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REVIEW ARTICLE

Exploring the plant volatile organic compounds in plant–insect interaction: A bibliometric analysis

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Abstract

Plant volatile organic compounds (VOCs) are key components in plant-insect interactions, greatly influencing herbivory, pollination and tritrophic interactions. Despite the growing body of research exploring the chemical, ecological and applied aspects of VOCs, a systematic bibliometric synthesis to consolidate existing knowledge and identify emerging trends is still lacking. This review employs bibliometric and thematic analyses on 362 peer-reviewed publications to map the intellectual landscape of VOC research in plant–insect ecology. Data were retrieved through a structured search strategy and screened based on language and publication type. Notable trends include a sharp rise in VOC-related publications after 2013, with major contributions from journals such as Journal of Chemical Ecology and New Phytologist. Leading authors such as M. Dicke and T.C.J. Turlings have helped shape the field's direction, while collaborative networks reveal strong international partnerships, especially among the US, China, Germany and the UK as determined by citation frequency and network centrality metrics. Thematic mapping shows central focus areas on insect responses, plant defences and chemical signalling, with rising interdisciplinary interest in genomics, microbial ecology and climate impacts. Notably, gaps persist in macroevolutionary studies, belowground VOC signalling and field-based validations. This review highlights the evolving research frontiers and encourages deeper integration of VOC research with sustainable agriculture, molecular ecology and environmental resilience. These findings provide a valuable reference for guiding future studies and fostering innovation in plant-insect chemical ecology.

Keywords: chemical ecology; defence mechanisms; floral volatiles; herbivory; microbial volatiles; pollination ecology; tritrophic interactions

Introduction

Plant volatile organic compounds (VOCs) are low molecular weight chemicals released from various plant tissues which act as critical chemical messengers that mediate diverse interactions between plants and insects. These interactions, encompassing attraction, repulsion, signalling and defence, are central to ecological dynamics and agricultural sustainability. VOCs act as semiochemicals that facilitate interspecies communication thereby guiding herbivores, pollinators and natural enemies of pests through complex olfactory landscapes (1, 2). Over 1700 different VOCs have been found in flowers alone, with roles that include attracting or deterring pollinators, predators and herbivores (3). Herbivore attack tends to induce VOCs, which are used as an indirect defence mechanism in attracting parasitoids or predators of the herbivores (4, 5). Additionally, VOCs participate in plant-to-plant signalling, alerting neighbouring plants to activate their own defence responses (6).

Recent studies have shed light on how VOCs contribute to both direct plant defence pathways and indirect defence through multitrophic interactions (7). These compounds have practical applications in environmentally friendly pest control strategies, such as the push-pull technique, odorant-releasing traps and breeding programmes aimed at enhancing beneficial VOC profiles in crops (8). Moreover, the subtle functions of minor volatile compounds, which have been neglected previously, are receiving an increasing amount of attention, as they may have large-scale effects on insect herbivores and pollinators applied by influencing behaviour (9). Highly selective multicomponent interactions, supported by exceptionally low concentration thresholds of VOCs and sophisticated chemosensory systems, enable insects to stay responsive to even the most complex VOC blends (3). A macroevolutionary view also illustrates the significance of the co-evolution of VOC-insect interactions, with such interactions affecting diversification of VOCs and insects (10). Modern phylogenetic tools now offer opportunities to investigate long term trends in the evolution of plant chemical communication. Recent experimental evidence demonstrates that VOCs may precondition neighbouring plants by causing them to increase their defence against further herbivory or abiotic stress. Such effects have been documented in crops like tea and chili pepper, where specific volatiles contribute to pest-resistant phenotypes (11, 12).

Despite the growing volume of VOC-related research, there has been limited effort to systematically consolidate and analyse this vast body of literature through a bibliometric perspective. Consequently, our understanding of the field's current structure, leading contributors, emerging themes and unexplored areas remains fragmented. Furthermore, the integration of VOC research with disciplines such as molecular genetics, evolutionary biology, bioinformatics and agronomy is still in its early stages.

Ecological and functional significance of VOCs in plant-insect interactions

VOCs are foundational to ecological signalling, enabling plants to engage in specific and complex interactions with insects. They contain terpenes, benzenoids and green leaf volatiles, which act as critical mediators in a wide variety of ecological functions, including attraction to pollinators and repellence to herbivores and attraction of natural enemies. Plants cannot physically escape threats and the physical extent of plant communication is largely limited to VOCs, which coordinate defence and survival responses among the diverse trophic levels. Plants in herbivore-infested systems release herbivore-induced plant volatiles (HIPVs) into the atmosphere as a form of airborne alarm signal to attract parasitic or predatory insects to curb the culpable herbivores (13).

