject indexing in humanities: A comparison between a local university repository and an international bibliographic service. *Journal of Documentation*, 76, 1193–1214. <https://doi.org/10.1108/JD-12-2019-0231>
- Gozzo, F. (2003). Systemic acquired resistance in crop protection: From nature to a chemical approach. *Journal of Agricultural and Food Chemistry*, 51, 4487–4503. <https://doi.org/10.1021/jf030025s>
- Green Journal. (2023). 10 Effective strategies for managing pest control operations sustainably. Retrieved on April 22, 2024 from <https://www.greenjournal.co.uk/2023/05/10-effective-strategies-for-managing-pest-control-operations-sustainably/>. Accessed 24 Apr 2023.
- Hagen, N. T. (2008). Harmonic allocation of authorship credit: Source-level correction of bibliometric bias assures accurate publication and citation analysis. *PLoS ONE*, 3, e4021. <https://doi.org/10.1371/journal.pone.0004021>
- Hall, C., Dawson, T. P., Macdiarmid, J. I., Matthews, R. B., & Smith, P. (2017). The impact of population growth and climate change on food security in Africa: Looking ahead to 2050. *International Journal of Agricultural Sustainability*, 15, 124–135. <https://doi.org/10.1080/14735903.2017.1293929>
- Hamadeh, N., Van Rompaey, C., Metreau, E., Eapen, A.G. (2022). New World Bank country classifications by income level: 2022–2023. World Bank Blogs.
- Hassani, A., Fathi, Z., Ghosta, Y., Abdollahi, A., Meshkatal-Sadat, M. H., & Jalili Marandi, R. (2012). Evaluation of plant essential oils for control of postharvest brown and gray mold rots on apricot. *Journal of Food Safety*, 32, 94–101. <https://doi.org/10.1111/j.1745-4565.2011.00353.x>
- Helgesson, G. (2021). The two faces of the corresponding author and the need to separate them. *Learned Publishing*, 34, 679–681. <https://doi.org/10.1002/leap.1385>
- Henkel, T., Brunne, R. M., Müller, H., & Reichel, F. (1999). Statistical investigation into the structural complementarity of natural products and synthetic compounds. *Angewandte Chemie International Edition*, 38, 643–646.
- Hollis, L. (2022). The global burden of crop loss: Evidence-based systems to tackle food security. Commonwealth Agricultural Bureaux International (CABI) Blog. Retrieved April 20, 2024 from <https://blog.cabi.org/2022/10/11/the-global-burden-of-crop-loss-evidence-based-systems-to-tackle-food-security/>.
- Hu, Z., Wang, Z., Liu, Y., & Wang, Q. (2018). Leveraging botanical resources for crop protection: The isolation, bioactivity and structure-activity relationships of Lycoris alkaloids. *Pest Management Science*, 74, 2783–2792. <https://doi.org/10.1002/ps.5065>
- Hua, L., Yong, C., Zhanguan, Z., Boqqiang, L., Guozheng, Q., & Shipping, T. (2018). Pathogenic mechanisms and control strategies of *Botrytis cinerea* causing post-harvest decay in fruits and vegetables. *Food Quality and Safety*, 2, 111–119. <https://doi.org/10.1093/fqsafefy016>
- Ingham, J. L. (1972). Phytoalexins and other natural products as factors in plant disease resistance. *Botanical Review*, 38, 343–424. <https://doi.org/10.1007/BF02860009>
- Isman, M. B., Miresmailli, S., & Machial, C. (2011). Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products. *Phytochemistry Reviews*, 10, 197–204. <https://doi.org/10.1007/s11101-010-9170-4>
- Jespers, A. B. K., & Waard, M. A. D. (1993). Natural products in plant protection. *Netherlands Journal of Plant Pathology*, 99, 109–117.
