

MAPPING THE LANDSCAPE OF VARROA MITE RESEARCH: A BIBLIOMETRIC ANALYSIS OF TECHNIQUES AND TRENDS

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Abstract. This paper builds on our previous work by conducting a comprehensive bibliometric analysis of Varroa mite research, addressing one of the most critical challenges in apiculture. Leveraging datasets and tools presented in our earlier conference paper, this study maps research trends, collaboration networks, and technological advancements in Varroa mite management. Through an in-depth exploration of co-authorship patterns, keyword co-occurrence, and bibliographic coupling, the analysis uncovers the field’s intellectual structure and collaborative landscape. Key findings highlight dominant themes such as chemical control methods, biological interventions, and the integration of advanced technologies like Artificial Intelligence (AI) and Internet of Things (IoT) for precise hive monitoring. The analysis also identifies emerging research regions and underrepresented countries, highlighting gaps in global collaboration and the need for a more inclusive research agenda. Furthermore, it underscores the ecological and economic urgency of combating Varroa infestations, especially in light of climate change, pollution, and habitat degradation. As a major conclusion, we propose the development of a new dataset with specific characteristics designed to enhance the detection and prediction of Varroa infestations. This dataset would support more precise monitoring through advanced AI models, enabling proactive and sustainable control strategies. By offering a roadmap for integrating innovative technologies into apicultural practices, this study contributes to safeguarding pollinators, preserving biodiversity, and ensuring global food security.

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1. INTRODUCTION

Building on our prior work on datasets for precision apiculture [1], this study focuses on Varroa mite research as a critical and timely domain in apicultural science. As one of the most damaging parasites that affect honey bee colonies worldwide, *Varroa destructor* represents a major threat to pollinator health and, by extension, agricultural productivity [2–5]. As pollinator populations continue to decline due to climate change, pesticide

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use, and habitat loss, managing Varroa mite infestations has become a pressing scientific and ecological priority, directly aligned with sustainability frameworks such as the One Health approach and agroecological resilience theory. This imperative is further amplified by the lack of standardized, high-quality datasets, which severely limits the comparability of research efforts and the development of robust AI-based detection systems. This study aims to conduct the first comprehensive bibliometric analysis dedicated to Varroa mite research, to identify collaboration networks, thematic trends, and technological intersections that can inform future research directions and support the development of standardized, multimodal datasets for precision apiculture.

This analytical survey systematically maps the intellectual landscape of Varroa mite research, identifying collaboration networks, thematic hotspots, and emerging trends to support more informed, regenerative decision-making in apiculture practices. Using Scopus-indexed literature and advanced bibliometric tools such as VOSviewer [6], the study traces the evolution of scholarly discourse around Varroa mite management, highlighting key contributors, research clusters, and collaboration patterns that shape the field. The analysis is grounded in ecological resilience thinking [7] and sustainability science [8], emphasizing the urgent need for integrative solutions that enhance both environmental health and agricultural viability. We highlight the growing use of Artificial Intelligence (AI) and Internet of Things (IoT) in this field, reflecting a broader shift toward precision agriculture and digital monitoring of ecosystems [1].

Our goal is to provide both a strategic overview of the current research ecosystem and a forward-looking perspective that supports adaptive management practices. The findings aim to serve as a roadmap for scholars, policymakers, and practitioners, highlighting collaboration gaps, underexplored regions, and opportunities for interdisciplinary innovation. In doing so, we position Varroa mite management not merely as a technical challenge but as a key node within larger systems of agroecological sustainability.

Bibliometric studies have been instrumental in tracking research trends, collaboration networks, and thematic evolution across fields, including apiculture. However, most prior efforts have centred on broader topics such as pollination efficiency, pesticide toxicity, or pollinator decline, with limited focus on pest-specific threats like *Varroa destructor*. Global analyses on pollinator decline [9–11] and bibliometric studies of pesticide research [12–14] provide essential context but often overlook the persistent impact of Varroa mites on colony collapse and ecosystem health.

This study addresses that gap by offering the first dedicated scientometric review of Varroa mite research. To our knowledge, this is the first bibliometric study to focus exclusively on Varroa mite literature, bridging technological innovation and ecological resilience frameworks in apiculture. We examine thematic co-occurrence, institutional collaboration, and citation networks, offering actionable insights for targeting future funding, building research partnerships, and guiding eco-friendly innovation. Beyond identifying dominant thematic clusters, the analysis highlights regional contributions, reveals cross-disciplinary intersections, and pinpoints actors driving innovation in Varroa mite management. This focus on AI and IoT places our research within the wider context of digital sustainability and adaptive ecosystem governance [15, 16].

Ultimately, this paper contributes to the literature by offering a strategic, evidence-based foundation for advancing sustainable and resilient Varroa control through integrated technological and ecological frameworks. The paper is organized as follows: Section 2 describes the methodology, detailing the research design, dataset selection, and analytical framework used for research profiling. Section 3 discusses the findings, including thematic trends, collaboration networks, and technological advances in Varroa mite research. Section 4 highlights the study’s limitations and identifies potential areas for future research, emphasizing the need for standardized, multimodal datasets. Finally, Section 5 presents the conclusion, summarizing the study’s contributions and outlining a roadmap for integrating AI and IoT into apicultural practices to improve Varroa mite management strategies.

2. METHODOLOGY

This section describes the structured process employed to map the Varroa mite research landscape, beginning with data resource construction and filtering strategies and continuing through data preparation and network

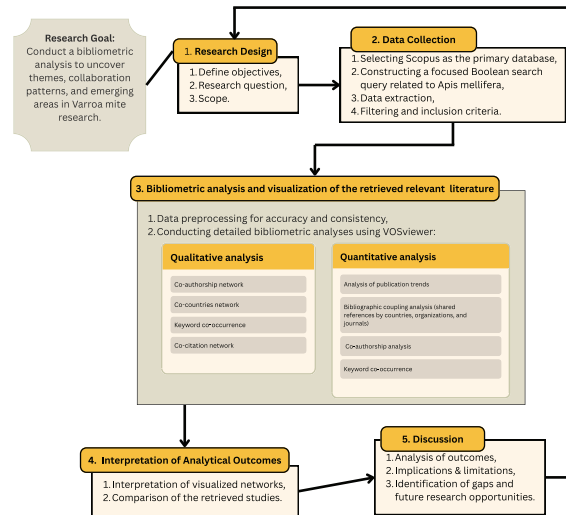


FIGURE 1. Comprehensive research workflow for bibliometric analysis of Varroa mite literature.

visualization. The goal is to ensure a transparent, replicable, and meaningful bibliometric analysis tailored to a high-impact ecological problem.

2.1. Research design and objectives

This study adopts a multi-step bibliometric framework to systematically uncover the structure, dynamics, and technological intersections within Varroa mite research. Specifically, the objectives are to identify dominant themes, cooperative structures, and emerging research areas [17], providing actionable insights and strategic guidance for future studies and policy decisions. By focusing on a combination of co-occurrence, co-authorship, and bibliographic analysis, the methodology allows for a multidimensional understanding of the field, enabling critical gaps. The research was carried out in five major stages, following the workflow depicted in Figure 1: (1) establishing the goals, research questions, and scope; (2) choosing the Scopus database and developing a targeted Boolean search strategy for *Apis mellifera* and *Varroa destructor*; (3) extracting, cleaning, and filtering the data; (4) using VOSviewer¹ to perform literature mapping and visualization; and (5) analysing the analytical results to find research trends, networks of collaboration, and technological intersections. To guarantee a thorough grasp of the research ecosystem, both qualitative (such as keyword co-occurrence and bibliographic coupling) and quantitative (such as publication trends and citation metrics) assessments were carried out. This workflow offers a replicable blueprint for future scientometric reviews in apiculture and beyond, encouraging standardized methodologies that enhance comparability across pest management studies.

2.2. Database selection and search strategy

Scopus was selected as the primary data source for this bibliometric study based on its extensive coverage of robust peer-reviewed literature, standardized metadata infrastructure. Its indexing policies ensure the inclusion of high-quality sources across a wide range of disciplines, including agricultural, environmental, and technological domains [18–21]. Compared to other widely used databases, such as Web of Science (WoS) and Dimensions.ai,² Scopus offers a more comprehensive, methodologically convenient, and technically compatible environment for bibliometric mapping and analysis.

¹ <https://www.vosviewer.com/>.

² <https://www.dimensions.ai/>.

TABLE 1. Comparison of key features across bibliometric databases for conducting an analytical survey.