Insects on the other hand have developed highly sensitive and specific olfactory receptors, enabling them to detect and interpret these volatile cues that affect the selection of hosts, egg laying and repelling behaviour (7). However, VOC-mediated interactions are not static. They are modulated by environmental factors, herbivore specificity and microbial symbionts. For example, endophytic fungi can alter VOC profiles in grasses, increasing resistance to herbivores via elevated production of repellent aldehydes such as nonanal (14). In much the same way, virus-infected plants can vary the production of VOC to encourage or deter the foraging of insect vectors, who may be attracted or repelled by the VOC profile depending on the state of the infection and the status of the insect vectors (15). VOCs additionally affect indirect defences through predator-prey relationships, e.g., predatory bugs alter their foraging responses in response to VOC cues released by thrips-infested flowers (16). Evolutionarily speaking, communication between plants and insects via VOCs has an expansive history with evidence pointing to herbivory-mediated plant diversification dating back to the mid-Cretaceous (17). Moreover, abiotic stressors such as ozone pollution can degrade floral VOCs, impairing pollinator attraction and potentially reducing crop yield (18).

Chemical diversity and biosynthesis of VOCs

VOCs are a chemically diverse and ecologically important group of secondary metabolites upon which a wide range of plant-insect interactions is founded. These compounds represent structurally different groups of terpenoids, benzenoids, phenylpropanoids, aliphatic aldehydes and esters which are biosynthesized using different metabolic pathways such as the mevalonic acid (MVA), methylerythritol phosphate (MEP) and the shikimic acid pathways (Table 1). Recent research has demonstrated the chemical diversity of floral VOCs to be not only determined by species but also by tissue-specificity, with leaves and petals commonly forming different mixtures which shows functional differentiation in the defensive and attracting mechanisms (25).

An important development in this field is the creation of the plant-associated VOC database (PVD), which integrates data on chemical structures, biosynthesis and ecological roles of plant-derived and microbe-derived VOCs (23). Within the phenylpropanoid class, compounds such as benzenoids exhibit dual roles, acting as attractants to pollinators while deterring herbivores. Their biosynthesis is tightly regulated by circadian rhythms and environmental cues like temperature and humidity (26). The complex nature of VOC-mediated signalling can also be explained by the functional diversity of individual compounds such as linalool, whose stereoisomers have different effects on insect behaviour, with one enantiomer attracting pollinators and another repelling herbivores (27). Also, green leaf volatiles (GLVs) are a subcategory of C6 alcohols and aldehydes produced through the lipoxygenase (LOX) pathway, that have been found to be some of the quickest-acting VOCs in response to biotic stress, commonly produced within a few seconds of herbivore damage (28).

Such dynamic and context-dependent VOC biosynthesis illustrates a highly flexible chemical signalling system shaped by plant genotype, environmental factors and cultivation practices. These variations influence pest resistance and are crucial in designing resilient crop systems (29). In total, such accumulated attention highlights how chemical diversity and the regulation of VOC biosynthesis are highly linked to ecological roles, evolutionary background and defensive mechanisms used by plants.

Table. 1. Diverse ecological roles of plant-emitted VOCs in biotic and abiotic contexts

VOC Class	Examples	Pathway	Ecological Role	Reference
Terpenoids	Linalool, (E)-β-ocimene, nerolidol	MEP (monoterpene), MVA (sesquiterpenes)	Attract parasitoids/predators, plant–plant signalling; antimicrobial, stress stabilization	(19, 20)
Benzenoids / phenylpropanoids	Methyl salicylate, benzaldehyde	Shikimate pathway	Activate systemic acquired resistance, attract pollinators and natural enemies	(21)
Fatty acid derivatives	Methyl jasmonate, jasmonic acid	LOX → jasmonate pathway	Systemic defense induction, defense gene activation, priming	(22)
Microbial VOCs	2,3 butanediol, acetoin	Bacterial metabolism (PGPR)	Enhance systemic resistance, recruit soil-dwelling natural enemies	(23)
Sulfur containing VOCs	Methanethiol, DMS, DMDS, isothiocyanates	Glucosinolate breakdown / sulfur amino acids	Recruit predators, defence priming in neighbouring plants	(24)
Nitrogenous VOCs	Indole, benzoxazinoid derivatives	Tryptophan-derived	Defense priming, herbivore deterrence and oviposition cues	(21)
Flavonoid VOCs	Quercetin derivatives	Flavonoid biosynthesis	Oviposition deterrence, feeding suppression	(21)

Advances in analytical techniques for VOC detection

Recent advancements in analytical techniques have greatly improved the detection, characterization and interpretation of plant VOCs involved in plant–insect interactions. A major step forward has been the transition from qualitative to quantitative gas chromatography-electroantennographic detection (GC-EAD), which allows more precise measurement of insect olfactory responses to plant volatiles. An advanced signal processing method that minimizes baseline drift and noise, enabling more accurate quantification of how different insect species respond to specific floral compounds was introduced (30). A comprehensive two-dimensional gas chromatography coupled with quadrupole time-of-flight mass spectrometry (GC×GC-QTOF—MS) with headspace solid-phase microextraction (HS—SPME), to analyse complex floral VOC blends and confirmed their behavioural impact on both male and female *Heortia vitessoides* through electrophysiological and bioassay validation was employed (31). Complementary techniques, such as gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), nuclear magnetic resonance (NMR) and infrared (IR) spectroscopy, are also increasingly applied to elucidate VOC structures and link them to ecological functions, including pollination, oviposition and herbivore deterrence (32).