- Jourand, P., Rapior, S., Fargette, M., & Mateille, T. (2004). Nematostatic effects of a leaf extract from *Crotalaria virgulata* subsp. *grantiana* on *Meloidogyne incognita* and its use to protect tomato roots. *Nematology*, 6, 79–84. <https://doi.org/10.1163/156854104323072955>
- Kahramanoğlu, İ., Panfilova, O., Kesimci, T. G., Bozhüyük, A. U., Gürbüz, R., & Alptekin, H. (2022). Control of postharvest gray mold at strawberry fruits caused by *Botrytis cinerea* and improving fruit storability through *Origanum onites* L. and *Ziziphora clinopodioides* L. volatile essential oils. *Agronomy*, 12, 389. <https://doi.org/10.3390/agronomy12020389>
- Kastrin, A., & Hristovski, D. (2021). Scientometric analysis and knowledge mapping of literature-based discovery (1986–2020). *Scientometrics*, 126, 1415–1451. <https://doi.org/10.1007/s11192-020-03811-z>
- Katz, L., & Baltz, R. H. (2016). Natural product discovery: Past, present, and future. *Journal of Industrial Microbiology and Biotechnology*, 43, 155–176. <https://doi.org/10.1007/s10295-015-1723-5>
- Kenyon, L., Kumar, S., Tsai, W. S., & Hughes, Jd. A. (2014). Virus diseases of peppers (*Capsicum* spp.) and their control. *Advances in Virus Research*, 90, 297–354. <https://doi.org/10.1016/B978-0-12-801246-8.00006-8>

- Khorram, F., & Ramezani, A. (2020). Cinnamon essential oil incorporated in shellac, a novel bio-product to maintain quality of 'Thomson navel' orange fruit. *Journal of Food Science and Technology*, 58, 2963–2972. <https://doi.org/10.1007/s13197-020-04798-4>
- Kiran, S. R., Devi, P. S., & Reddy, K. J. (2007). Bioactivity of essential oils and sesquiterpenes of *Chloroxylon swietenia* DC against *Helicoverpa armigera*. *Current Science*, 93, 544–548.
- Kleminski, R., Kazienko, P., & Kajdanowicz, T. (2020). Analysis of direct citation, co-citation and bibliographic coupling in scientific topic identification. *Journal of the Association for Information Science and Technology*, 48, 349–373. <https://doi.org/10.1177/0165551520962775>
- Kokol, P., Blažun Vošner, H., & Završnik, J. (2021). Application of bibliometrics in medicine: A historical bibliometrics analysis. *Health Information and Libraries Journal*, 38, 125–138. <https://doi.org/10.1111/hir.12295>
- Korsten, L. (2004). Biological control in Africa: Can it provide a sustainable solution for control of fruit diseases? *South African Journal of Botany*, 70, 128–139.
- Krenz, B., Niehl, A., & Büttner, C. (2024). Charting the course of plant virology: Innovations in diagnostics and beyond—reports from the DPG meeting. *Journal of Plant Diseases and Protection*, 131, 1–7. <https://doi.org/10.1007/s41348-023-00818-5>
- Liu, R. L., & Hsu, C. K. (2019). Improving bibliographic coupling with category-based cocitation. *Applied Sciences*, 9, 5176. <https://doi.org/10.3390/app9235176>
- López-Pernas, S., Saqr, M., & Apiola, M. (2023). Scientometrics: A concise introduction and a detailed methodology for mapping the scientific field of computing education research. In M. Apiola, S. López-Pernas, & M. Saqr (Eds.), *Past, present and future of computing education research*. Cham: Springer. https://doi.org/10.1007/978-3-031-25336-2_5
- Lozano, S., Calzada-Infante, L., Adenso-Díaz, B., & García, S. (2019). Complex network analysis of keywords co-occurrence in the recent efficiency analysis literature. *Scientometrics*, 120, 609–629. <https://doi.org/10.1007/s11192-019-03132-w>
- Mahmoud, G. A. (2016). The efficiency of using some medicinal and aromatic plant extracts on keeping quality and resists postharvest diseases of apple. *International Journal of ChemTech Research*, 9, 178–187.