Feature	Scopus	Web of Science	Dimensions.ai
Journal coverage	Extensive; multi-disciplinary coverage; indexes over 25 000 active titles [22]	Comprehensive but selective; indexes approximately 21 000 journals across various disciplines [23, 24]	Broad; integrates multiple publication types, over 140 million publications, 82.22% more journals than WoS, and 48.17% more than Scopus [25, 26]
Data and metadata quality	High; standardized and comprehensive [21]	High; rigorous indexing standards [23]	Variable; standardized yet less controlled [27]
Bibliometric indicators	Extensive [19]	Traditional indicators [28]	Lacks some traditional indicators but includes rich citation analytics and altmetrics [25]
Compatibility with software (<i>e.g.</i> , VOSviewer)	Excellent [6]	Excellent [6]	Good but requires preprocessing [25]
Ease of data extraction	User-friendly; CSV and RIS formats [21]	Moderate; exports in multiple formats (<i>e.g.</i> , RIS, Excel) [23]	User-friendly; extensive export options [25]
Interdisciplinary research support	Excellent; broad disciplinary span [21]	Good; strong in science and engineering disciplines [24]	Excellent; interdisciplinary and open-access publications [27]
Data accessibility	Subscription-based [19]	Subscription-based [23]	Partially open-access; subscription for advanced analytics [25]
Citation analysis reliability	High; well-established citation database [21]	High; authoritative citation indexing [23]	Good; newer but rapidly evolving database [27]

As presented in Table 1, Scopus indexes over 25 000 journals and provides rich bibliographic data [22], including titles, abstracts, keywords, authorship information, affiliations, and cited references. These elements are crucial for constructing reproducible co-authorship, co-citation, and keyword co-occurrence networks. Additionally, Scopus supports the direct export of large information sets in standardized formats, which facilitates integration with bibliometric software such as VOSviewer and Bibliometrix.

By contrast, although authoritative and long-established WoS is more selective in scope, indexing approximately 21 000 journals [23]. It emphasizes high-impact sources and delivers reliable metrics such as the Journal Impact Factor (JIF) and Eigenfactor (EF) Score. However, its narrower coverage and restrictive export limits can hinder large-scale or interdisciplinary bibliometric investigations. Dimensions.ai, on the other hand, offers the broadest coverage with over 140 million records and includes modern, article-level metrics such as the Field-Weighted Citation Impact (FWCI) and Altmetric Attention Scores [25, 27]. While suitable for real-time analytics and societal impact assessments, Dimensions lacks traditional journal indicators (*e.g.*, JIF, SCImago Journal Rank (SJR), Source-Normalized Impact per Paper (SNIP)) and requires preprocessing to ensure compatibility with standard scientometric tools.

Figure 2 illustrates the distribution of key citation metrics across the three databases. Notably, Scopus supports all major indicators required for both traditional and contemporary research evaluation, including CiteScore, SJR, SNIP, citation counts, and h-index. This balanced availability of diverse metrics enhances both the breadth and depth of analysis.

These considerations justify the selection of Scopus as the most appropriate database for this bibliometric investigation. Its comprehensive multidisciplinary coverage, availability of both classical and advanced citation

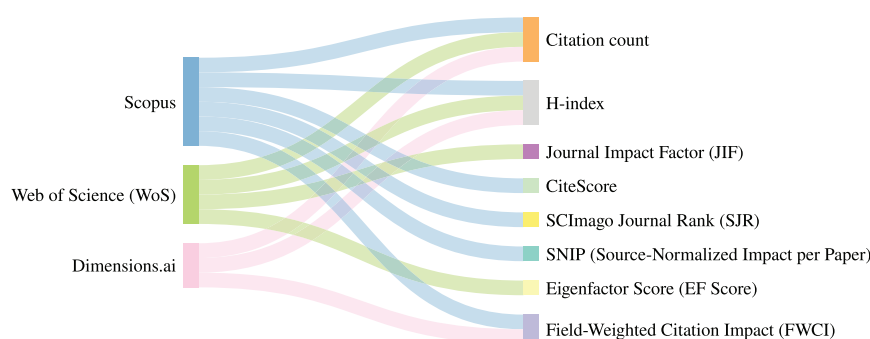


FIGURE 2. Comparative diagram of key citation metrics' availability across Scopus, Web of Science (WoS), and Dimensions.ai.

indicators, and strong interoperability with analytic tools provide the methodological rigor and analytical flexibility required to address the study's objectives. Nonetheless, it is important to acknowledge that Scopus does not index all scientific journals, particularly some regionally focused or non-English publications, which may limit the completeness and diversity of the dataset.

2.2.1. Search query definition

A well-constructed search query helps narrow the focus to the most relevant scientific literature, improving both the efficiency and accuracy of the information gathering process, and ensuring the retrieval of relevant publications while minimizing irrelevant records. This approach facilitates a robust foundation for subsequent bibliometric analyses.

Keywords selection: Defining an effective search query involves selecting precise keywords related to the biology, impact, and control of Varroa mites, and aligning with the multifaceted nature of the research field, incorporating studies on practical interventions, technological advancements, and theoretical approaches. As depicted in Figure 3, keywords were selected based on their direct relevance to the core topic of *Varroa destructor* involving *Apis mellifera*, the most economically significant and widely studied honey bee species in apiculture research. The term "Varroa destructor" OR "Varroa mite" captures the primary focus of the study, the parasitic mite itself, ensuring comprehensive coverage of studies explicitly addressing this species. Including keywords closely associated with "control" and "management" practices is motivated by the need to encompass diverse approaches to addressing Varroa mite infestations, from traditional methods like chemical treatments to modern strategies such as AI-based monitoring. This taxonomy of keywords can inform future data collection frameworks and support the development of domain-specific ontologies for automated literature classification in the field.

Constructing the search query: A targeted query was carefully conceived, combining the selected keywords strategically using "Boolean operators" to balance specificity and inclusivity, ensuring the search encompasses all relevant literature and reflecting both the biological and technical aspects of Varroa mite research. The **AND** operator is used to refine the search, ensuring that the retrieved documents covered critical aspects of the research area, such as Varroa mite control, monitoring, and management techniques. This operator narrows the scope to target publications directly addressing the topic of interest. Conversely, the **OR** operator is utilized to broaden the search by incorporating synonyms and closely related terms. This expanded the query to include a wider range of documents, capturing diverse perspectives and approaches within the field.

Providing broad insights into the research landscape, we conducted a search based on the following search query:

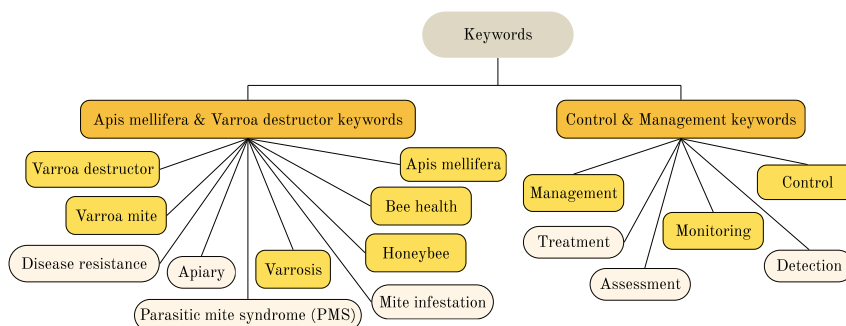


FIGURE 3. Conceptual keyword taxonomy underpinning the bibliometric search strategy of Varroa destructor research.

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(TITLE-ABS-KEY("Varroa destructor" OR "Varroa mite" OR "Disease resistance" OR "Varroasis" OR "Varroa" OR "Mite infestation" OR "Parasitic mite syndrome" OR "Bee health") AND ("Apis mellifera" OR "Honeybee" OR "Apiary") AND ("Control" OR "Management" OR "Monitoring" OR "Treatment" OR "Assessment" OR "Detection"))

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Selecting broad yet focused terms, the query ensures that the knowledge base includes relevant literature across various disciplines, including agriculture, biology, environmental science, and computer science. This multidisciplinary approach enhances the robustness of the bibliometric analysis, allowing for a comprehensive mapping of the research landscape.

2.2.2. Data extraction

The bibliographic data were exported from Scopus in Comma-Separated Values (CSV) format, ensuring compatibility with VOSviewer for analysis and visualization. Key fields included authors, affiliations, publication year, title, abstract, keywords, and references.