- Manoj Kumar, L., George, R. J., & Anisha, P. S. (2023). Bibliometric analysis for medical research. *Indian Journal of Psychological Medicine*, 45, 277–282. <https://doi.org/10.1177/02537176221103617>
- Marpudi, S. L., Abirami, L. S. S., Pushkala, R., & Srividya, N. (2011). Enhancement of storage life and quality maintenance of papaya fruits using *Aloe vera*-based antimicrobial coating. *Indian Journal of Biotechnology*, 10, 83–89.
- Mekbib, S. B., Regnier, T. J. C., Sivakumar, D., & Korsten, L. (2009). Evaluation of Ethiopian plant extracts, *Acacia seyal* and *Withania somnifera*, to control green mould and ensure quality maintenance of citrus (*Citrus sinensis* L.). *Fruits*, 64, 13.
- Mohammadi, S., Aroiee, H., Aminifard, M. H., Tehranifar, A., & Jahanbakhsh, V. (2013). Effect of fungicidal essential oils against *Botrytis cinerea* and *Rhizopus stolonifer* rot fungus *in vitro* conditions. *Archives of Phytopathology and Plant Protection*, 47, 1603–1610. <https://doi.org/10.1080/03235408.2013.853456>
- Mohammadi, A., Hashemi, M., & Hosseini, S. M. (2015). Nanoencapsulation of *Zataria multiflora* essential oil preparation and characterization with enhanced antifungal activity for controlling *Botrytis cinerea*, the causal agent of gray mould disease. *Innovative Food Science and Emerging Technologies*, 28, 73–80. <https://doi.org/10.1016/j.ifset.2014.12.011>
- Morais, W. C. C., Lima, M. A. P., Zanuncio, J. C., Oliveira, M. A., Braganca, M. A. L., Serrão, J. E., & Lucia, T. M. C. D. (2015). Extracts of *Ageratum conyzoides*, *Coriandrum sativum* and *Mentha piperita* inhibit the growth of the symbiotic fungus of leaf-cutting ants. *Industrial Crops and Products*, 65, 463–466. <https://doi.org/10.1016/j.indcrop.2014.10.054>
- Mpho, M., Sivakumar, D., Sellamuthu, P. S., & Bautista-Baños, S. (2013). Use of lemongrass oil and modified atmosphere packaging on control of anthracnose and quality maintenance in avocado cultivars. *Journal of Food Quality*, 36, 198–208. <https://doi.org/10.1111/jfq.12027>
- Mutz, R., & Daniel, H. (2019). How to consider fractional counting and field normalization in the statistical modeling of bibliometric data: A multilevel Poisson regression approach. *Journal of Informetrics*, 13, 643–657. <https://doi.org/10.1016/j.joi.2019.03.007>
- Mwinga, J. L., Otang-Mbeng, W., Kubheka, B. P., & Aremu, A. O. (2023). An appraisal on the ethnobotany and antimicrobial activity of botanicals used for managing plant diseases in South Africa. *Crop Protection*, 174, 106423. <https://doi.org/10.1016/j.cropro.2023.106423>
- Nchu, F. (2024). Sustainable biological control of pests: The way forward. *Applied Sciences*, 14, Article 2669. <https://doi.org/10.3390/app14072669>
- Niño, J., Correa, Y. M., & Mosquera, O. M. (2011). *In vitro* evaluation of Colombian plant extracts against Black Sigatoka (*Mycosphaerella fijiensis* Morelet). *Archives of Phytopathology and Plant Protection*, 44, 791–803. <https://doi.org/10.1080/03235401003672939>
- Nxumalo, K. A., Aremu, A. O., & Fawole, O. A. (2021). Potentials of medicinal plant extracts as an alternative to synthetic chemicals in postharvest protection and preservation of horticultural crops: A review. *Sustainability*, 13, 5897.