2.2.3. Filtering and inclusion criteria

Retrieving relevant literature is a crucial step in literature mapping to ensure that the study is based on comprehensive and pertinent data. As previously stated, the search was carried out using the aforementioned query string in Scopus.³ The initial search yielded 1995 papers, showing the increasing interest in Varroa mite investigations on *Apis mellifera* species throughout time and pointing to a significant amount of research.

It is crucial to employ certain filters to guarantee a targeted and pertinent evaluation of the literature. The structured data is refined through this filtering procedure to directly address the goals and research issues, increasing the analysis's applicability. The database search is conducted utilizing the following filters:

Date range: We focused on the last 20 years (from 2004 to 2024) to capture a broad range of developments and emerging trends in Varroa mite research. This extended time frame allows for an in-depth exploration of how the field has evolved, particularly in response to the growing global awareness of environmental challenges. The number of selected papers after applying the date range filter has diminished from 1995 to 1677 papers.

In recent years, factors such as climate change, pollution, habitat loss, and the increasing use of agrochemicals have had profound effects on bee health. These stressors exacerbate the impact of Varroa mites on honey bee populations, making them more susceptible to diseases and colony collapse [29]. Since honey bees, especially *Apis mellifera*, play a crucial role as pollinators in maintaining biodiversity and supporting global food production, their decline has far-reaching consequences for ecosystems and agricultural sustainability. This

³ <https://www.scopus.com/>.

has spurred significant interest among researchers to develop innovative solutions for mitigating the effects of Varroa mites and safeguarding bee health [16, 30–34]. The increasing urgency to address these challenges is reflected in the surge of publications on the topic in recent years, underscoring the critical importance of this field of study for environmental and ecological stability.

Document type: We limited the selection to peer-reviewed journal articles and conference proceedings to ensure high-quality and reliable sources. Peer-reviewed journals provide rigorous research evaluations, guaranteeing the credibility and robustness of the studies included. Conference proceedings, on the other hand, often feature cutting-edge findings and innovative approaches that are not yet available in journal publications. By focusing on these two document types, we ensure that the dataset comprises comprehensive and authoritative contributions to the field while capturing the latest advancements and emerging ideas in Varroa mite research. After applying the document type filter, the number of selected papers decreased from 1677 to 1655.

Research themes: The selected research themes focused on addressing the multifaceted challenges posed by Varroa mites, particularly in the context of their impact on honey bee populations and ecosystems. These themes encompassed a wide range of topics, including biological and chemical control methods, monitoring techniques, the role of environmental stressors, and emerging technologies such as AI and IoT for hive management. By capturing these diverse areas, the analysis aimed to provide a holistic understanding of current advancements, identify gaps in knowledge, and explore potential interdisciplinary solutions to enhance bee health and mitigate environmental risks. Applying this filter reduced search results to 1411 papers.

Languages: To assure access to a variety of research data and to keep the study manageable, we focused on evaluating English-language publications. English serves as the predominant language in scientific discourse, including high-impact and widely cited works. Limiting the study to English also facilitates the consistent evaluation of findings and avoids challenges associated with language-specific terminologies and translations.

Geographic constraints: The search was designed to include global contributions without imposing geographic restrictions. This approach allowed for a comprehensive analysis of Varroa mite research conducted across different regions, capturing variations in research priorities, environmental conditions, and collaborative networks. The global scope includes region-specific insights while highlighting international efforts to address this pressing issue.

The filtering process refined the data resource to include only 1352 documents meeting these criteria, ensuring relevance to the study objectives and enhancing the reliability of the analysis. By applying stringent filters such as date range, document type, and language, the dataset was tailored to align closely with the research focus on Varroa mite management and its implications. This systematic approach not only eliminated irrelevant or low-quality sources but also concentrated on studies that contribute significantly to understanding and addressing the challenges posed by Varroa mites. Consequently, the refined knowledge base provides a robust foundation for uncovering key insights, trends, and collaborations in this critical area of research.

2.3. Analysis and visualization's interpretation

In this phase, we analysed the bibliometric data to uncover key insights, research trends, and collaboration networks in Varroa mite research. The analysis was conducted using VOSviewer, a powerful software tool designed for constructing and visualizing bibliometric network maps [6]. Providing a range of analytical capabilities, including co-authorship, co-occurrence, co-citation, and bibliographic coupling analyses, is essential for comprehensively mapping the research landscape. Each map is then interpreted to draw meaningful insights into the state of research and identify gaps for future work.

The following steps were undertaken during the analysis and visualization phase:

Data preparation and preprocessing for VOSviewer compatibility: To ensure compatibility with VOSviewer, the information set retrieved from Scopus underwent a comprehensive preprocessing phase. VOSviewer requires data to follow a specific structure, typically in CSV or Research Information Systems (RIS) format, with consistent delimiters and clearly defined fields. For this analysis, we exported the dataset in CSV format, including all key bibliographic elements such as authors, titles, abstracts, keywords, affiliations, and citation counts.

A significant focus during preprocessing was the standardization and cleaning of metadata to enhance the accuracy and integrity of the bibliometric visualizations. One common issue encountered was inconsistencies in author names, where a single author could appear in multiple formats (*e.g.*, “Medina-Flores C.A.” *vs.* “Medina-Flores, Carlos Aurelio”). To resolve this, author names were reformatted to a consistent structure, using “Last name FIRST INITIAL.” in one column and full names in another. When available, unique identifiers such as Scopus Author IDs were used to distinguish between individuals with similar or identical names. Notably, VOSviewer offers built-in functionality to detect and merge name variants, which further streamlines this process and improves data reliability.

In addition to author name normalization, we conducted validation and cleaning procedures to ensure structural consistency across the knowledge base. These steps were performed using OpenRefine,⁴ an open-source tool designed for data transformation and quality assurance. It enabled efficient batch editing of similar entries, detection of metadata inconsistencies, harmonization of critical fields, removal of non-UTF-8 characters, extraneous white space, and invisible formatting marks. These subtle inconsistencies can cause errors or misinterpretations in the network generation process.

Tools for analysis: VOSviewer is employed to generate visualizations of bibliometric data. The analysis focused on three key dimensions, each offering distinct insights into the structure and development of research on Varroa mites:

- (1) **Co-authorship analysis:** This dimension aims to visualize collaboration networks among researchers, enabling the identification of key contributors and the mapping of international and interdisciplinary partnerships. It provides a clearer understanding of the collaborative structure within the field.
- (2) **Co-occurrence analysis:** This method uncovers major themes, research trends, and emerging topics by examining frequently occurring keywords. It highlights the conceptual structure of the field and the evolution of scientific discourse surrounding Varroa mites.
- (3) **Bibliographic coupling:** This technique groups documents based on shared references, revealing thematic clusters and illustrating how different studies are interconnected through common intellectual foundations. It offers deeper insight into the thematic landscape of the literature.

Following data preprocessing and validation, the cleaned dataset was imported into VOSviewer to generate a series of visualizations. These visual representations provide a multifaceted view of the Varroa mite research landscape, highlighting collaborative relationships, thematic concentrations, citation linkages, and shared intellectual foundations across the literature.

2.3.1. Co-authorship analysis

Co-authorship analysis serves as a powerful method to map scientific linkages among researchers, institutions, and countries involved in Varroa mite research. By examining co-authored publications, we can identify influential researchers, discover collaborative clusters, and assess the degree of international and interdisciplinary cooperation within the field. Figure 4 presents a global network visualization of the co-authorship landscape.

In this map, network (Fig. 4a) represents the co-authorship among research groups based on citation counts. This visualization enables us to pinpoint central contributors, detect well-established research groups, and

⁴ <https://openrefine.org/>.