- Ogunnupebi, T. A., Oluyori, A. P., Dada, A. O., Oladeji, O. S., Inyinbor, A. A., & Egharevba, G. O. (2020). Promising natural products in crop protection and food preservation: Basis, advances, and future prospects. *International Journal of Agronomy*, 2020, 8840046. <https://doi.org/10.1155/2020/8840046>
- Ogunsola, J. F., & Ogunsola, K. E. (2023). Antifungal activity of *Phyllanthus amarus*, *Passiflora foetida* and *Costus afer* against *Colletotrichum* species causing leaf blight on *Citrullus lanatus* (Egusi melon). *Journal of Plant Diseases and Protection*, 130, 301–313. <https://doi.org/10.1007/s41348-022-00690-9>
- Olson, S. (2015). An analysis of the biopesticide market now and where it is going. *Outlooks on Pest Management*, 26, 203–206. https://doi.org/10.1564/v26_oct_04

- Oyewola, D. O., Dada, E. G. (2022). Exploring machine learning: A scientometrics approach using bibliometrix and VOSviewer. *SN Applied Sciences*, 4. <https://doi.org/10.1007/s42452-022-05027-7>
- Palou, L., Valencia-Chamorro, S. A., & Pérez-Gago, M. B. (2015). Antifungal edible coatings for fresh citrus fruit: A review. *Coatings*, 5, 962–986. <https://doi.org/10.3390/coatings5040962>
- Pérez-Izquierdo, C., Serrano-Pérez, P., & Rodríguez-Molina, M. C. (2022). Chemical composition, antifungal and phytotoxic activities of *Cistus ladanifer* L. essential oil and hydrolate. *Biocatalysis and Agricultural Biotechnology*, 45, 102527. <https://doi.org/10.1016/j.cbac.2022.102527>
- Pilkington, L. I. (2022). Towards the use of natural compounds for crop protection and food safety. *Foods*, 11, 648.
- Purkait, A., Biswas, S., Saha, S., Hazra, D. K., Roy, K., Biswas, P. K., Ghosh, S. K., & Kole, R. K. (2019). Formulation of plant based insecticides, their bio-efficacy evaluation and chemical characterization. *Crop Protection*, 125, 104907. <https://doi.org/10.1016/j.cropro.2019.104907>
- Ramezani, A., Azadi, M., Mostowfizadeh-Ghalamfarsa, R., & Saharkhiz, M. J. (2016). Effect of *Zataria multiflora* Boiss and *Thymus vulgaris* L. essential oils on black rot of 'Washington Navel' orange fruit. *Postharvest Biology and Technology*, 112, 152–158. <https://doi.org/10.1016/j.postharvbio.2015.10.011>
- Raveau, R., Fontaine, J., Soltani, A., Mediouni Ben Jemâa, J., Laruelle, F., & Lounès-Hadj Sahraoui, A. (2022). *In vitro* potential of clary sage and coriander essential oils as crop protection and post-harvest decay control products. *Foods*, 11, 312. <https://doi.org/10.3390/foods11030312>
- Rehman, M. A., Ali, S., Khan, M. N., Ahmad, S., & Ali, M. A. (2020). Comparative efficacy of different antibiotics, fungicides and botanical extract for the control of citrus canker of kinnow mandarin. *Pakistan Journal of Phytopathology*, 32, 113–119. <https://doi.org/10.33866/phytopathol.030.02.0573>
- Rizzo, D. M., Lichtveld, M., Mazet, J. A. K., Togami, E., & Miller, S. A. (2021). Plant health and its effects on food safety and security in a One Health framework: Four case studies. *One Health Outlook*, 3, 6. <https://doi.org/10.1186/s42522-021-00038-7>