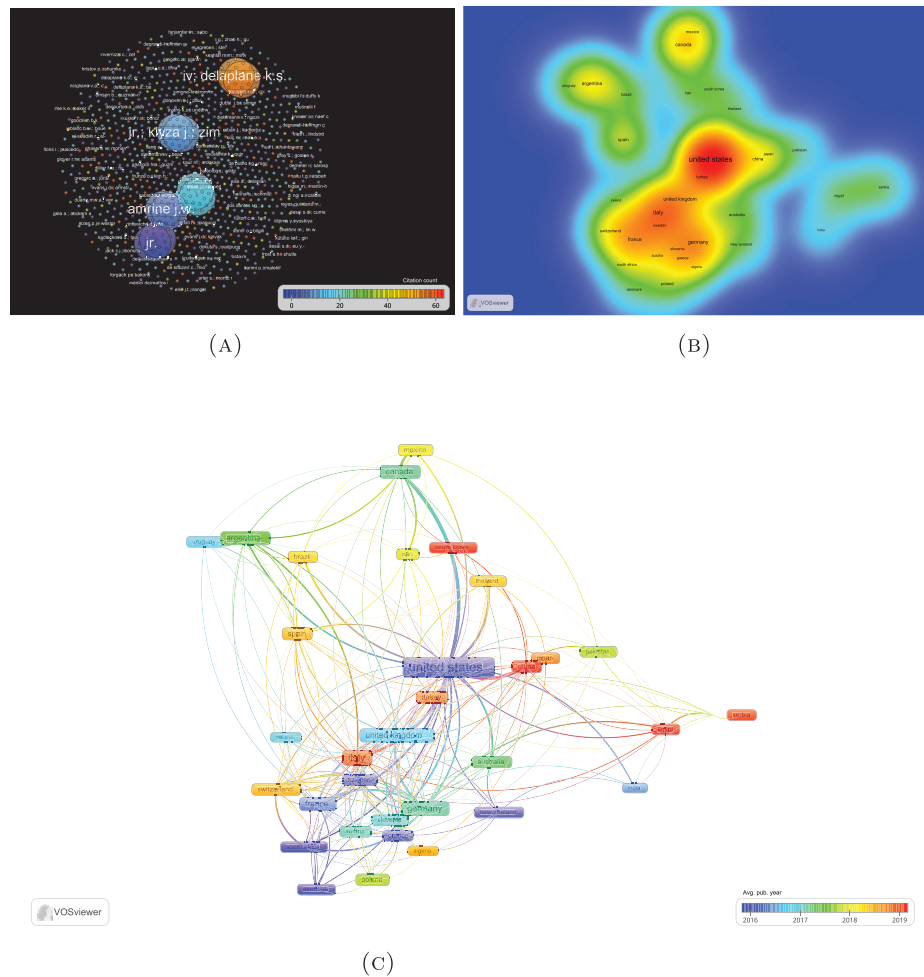


FIGURE 4. Co-authorship networks in Varroa mite research: (a) Citation-weighted collaboration among authors, identifying key researchers and central clusters; (b) Geographic distribution and density of country-level research output; (c) Temporal evolution of international collaboration, with color coding representing average publication year to highlight emerging and established research hubs.

uncover potential collaboration gaps. Each node represents an author, while the size of a node reflects the strength of collaboration (particularly how often that author has co-published with others, weighted by citation impact). The clustering of authors in distinct color-coded groups also reveals thematic or institutional affiliations, providing further insight into the structure of the research community. Analysis of the network highlights some densely connected clusters, indicative of well-established research groups with strong internal collaboration, reveals some highly central contributors, such as *Delaplane Keith S*, *Dietemann Vincent*, *Amrine James W.*, and *Klyza James*, whose frequent collaborations or high citation counts position them as prominent and central figures in the field, suggesting robust co-authorship activity across multiple research subgroups. This positioning implies a dual role as both prolific researchers and bridges between thematically distinct, otherwise disconnected clusters, likely spanning areas such as honeybee health, pest management, and policy-related environmental studies.

Conversely, the network structure also reveals notable collaboration gaps. Several authors appear on the periphery with limited or even no connections to the central research cores. These peripheral nodes may represent emerging researchers, specialized experts working in niche domains, or geographically distant contributors who are yet to be fully integrated into the broader collaborative ecosystem. Bridging these gaps could facilitate knowledge transfer, foster interdisciplinary approaches, and strengthen the overall resilience of the research community.

Furthermore, the recurrence of certain author names, such as *Delaplane K.S.* and *Dietemann V.*, in multiple clusters suggests cross-thematic engagement, underscoring their roles not only as collaborators but also as connectors among diverse subfields. These boundary-spanning contributors may offer critical insight for unifying fragmented areas of study and promoting integrated approaches to pressing challenges in apicultural science.

The country-level co-authorship networks provide a macroscopic view of global research partnership dynamics within the Varroa mite research. The density visualization in (Fig. 4b) highlights prominent hubs of scientific activity, with countries such as the United States, Italy, Germany, France, and Canada exhibiting the highest levels of collaborative linkage and research productivity. These nations form the core of the global research network, with dense interconnections suggesting both frequent co-authorship and strong mutual engagement across borders. In contrast, countries like Uruguay, Serbia, Pakistan, and Algeria appear on the periphery of the network with fewer or weaker links, pointing to lower integration into the international research landscape.

The overlay visualization in (Fig. 4c), which incorporates the average publication year, further reveals temporal dynamics in international research collaboration. In this network, node colors range from blue (older average publication years) to red (more recent activity), providing a clear temporal lens on the evolution of global collaboration. Countries such as the United States, Sweden, France, and the United Kingdom are shaded in blue tones, indicating that these nations have been active in this research domain for a longer time and have formed early, well-established collaborative networks. Their early and sustained participation reflects mature infrastructures and deep-rooted international partnerships. Conversely, countries like Pakistan, Iran, Brazil, Algeria, Serbia, and China are colored in lighter green to red hues, signifying more recent average publication years. This suggests that these nations have become more actively involved in the field in the latter half of the studied period, highlighting a growing research presence and increasing integration into global scholarly collaboration. These emerging participants bring valuable perspectives and are likely expanding their roles through bilateral and multilateral partnerships.

However, gaps remain evident. Several countries, particularly from Africa, Southeast Asia, and Latin America, are positioned on the network's periphery, indicating limited collaborative intensity. Nations such as Uruguay, Mexico, India, and Serbia, while present, show fewer co-authorship connections and lower centrality, suggesting untapped potential for deeper scientific engagement. Strengthening these emerging links with core research hubs, especially those in the darker blue clusters, could foster knowledge sharing and reduce global disparities in research capacity and visibility. These collaboration gaps also present a clear policy opportunity: targeted support for international exchanges and cross-border consortia could accelerate the integration of underrepresented regions into the global Varroa mite research ecosystem.

2.3.2. Co-occurrence analysis

The keyword co-occurrence network in Figure 5 is employed to identify prominent themes, emerging research trends, and conceptual relationships within the Varroa mite literature. In this context, visualisation in Figure 5a displays the extracted keywords as nodes, with node size reflecting frequency of occurrence, and thus relative importance, while colors and links denote clusters of co-occurring keywords, indicating thematic groupings. Preliminary tests with varying thresholds (representing the minimum number of occurrences required for a keyword to be included) were conducted, and 34 was selected as the optimal cut-off point to preserve conceptual clarity while minimizing network sparsity. The resulting network unveils the intricate web of research themes in Varroa mite studies, with "*Varroa destructor*" and "*apis mellifera*" positioned as central nodes, reflecting their foundational role in the literature. Dominant research clusters around keywords such as "*pest control*", "*acaricide*", "*pesticide*", and related control methods underscore the strong scholarly emphasis on chemical approaches for

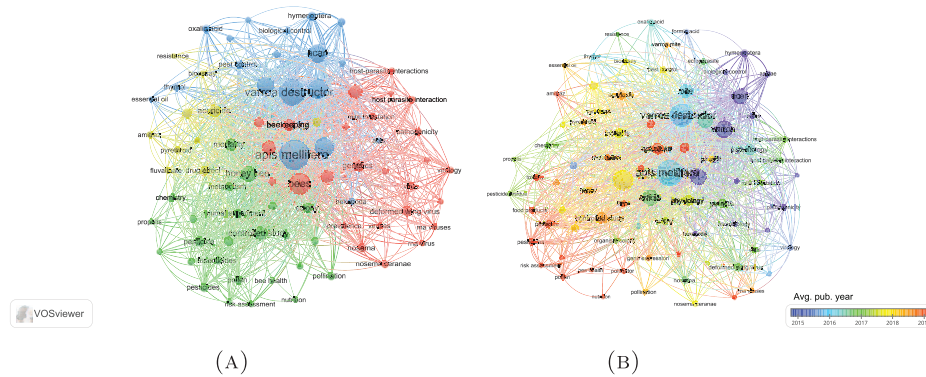


FIGURE 5. Keyword co-occurrence analysis in Varroa mite literature: (a) Thematic clusters based on frequent co-occurrence; (b) Overlay visualization coded by average publication year.

managing Varroa infestations. The substantial occurrence and connectivity of terms such as “amitraz”, “thymol”, “oxalic acid”, and “fluvalinate” confirm these chemical agents as principal strategies currently deployed in apicultural practices. However, their co-occurrence with terms like “mortality”, “resistance”, and “insecticides” signals ongoing concerns regarding chemical resistance, bee toxicity, and residual environmental impacts, highlighting the need for more resilient control alternatives. Concurrently, emerging keywords such as “biological control”, “propolis”, “essential oil”, and “nutrition” suggest a significant and growing interest in natural and environmentally friendly strategies. These themes indicate a shift towards Integrated Pest Management (IPM) and sustainable practices, aiming to balance pest control with ecosystem health and pollinator safety.

Moreover, considerable attention is directed toward pathogen-related terms, such as “Deformed Wing Virus” (DWV), “RNA viruses”, “virology”, “Nosema ceranae”, and terms related to host-parasite dynamics (“host-parasite interactions”, “pathogenicity”, “prevalence”, and “mite infestation”). This cluster highlights an intensified recognition of the epidemiological dimensions of Varroa infestations, emphasizing the complexity of interactions between Varroa mites, viral pathogens, and host bees. This underscores the necessity for integrated research approaches that simultaneously address pest control, bee immunity, and pathogen management. Additionally, keywords linked to genetic and physiological studies (“genetics”, “metabolism”, “drug effect”, “bioassay”, and “risk assessment”) reflect an ongoing effort to understand deeper biological and genetic resistance mechanisms within bee populations. These aspects are critical for developing resilient bee breeds that are inherently resistant or tolerant to Varroa infestations.

Despite the richness of existing research, there remain clear gaps. Notably, keywords explicitly addressing broader ecological and environmental factors, such as “climate change”, “pollution”, “ecosystem health”, and interactions with agricultural practices like “pollination” are unrepresented. The relatively weak depiction of these terms indicates limited research on how environmental changes and anthropogenic stressors exacerbate Varroa mite impacts, highlighting a critical area for future exploration.

To complement the structural insights of the co-occurrence network, it is crucial to examine the temporal distribution of keywords, as this sheds light on how research priorities have evolved over time and highlights the emergence of new thematic directions. Figure 5b presents an overlay visualization of the co-occurrence network, where color coding reflects the average publication year associated with each keyword, node size and links remain unchanged. Older terms are shown in blue or purple, while more recent topics appear in yellow to orange tones. This temporal gradient offers a nuanced perspective on thematic evolution. From the overlay, foundational terms such as “varroa”, “varroa destructor”, “Apis mellifera”, and “acaricide” are predominantly

blue or purple, indicating their early and enduring significance. These terms form the backbone of Varroa mite research, particularly in areas like mite biology, chemical control (e.g., “*amitraz*”, “*thymol*”, “*formic acid*”, “*oxalic acid*”), and host-parasite interactions.

In contrast, newer and increasingly emphasized keywords, such as “*RNA viruses*”, “*nutrition*”, “*bee health*”, “*pollination*”, “*biological control*”, and “*essential oil*”, are highlighted in yellow to orange tones. This color shift reflects a transition in research focus from primarily chemical and parasitological perspectives toward more integrated, ecological, and health-centered approaches. The rising prominence of terms related to colony health and non-chemical interventions indicates a broadening of research to include molecular biology, disease transmission, and resilient apiculture practices.

Conversely, the persistent blue tones and diminishing node sizes of older chemical treatment terms indicate a gradual decline in scholarly attention toward traditional acaricides. This reflects a field that, while grounded in established knowledge, is increasingly shifting toward new, interdisciplinary directions. The overlay visualization captures not only the current state of Varroa mite research but also its evolution over time. By highlighting enduring, declining, and emerging themes, it offers valuable insights for researchers and policymakers seeking to address ongoing challenges and leverage new opportunities in apicultural science.

2.3.3. Bibliographic coupling analysis

Bibliographic coupling analysis systematically reveals thematic clusters and interconnectedness within Varroa mite research by examining documents that share common references. This analysis was conducted from distinct perspectives:

Bibliographic coupling by authors: The bibliographic coupling by authors’ network offers critical insights into the intellectual structure and thematic cohesion of Varroa mite research. In this visualization, node proximity and line strength indicate how closely authors are conceptually linked through shared references, suggesting similar methodological frameworks or research directions. The map reveals several distinct color-coded clusters, each representing a group of authors who frequently cite overlapping bodies of literature. Dense and interconnected clusters indicate well-established themes such as chemical control strategies, biological interactions, and pest management. Conversely, less densely connected or emerging clusters suggest newer areas of exploration, such as genetic resistance, innovative control methods, or the incorporation of advanced technologies like IoT and AI for precision apiculture.

As illustrated in Figure 6, rather than a single dominant core, the network displays multiple semi-dense subgroups, indicating the presence of specialized yet somewhat fragmented research communities. Most authors are moderately linked, suggesting diverse referencing patterns across the field. No single author overwhelmingly dominates the network in terms of bibliographic coupling strength. The network further highlights potential collaboration opportunities through weakly connected or isolated authors. Researchers, in the purple cluster, situated on the periphery or exhibiting fewer connections, point to untapped opportunities for interdisciplinary collaborations. Integrating these peripheral authors into more central research clusters could bridge existing thematic gaps, fostering innovation and enhancing comprehensive understanding within Varroa mite research.

Bibliographic coupling by organizations: The organizational bibliographic coupling network highlights key research institutions that have significantly shaped the field and reveals clusters of specialized research. For instance, European institutions exhibit a strong focus on IPM strategies, while North American institutions prioritize studies on acaricides and disease dynamics, such as the link between Varroa mites and DWV.

The network in Figure 7 depicts universities like the *Swedish University of Agricultural Sciences*, and institutions such as the *Apicultural Research Chinese Academy* as dominant nodes, reflecting their leadership in generating impactful and widely referenced research, demonstrating the importance of academic institutions in driving advancements in Varroa mite management and honey bee health. To further contextualize this landscape, Table 2 presents the top five leading organizations in terms of bibliographic coupling strength, document count, and citations. These institutions not only lead in research productivity but also exhibit strong concep-

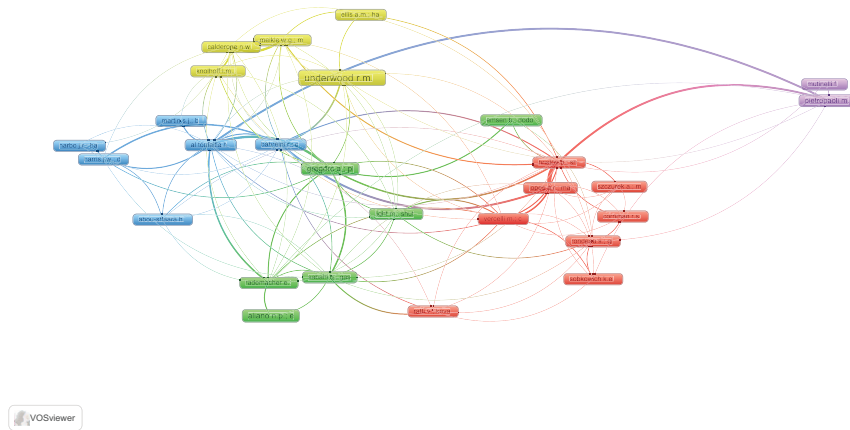


FIGURE 6. Bibliographic coupling network among authors with at least two shared references, visualizing thematic proximity and shared intellectual foundations.

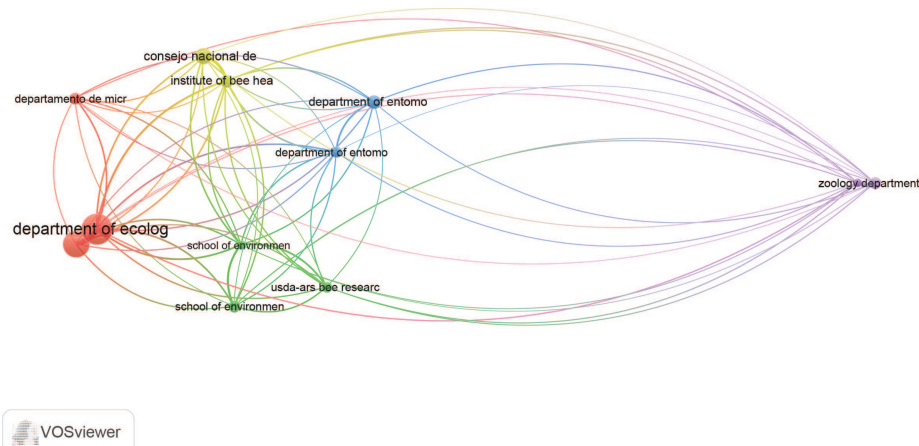


FIGURE 7. Network of leading institutions in Varroa mite research based on bibliographic coupling strength, showing collaboration patterns and thematic alignment.

tual linkages to other entities in the field, reinforcing their central role in shaping the intellectual foundation of Varroa mite studies.