- Russell, P. E. (2005). A century of fungicide evolution. *Journal of Agricultural Science*, 143, 11–25. <https://doi.org/10.1017/S0021859605004971>
- Sabe, M., Chen, C., Perez, N., Solmi, M., Mucci, A., Galderisi, S., Strauss, G. P., & Kaiser, S. (2023). Thirty years of research on negative symptoms of schizophrenia: A Scientometric analysis of hotspots, bursts, and research trends. *Neuroscience and Biobehavioral Reviews*, 144, 104979. <https://doi.org/10.1016/j.neubiorev.2022.104979>
- Sadhasivam, S., Shapiro, O. H., Ziv, C., Barda, O., Zakin, V., & Sionov, E. (2019). Synergistic inhibition of mycotoxigenic fungi and mycotoxin production by combination of pomegranate peel extract and azole fungicide. *Frontiers in Microbiology*, 10, 1919. <https://doi.org/10.3389/fmicb.2019.01919>
- Santino, A., Poltronieri, P., & Mita, G. (2005). Advances on plant products with potential to control toxigenic fungi: A review. *Food Additives and Contaminants*, 22, 389–395. <https://doi.org/10.1080/02652030500058429>
- Schäfermeier, B., Hirth, J., & Hanika, T. (2023). Research topic flows in co-authorship networks. *Scientometrics*, 128, 5051–5078. <https://doi.org/10.1007/s11192-022-04529-w>
- Sekhon, B. (2014). Nanotechnology in agri-food production: An overview. *Nanotechnology, Science and Applications*, 7, 31–53.
- Sellamuthu, P. S., Mafune, M., Sivakumar, D., & Soundy, P. (2013). Thyme oil vapour and modified atmosphere packaging reduce anthracnose incidence and maintain fruit quality in avocado. *Journal of the Science of Food and Agriculture*, 93, 3024–3031. <https://doi.org/10.1002/jsfa.6135>
- Sganzerla, W. G., Ampese, L. C., Mussatto, S. I., & Forster-Carneiro, T. (2021). A bibliometric analysis on potential uses of brewer's spent grains in a biorefinery for the circular economy transition of the beer industry. *Biofuels, Bioproducts and Biorefining*, 15, 1965–1988. <https://doi.org/10.1002/bbb.2290>
- Sivakumar, D., & Bautista-Baños, S. (2014). A review on the use of essential oils for postharvest decay control and maintenance of fruit quality during storage. *Crop Protection*, 64, 27–37. <https://doi.org/10.1016/j.cropro.2014.05.012>
- Sivertsen, G., Rousseau, R., & Zhang, L. (2019). Measuring scientific contributions with modified fractional counting. *Journal of Informetrics*, 13, 679–694. <https://doi.org/10.1016/j.joi.2019.03.010>
- Soto, M. (2017). *APA PsycInfo expert tip: Searching by keyword, index term and more*. Washington, DC: American Psychological Association (APA) Publishing Blog. <https://blog.apapubs.org/2017/01/19/psycinfo-expert-tip-searching-by-keyword-index-term-and-more/>. Accessed 7 Nov 2023
- Stetter, J., & Lieb, F. (2000). Innovation in crop protection: Trends in research. *Angewandte Chemie International Edition*, 39, 1724–1744.
- Sturz, A. V., Lynch, D. H., Martin, R. C., & Driscoll, A. M. (2006). Influence of compost tea, powdered kelp, and Manzate® 75 on bacterial-community composition, and antibiosis against *Phytophthora infestans* in the potato phylloplane. *Canadian Journal of Plant Pathology*, 28, 52–62.