This ranking further confirms the leading role of both Western and emerging institutions, with notable contributions from Egypt and China, suggesting a growing diversification in the global research effort. Nonetheless, the absence of institutions from Latin America or Sub-Saharan Africa in the top tier reflects persisting regional disparities that warrant strategic international collaboration initiatives.

This analysis underscores the pivotal role of specialized research centers and universities in advancing knowledge and fostering innovation. It also highlights the need for greater collaboration among institutions in regions heavily reliant on pollination for agriculture but with limited research infrastructure.

Bibliographic coupling by sources: The bibliographic coupling of journals, as illustrated in Figure 8, provides valuable insights into the dissemination patterns and thematic alignment of Varroa mite research. Prominent journals such as the *Journal of Apicultural Research* and *Apidologie* (in the red cluster) serve as key publication

TABLE 2. Top five leading research institutions in Varroa mite studies based on bibliographic coupling strength.

Organization name	N° of documents	N° of citations	Total link strength
Dep. of ecology, Swedish uni. Agri. Scien.	9	929	387
Dep. of entomology, uni. of Georgia.	5	687	302
Inst. Apicul. Res. Chinese Acad. Agri. Scien.	6	81	251
Zoology dep. Fac. of Sci. Tanta Uni. Egypt.	8	145	231
Inst. bee health, Vetsuisse fac., Uni. Bern, Switzerland.	7	167	215

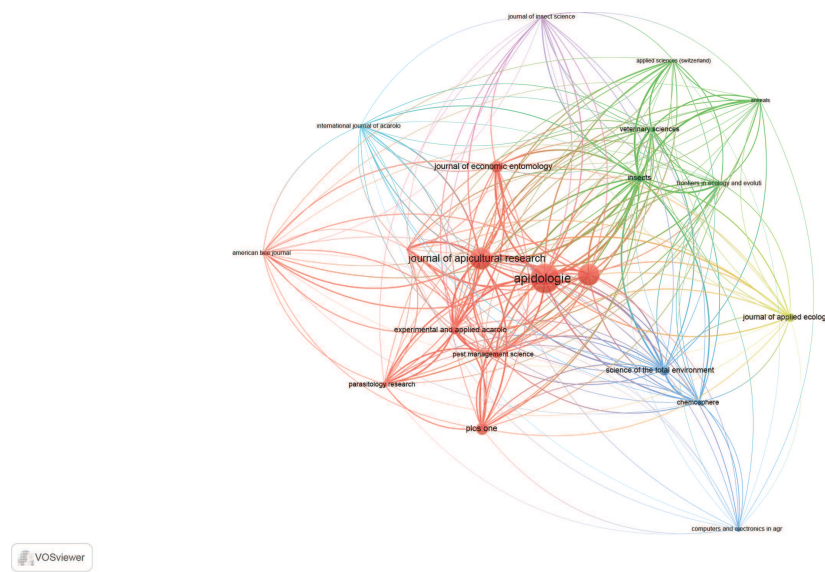


FIGURE 8. Journal-level bibliographic coupling network showing core and peripheral publication venues in Varroa mite research.

platforms, reflecting their longstanding focus on apiculture and pollinator health. Interdisciplinary journals like *PLOS ONE* and *Science of the Total Environment* (in the blue cluster) also feature prominently, underscoring the cross-disciplinary nature of Varroa mite research that bridges entomology, environmental sciences, and agricultural sustainability.

The network structure reveals distinct thematic clusters, indicating focal publication areas:

- (1) *Pest management and acaricides*: Journals like *Pest Management Science* emphasize chemical control strategies, resistance mechanisms, and acaricide application.
- (2) *Environmental and ecosystem health*: *Science of the Total Environment* highlights studies exploring the broader ecological impacts of Varroa mites in the context of climate change and habitat degradation.
- (3) *Bee biology and health*: *Journal of Invertebrate Pathology* and *Veterinary Sciences* focus on the physiological and molecular responses of honeybees to parasitic stress and viral infections.

While the coupling analysis successfully illustrates how publication venues align with research themes, it also presents an opportunity for critical evaluation. Specifically, the network reveals a strong concentration of output within specialized apicultural and entomological journals. Although this reflects disciplinary coherence, it may

also indicate a thematic siloing that limits cross-pollination with fields such as precision agriculture, climate science, or biotechnology.

Moreover, the peripheral positioning of certain technical and emerging-topic journals, such as *Computers and Electronics in Agriculture*, suggests that technology-driven approaches to Varroa control, particularly those involving AI, IoT, and real-time hive monitoring, are still underrepresented in core dissemination channels. This misalignment may hinder the integration of modern innovations into mainstream apicultural discourse.

To better support the study's objectives, especially its emphasis on sustainability, digital technologies, and multidisciplinary integration, future bibliometric assessments should explore strategies for strengthening the visibility of these emerging domains. Encouraging submissions to interdisciplinary journals and fostering collaborations across environmental science, computer engineering, and biology could help bridge the thematic gaps highlighted by this network.

3. DISCUSSION

The present bibliometric analysis reveals both the structural maturity and thematic fragmentation of the research landscape, underscoring the central role of Varroa mite research in advancing apiculture practices amidst increasing ecological challenges [35, 36]. While global output has steadily increased over the past two decades, and prominent institutions and authors have shaped the discourse, significant gaps persist in collaboration intensity, thematic integration, and translational application. The following key findings and implications were identified:

3.1. Publication trends

The steady growth in publication numbers over the last two decades reflects an intensifying global awareness of Varroa destructor as a central driver of colony collapse and pollinator decline. Peaks in research activity correlate with heightened awareness of pollinator decline and its impact on global food security. This trend highlights the urgency and relevance of Varroa mite management as a research priority, particularly in light of the rise in pollution and the significant shifts in climate and temperature.

3.2. Key journals and authors

Dominant journals such as the *Journal of Apicultural Research* and *Apidologie* were identified as primary dissemination platforms for Varroa mite studies, underscoring their foundational role in shaping the field's discourse and establishing methodological benchmarks [15, 37, 38]. These journals serve as central nodes in the bibliographic coupling network of sources, particularly within clusters focused on pest control and honey bee pathology, thereby anchoring much of the global literature within established disciplinary boundaries. At the author level, co-authorship analysis highlights a multi-centered structure. Established figures like *Delaplane* and *Dietemann* act as intellectual anchors, with high centrality and bridging roles across research clusters. However, a notable periphery of emerging and regional researchers, particularly from North Africa, South America, and Southeast Asia, remains weakly integrated. This is mirrored in bibliographic coupling by authors, which reveals thematic silos and limited cross-cluster citation behaviour, indicating underexploited opportunities for knowledge exchange across subfields such as chemical ecology, genetics, and sensor-based hive monitoring. Journal coupling analysis further emphasizes thematic segmentation. While interdisciplinary journals like *PLOS ONE* and *Science of the Total Environment* are gaining presence, they remain peripheral to the core apicultural publishing landscape. This suggests that technology-driven and ecological research struggles to penetrate mainstream apicultural discourse, limiting visibility and integration of emerging themes such as AI, IoT, and climate-sensitive pest modeling.

To address the strengths and structural gaps revealed by these networked patterns, we propose a series of integrated strategies aimed at enhancing scholarly connectivity and inclusivity. Bridging thematic silos can be achieved by initiating cross-disciplinary special issues in both core and interdisciplinary journals, encouraging collaboration among entomologists, data scientists, and environmental researchers. Journal diversification should

TABLE 3. Top five countries by research productivity and influence in Varroa mite literature.

Country	Total number of academic documents	Number of citations	Total link strength
USA	348	13 936	202
Italy	127	4222	167
Germany	112	6392	174
France	95	5112	129
Canada	94	2029	62

also be promoted by guiding submissions toward underutilized but high-impact interdisciplinary outlets capable of amplifying both technological and ecological insights. Establishing collaborative author networks through the involvement of central figures, serving as conveners of thematic workshops and international symposia, can help engage underrepresented researchers. Additionally, fostering author mobility and mentorship programs, particularly between high-output institutions and emerging research centers, will support capacity building and knowledge exchange. Finally, the development of citation-sharing platforms or thematic repositories can increase access to grey literature and regional studies typically excluded from mainstream publications, thereby enhancing visibility and citation potential.

3.3. Geographic contributions

The analysis revealed that countries mentioned in Table 3 dominate Varroa mite research, not only in terms of publication volume but also through high citation impact and dense international co-authorship networks (*e.g.*, the United States ranks as the leading contributor, with 13936 citations across 348 academic publications). These nations occupy central positions in both the co-authorship and bibliographic coupling maps, indicating strong institutional infrastructure, long-standing research traditions, and active participation in shaping global research directions. Their collaborations span multiple themes, from chemical control and host-pathogen interactions to breeding and genomics, demonstrating thematic breadth as well as leadership in methodological development. In contrast, emerging regions, particularly in North Africa, are beginning to gain visibility and network strength. Notably, *Algeria* has shown significant progress since 2018, with research institutions increasingly participating in international collaborations, establishing bibliographic and co-authorship links with established global centers, and applying advanced solutions such as IoT, AI, and satellite-based environmental monitoring [1,39–42]. These advances reflect a shift from observational studies to data-driven and predictive approaches, positioning the region as a promising contributor to the precision apiculture paradigm in northern Africa.

However, the bibliometric networks also reveal systemic gaps. Many countries across Sub-Saharan Africa, Southeast Asia, and Latin America remain underrepresented or absent from the global research landscape. These regions often face high ecological and economic vulnerability to Varroa-related pollinator decline, yet lack the institutional capacity, funding, or international visibility needed to contribute meaningfully to global discourse. Even where research exists, language barriers, paywalled journals, and limited conference access often inhibit knowledge diffusion and citation traction.

To accelerate the integration of such regions into the global research ecosystem, several targeted actions should be undertaken. International partnerships must be formalized through long-term cooperation agreements that encompass joint funding initiatives, shared research infrastructure, and reciprocal training exchanges. Supporting region-specific research programs that align cutting-edge global innovations, such as AI tools, with local contexts, constraints, and beekeeping practices is also crucial, particularly in arid, tropical, or mountainous environments. Furthermore, establishing multilingual, open-access repositories for Varroa-related knowledge bases and publications will democratize access to knowledge and promote South-South knowledge exchange. In addition, launching network accelerators for short-term initiatives that identify and fund early-career researchers from underrepresented countries to participate in collaborative projects with high-output institutions can enhance

global inclusivity. Finally, strengthening the indexing and visibility of regional journals through partnerships with international databases such as Scopus will ensure broader inclusion in bibliometric assessments. Ultimately, reducing geographic disparities in Varroa mite research is not merely a matter of equity; it is fundamental to enhancing the global resilience of beekeeping systems. Because Varroa dynamics are shaped by region-specific climates, bee genetics, and socio-economic factors, integrating diverse research perspectives is essential to improving model generalizability, intervention efficacy, and policy relevance. Building an inclusive and globally representative research network is, therefore, both a scientific imperative and a strategic priority.

3.4. Keyword and theme analysis

The keyword co-occurrence analysis revealed a well-defined thematic core in Varroa mite research, anchored around chemical control methods. Terms such as *“amitraz”*, *“thymol”*, *“fluvalinate”*, and *“oxalic acid”* dominate the network, reflecting the long-standing reliance on acaricides as the primary line of defense against infestations. These chemicals are frequently co-mentioned with *“resistance”*, *“mortality”*, and *“pesticide”*, suggesting ongoing concerns around efficacy, toxicity, and environmental side effects, issues that have long fuelled debate about the sustainability of chemical interventions in apiculture [43–45].

However, the presence and growing connectivity of keywords like *“biological control”*, *“hygienic behaviour”*, and *“breeding for resistance”* point to an evolving research agenda increasingly interested in alternative, bee-centered approaches. These terms signal an expanding effort to explore IPM frameworks that combine selective breeding, behavioural resilience, and natural compounds to mitigate Varroa impact. Although these themes remain secondary to chemical control in terms of network density, their upward trend suggests a paradigm shift toward more ecologically grounded management strategies. Recent temporal trends in keyword usage indicate that this diversification of control strategies is not only thematic but also chronological. Earlier research consistently emphasized traditional chemical treatments such as amitraz, oxalic acid, and fluvalinate, but over time, these have begun to lose prominence. In contrast, more recent studies have increasingly focused on terms like biological control, bee health, essential oil, and nutrition, which now appear with greater frequency and centrality. This evolution reflects a growing shift in scholarly attention toward ecologically balanced and health-conscious interventions.

A particularly promising development is the co-occurrence of technology-oriented terms such as *“AI”*, *“machine learning”*, and *“sensor networks”*. These indicate a nascent but rapidly growing interest in precision beekeeping, where real-time data on hive conditions, mite populations, and environmental stressors can inform dynamic, predictive responses. Early studies suggest that AI can be used for automated mite detection, hive health monitoring, and behavioural pattern recognition, potentially reducing the need for invasive treatments and manual inspections [46].

Crucially, the inclusion of broader environmental themes such as *“climate change”*, *“ecosystem health”*, and *“pollination services”* marks a conceptual broadening of the Varroa mite research field. These keywords reflect a growing recognition that Varroa infestations are not merely technical challenges, but symptoms of deeper ecological dysfunction. Overlay analysis further reveals that newer research threads are expanding this thematic scope. Keywords related to disease ecology, such as RNA viruses, deformed wing virus, and *Nosema ceranae*, have become increasingly prevalent in recent years. This temporal progression underscores a research trajectory that now accounts for complex biological interactions, positioning Varroa not just as a pest but as a trigger in wider virological and immunological crises within hives. The compounded impacts of climate variability, habitat fragmentation, and pesticide exposure are increasingly viewed as critical cofactors shaping Varroa dynamics and undermining bee colony resilience [47, 48]. In parallel, the emergence of keywords like *“biological control”* and *“AI in apiculture”* signals a shift in research priorities toward environmentally sound and technology-enabled solutions. Together, these thematic developments underscore the need for increased investment in interdisciplinary approaches that integrate ecological insight with data-driven innovation to advance long-term, adaptive pest management strategies.

To align research efforts with the increasing complexity of Varroa mite dynamics, several strategic directions should be pursued in a coordinated and integrated manner. First, promoting systems-based research that

synthesizes mite biology with environmental, behavioural, and genomic data is essential to developing a more holistic understanding of colony health. In parallel, long-term, field-based studies on biological control methods and selective breeding programs, conducted across diverse ecological conditions, are needed to validate laboratory findings and assess real-world applicability. Additionally, supporting the development and deployment of low-cost AI and sensor technologies for hive monitoring is particularly critical in regions with limited access to conventional chemical treatments. At the funding level, expanding thematic calls for proposals within major research agencies can help prioritize projects situated at the intersection of pollinator health, climate adaptation, and sustainable agriculture. Finally, integrating environmental data layers such as temperature, humidity, and land use into Varroa risk models will allow for more accurate assessments of spatial and seasonal variability in infestation patterns, ultimately enhancing the precision of predictive tools and intervention strategies. These temporal shifts not only chart the evolving focus of Varroa research but also highlight strategic entry points for emerging technologies and interdisciplinary approaches that align with current ecological and health-centric priorities.

3.5. Emerging technologies

Modern technologies such as AI-driven hive monitoring, IoT-based real-time data collection, and predictive analytics are emerging as powerful tools in the fight against Varroa mite infestations. These technologies promise to enhance monitoring precision, reduce dependency on chemical treatments, and integrate environmental variables into decision-making processes. However, their limited adoption in regions with constrained resources underscores the need for global technology transfer and capacity-building initiatives [49–54].

Building on this momentum, our research team has developed and tested a prototype smart beehive equipped with IoT sensors capable of monitoring key parameters such as internal temperature, humidity, hive weight, acoustic signals, and entrance activity through image capture [39,40]. This data will be analysed using AI models to detect anomalies, generate predictive insights, and provide beekeepers with timely alerts tailored to each colony's condition. The system architecture leverages low-power wide-area network (using Long Range (LoRa) technology) [41,42] and, where infrastructure is lacking, satellite communication through ongoing collaboration with the Algerian Space Agency (ASAL). Power autonomy is achieved via solar energy, a viable solution given Algeria's geographic advantage as a sun-rich region. These design choices collectively address key feasibility challenges, such as energy supply, connectivity, and cost, thus making the technology more accessible for rural or remote apicultural settings. Importantly, local beekeepers have shown a high degree of receptivity, actively engaging in both the deployment and feedback processes, further validating the system's practical viability.