- Sukorini, H., Sangchotek, S., & Khewkhom, N. (2013). Control of postharvest green mold of citrus fruit with yeasts, medicinal plants, and their combination. *Postharvest Biology and Technology*, 79, 24–31. <https://doi.org/10.1016/j.postharvbio.2013.01.001>
- Sumalan, R. M., Kuganov, R., Obistoiu, D., Popescu, I., Radulov, I., Alexa, E., Negrea, M., Salimzoda, A. F., Sumalan, R. L., & Cocan, I. (2020). Assessment of mint, basil, and lavender essential oil vapor-phase in antifungal protection and lemon fruit quality. *Molecules*, 25, 1831. <https://doi.org/10.3390/molecules25081831>
- Sundling, P. (2023). Author contributions and allocation of authorship credit: Testing the validity of different counting methods in the field of chemical biology. *Scientometrics*, 128, 2737–2762. <https://doi.org/10.1007/s11192-023-04680-y>

- Szomszor, M., Adams, J., Fry, R., Gebert, C., Pendlebury, D. A., Potter, R. W. K., & Rogers, G. (2021). Interpreting bibliometric data. *Frontiers in Research Metrics and Analytics*, 5, 628703. <https://doi.org/10.3389/frma.2020.628703>
- Tan, L. P. (2022). Bibliometrics of social entrepreneurship research: Cocitation and bibliographic coupling analyses. *Cogent Business & Management*, 9, 2124594. <https://doi.org/10.1080/23311975.2022.2124594>
- Tatineni, S., & Hein, G. L. (2023). Plant viruses of agricultural importance: Current and future perspectives of virus disease management strategies. *Phytopathology*, 113, 117–141. <https://doi.org/10.1094/PHYTO-05-22-0167-RVW>
- Tembo, Y., Mkindi, A. G., Mkenda, P. A., Mpumi, N., Mwanauta, R., Stevenson, P. C., Ndakidemi, P. A., & Belmain, S. R. (2018). Pesticidal plant extracts improve yield and reduce insect pests on legume crops without harming beneficial arthropods. *Frontiers in Plant Science*, 9, 1425. <https://doi.org/10.3389/fpls.2018.01425>
- Thind, T. S. (2021). Changing trends in discovery of new fungicides: A perspective. *Indian Phytopathology*, 74, 875–883. <https://doi.org/10.1007/s42360-021-00411-6>
- United Nations. (2024). Food security and nutrition and sustainable agriculture (Sustainable Development Goals, Issue. <https://sdgs.un.org/topics/food-security-and-nutrition-and-sustainable-agriculture>. Accessed 24 Apr 2024.
- Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84, 523–538. <https://doi.org/10.1007/S11192-009-0146-3>
- Vargas, A. C., Espinoza-Mina, M., Alvarez, D. L., Espinosa, J. N. (2022). Bibliometric software: The most commonly used in research. In: ICAIW 2022: Workshops at the 5th International Conference on Applied Informatics, Arequipa, Peru. CEUR Workshop Proceedings (CEUR-WS.org).
- Willet, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., ... Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393, 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Williams, W. (1985). Cereal production, crop protection and plant breeding. *Annals of Applied Biology*, 106, 133–141.
- Yan, J., Wu, H., Chen, K., Feng, J., & Zhang, Y. (2021). Anti-fungal activities and mode of action of *Cymbopogon citratus*, *Thymus vulgaris*, and *Origanum heracleoticum* essential oil vapors against *Botrytis cinerea* and their potential application to control postharvest strawberry gray mold. *Foods*, 10, 2451. <https://doi.org/10.3390/foods10102451>
- Yanpirat, P., & Vajrodanya, S. (2015). Antifungal activity of *Persicaria odorata* extract against anthracnose caused by *Colletotrichum capsici* and *Colletotrichum gloeosporioides*. *Malaysian Applied Biology*, 44, 69–73.
- Zhou, J., Song, D., Ma, J., Zhang, G., Wu, C., Chen, Q., & Zeng, L. (2023). Research trends in the mental health and multimorbidity of older people from 2002 to 2022: A bibliometric analysis via CiteSpace. *Frontiers in Psychiatry*, 14, 1117554. <https://doi.org/10.3389/fpsy.2023.1117554>



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Plants as an alternative to the use of chemicals for crop protection against biotic threats: trends and future perspectives

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