A central outcome of this work is the ongoing development of what will be the first multimodal structured data for smart apiculture in smart beekeeping, and particularly Varroa mite research. The dataset integrates a diverse array of data types, including: visual imagery (from both satellite sources and entrance-facing cameras capturing bee activity), temperature and humidity readings, hive weight measurements, acoustic signals from within the hive, and region-specific environmental variables such as climate conditions and forage availability (bloom cycles and water sources).

Data collection follows a hybrid approach, combining manual and automated methods to ensure both contextual depth and continuous measurement. Regional information on forage availability, specifically the types of blooms and their seasonal calendars within the studied areas of Algeria, as well as the presence of water sources, is gathered manually and verified in collaboration with local agricultural specialists. Concurrently, a network of IoT sensors installed directly within the hives captures the remaining parameters, such as temperature, humidity, acoustic signals, hive weight, and entrance activity, enabling uninterrupted, real-time monitoring. This sensor-based infrastructure is further complemented by manual annotations from beekeepers, who observe and record key events, including the visible presence of Varroa mites. These human-verified annotations serve as essential ground truth data, significantly enriching the data resource for the development and training of AI-driven detection and prediction models.

The textual components and annotations of the dataset are being structured in CSV format to facilitate broad usability and seamless integration with popular Machine Learning (ML) and data analysis tools. Importantly,

it is intended to be open-access, contributing to a more inclusive and collaborative research ecosystem. The core objectives of this information set are threefold: (1) detection of anomalies and the presence of Varroa mites; (2) prediction of infestation level, risk, and environmental stressors based on hive conditions; and (3) real-time monitoring to support precision interventions. By capturing both internal hive metrics and external ecological factors, this initiative aims to empower data-driven decision-making for beekeepers and researchers alike, particularly in underrepresented and climatically vulnerable regions.

Unlike existing datasets, which often lack contextual specificity or rely on unimodal data sources, this resource is uniquely designed to reflect the ecological realities of unrepresented regions, particularly in arid and semi-arid zones. While data collection is still in progress, the initiative lays critical groundwork for scalable AI-enabled apicultural practices that prioritize sustainability, resilience, and global accessibility, offering an adaptable model for other regions facing similar environmental and technological constraints.

3.6. Implications for apiculture

This analysis provides a roadmap for addressing critical gaps and advancing apiculture research through a more integrated, inclusive, and technologically adaptive approach:

- ***Foster interdisciplinary collaboration:*** Closer integration between entomology, environmental science, and data-driven technologies is essential for developing context-aware solutions that move beyond conventional control methods. Our work exemplifies this approach by fusing biological insight with AI and IoT tools to support hive-level decision-making and predictive beehive management.
- ***Expand global participation:*** Strengthening research engagement from underrepresented regions enhances the diversity and relevance of apicultural knowledge. Our deployment of IoT-based hive monitoring systems in Algeria demonstrates how globally developed technologies can be adapted locally with strong institutional and beekeeper collaboration, ensuring ecological and cultural fit.
- ***Promote sustainable innovation:*** Shifting from chemical dependence to long-term practices, such as selective breeding, environmental modeling, and AI-assisted diagnostics, aligns with global sustainability goals. These interventions not only reduce environmental risk but also improve long-term colony resilience and support food system stability.

The findings emphasize that, while notable progress has been achieved, emerging technologies and growing regional innovation capacity offer untapped opportunities to transform Varroa mite management into a more resilient and globally responsive dimension of apicultural science.

4. LIMITATIONS AND FUTURE DIRECTIONS

While this study offers a detailed mapping of the Varroa mite research landscape, several constraints may have shaped the analysis and should be acknowledged.

Lack of data standardization and interoperability: A central limitation is the inconsistency in datasets across studies. The absence of harmonized methodologies, terminologies, and formats complicates data integration and hinders the development of robust, generalizable AI-driven monitoring tools. This fragmentation undermines efforts to draw broad, cross-context conclusions or implement transferable solutions.

Geographic, linguistic, and disciplinary gaps: The research relies predominantly on English-language publications from the Scopus database, introducing a language and regional skew. As a result, valuable insights from non-English sources or locally published work, particularly in Latin America, Southeast Asia, and Sub-Saharan Africa, are likely underrepresented. Furthermore, there is a noticeable absence of contributions from certain academic domains, including sociology, indigenous studies, and traditional ecological knowledge, which could enrich the understanding of local beekeeping practices and challenges.

Imbalance in research focus and technology integration: The current body of work remains heavily weighted toward chemical control methods, while ecological, behavioural, and technological strategies (such as sensor-based hive monitoring, AI diagnostics, or climate-linked modeling) receive less attention. This thematic concentration limits innovation and delays the adoption of more sustainable, system-oriented pest management practices.

Underrepresentation of vulnerable and biodiverse regions: The findings reveal uneven global participation, with North America and Western Europe dominating the research output and collaborative networks. Many high-risk yet biodiverse areas remain marginal in the academic discourse due to limited access to funding, training, and digital infrastructure.

4.1. Recommendations for future research

To create a more inclusive and forward-looking knowledge ecosystem, we propose the following strategic directions:

- *Standardize and enrich data collection:* Adopt common protocols for building multimodal datasets that integrate environmental, biological, and technological variables. Such frameworks should facilitate cross-study comparisons and enhance the predictive power of AI and machine learning models in apiculture.
- *Expand inclusivity in language and disciplines:* Encourage the indexing and recognition of non-English and regional publications. Promote cross-disciplinary approaches by involving ecologists, technologists, data scientists, and policy experts to bridge thematic silos and generate holistic solutions.
- *Foster equitable global partnerships:* Support the co-creation of monitoring tools and research projects with institutions in underrepresented regions. European Union programs such as the *Partnership for Research and Innovation in the Mediterranean Area (PRIMA)* and *Interreg NEXT MED (Mediterranean Sea Basin Programme)* offer concrete opportunities for North-South collaborations that emphasize mutual knowledge exchange, capacity building, and shared innovation.
- *Establish regional innovation hubs:* Create and fund local centers of excellence that focus on precision beekeeping and ecological resilience. These hubs can adapt global tools to regional needs, test sustainable interventions, and connect beekeepers, scientists, and policymakers.
- *Promote open access and knowledge sharing:* Develop multilingual, open-access repositories for Varroa research, datasets, and training resources. These platforms should enable equitable access to information and encourage participation from early-career researchers, especially in resource-constrained areas.

By addressing these limitations through targeted and collaborative initiatives, the global research community can evolve toward a more adaptive, inclusive, and digitally enabled approach to Varroa mite management, one that recognizes the interconnectedness of ecological systems, technological capacity, and cultural contexts.

5. CONCLUSION

This study offers the first focused bibliometric analysis of Varroa mite research, uncovering significant patterns in publication trends, collaborative networks, and thematic evolution. It identifies dominant research clusters, such as chemical control and host-pathogen interactions, while revealing underexplored domains including AI-based diagnostics, ecological modeling, and real-time hive monitoring. The findings expose a fragmented research landscape, shaped by geographic imbalances and thematic silos, which limit cross-regional knowledge exchange and inhibit the integration of holistic, systems-based approaches.

A central contribution of this work is its critical assessment of data-related shortcomings. The study highlights the lack of standardized, multimodal datasets as a major bottleneck for developing accurate, context-sensitive models. This limitation is particularly evident in underrepresented regions, where both data scarcity and technological barriers reduce the impact of current research. Addressing these deficiencies is not only a methodological imperative, but it is a prerequisite for achieving global relevance and equity in precision apiculture.

Practically, this analysis provides a roadmap for bridging the divide between research innovation and field-level implementation. By proposing the development of inclusive, sensor-driven, and AI-enhanced data frameworks, demonstrated through the Algeria–Tunisia initiative, the study charts a path toward predictive, localized, and sustainable Varroa mite management. These tools can empower beekeepers to transition from reactive to proactive strategies, ultimately improving hive health, reducing chemical dependency, and increasing operational resilience.

The study also underscores the urgency of interdisciplinary collaboration. Future research should not only span entomology and environmental science but also actively incorporate expertise from data science, hardware engineering, and policy-making. Formal partnerships, especially those involving emerging research centers in climate-vulnerable regions, must be prioritized to scale these innovations and ensure their adaptability to diverse agroecological contexts.

In summary, this work contributes both theoretically and practically: it critiques the structural and data-driven limitations of the field, provides concrete strategies for technological advancement, and underscores the global necessity of collaborative, inclusive research. These insights establish a critical foundation for transforming Varroa mite control from a fragmented scientific pursuit into an integrated, precision-guided component of sustainable agriculture.

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