Beyond laboratory tools, recent work has emphasized field-deployable technologies. The use of real-time VOC sensors for disease surveillance in insects, offering a non-invasive and scalable approach to VOC-based monitoring (33). Such innovations represent a shift toward practical applications, extending VOC research beyond controlled laboratory environments into agricultural and ecological contexts. Together, these developments are equipping chemists, entomologists and agricultural scientists with powerful tools to detect, quantify and interpret plant VOCs with unprecedented resolution and ecological relevance.

Applied perspectives: VOCs in agricultural pest management

A recent trend highlights the increasing use of VOCs as a potential and renewable source of pesticides in agricultural pest control. The use of their ecological functions—particularly as attractants, repellents and signalling agents—is rapidly being exploited to augment biological control measures, particularly within integrated pest management (IPM) programs. Plant volatiles are frequently used by insect pests in host location and VOCs make suitable targets for behaviour-altering traps or manipulation at the field scale. Recent research has shown that selected compounds (e.g. linalool and eucalyptol extracted from *Rosmarinus officinalis*) display strong attractant or repellent activity against one of the most significant agricultural pests, *Spodoptera exigua*, providing the targeted and residue-free control methods (34). Additionally, companion planting treatments involving VOC-releasing functional plants like *Cnidium monnieri*, have demonstrated the capacity to attract predatory lacewings (*Chrysoperla sinica*) increasing the number of natural enemies in crops and decreasing pest infestations (35). These findings underscore the promise of VOC-based strategies in advancing sustainable and ecologically sound pest control systems.

The application of HIPVs to recruit parasitoids and predators at a broader landscape scale has expanded, converting plant volatiles into indirect defensive mechanisms. However, their efficacy is dependent upon the species of pests, as well as environmental circumstances (36). More recently, meta-analyses have shown that adding host plant volatiles to sex pheromones further increases the goodness of traps especially on capturing female Lepidoptera—one of the main weaknesses of pheromone-only systems (37). Also, microbial VOCs (mVOCs) of beneficial bacteria and fungi are becoming popular, because plants have resistance to a wide range of pests and disease-causing organisms and suppress pest populations, which has the added value of enhancing plant health (38). However, obstacles still exist, especially in the case of field stability of volatiles, dose optimization and intermixability under various environmental conditions. Nevertheless, the creation of VOC databases, electrophysiological screening tools and formulation technologies has accelerated the pace of identifying and implementing efficient compounds. The incorporation of VOCs within pest management systems signifies an evolutionary transition to agriculture and food security—one that relates to the paradigm of ecological engineering, instead of chemical suppression, long-term sustainability objectives, less pesticide dependency and eco-resiliency.

Emerging trends and interdisciplinary integration

New trends in the research of plant VOCs indicate their transition to an interdisciplinary direction, connecting chemical ecology with genomics, climate change and precision agriculture. Among the new trends, studies are helping to elucidate how VOCs mediate systemic resistance and plant social immunity, particularly in response to biotic stress from insect herbivory. As one example, transcriptional changes in tea plants in response to stressed neighbours exposed to detrimental VOCs are measurably low, improving their own defence (11). Another expanding area entails climate-modulated VOC studies, where high levels of ozone and CO_2 have been found to modify VOC composition and deteriorate their ecological role, especially in relation to pollination and attraction of natural enemies (39). VOC emissions are currently also being mapped against plant genotype and insect community diversity in an agricultural setting, revealing that cultivar choice can influence VOC profiles and influence pest interactions (12). VOC research has also witnessed the entry of microbial ecology, due to the growing understanding of the role of soil microbiota and endophyte and the way they alter the biosynthesis of VOCs and, in turn, the insect behaviour above ground (14). Simultaneously, there is a prospect of using VOC-based models in digital agriculture and pest forecasting, leveraging remote sensing and sensor networks as a part of scaling back the laboratory-based insights and introducing field-scale surveillance platforms (29). Collectively, these developments depict the trend toward systems-level insights of VOC functions within ecological and agricultural realms.

Purpose and scope of the review

VOCs serve as vital chemical signals that drive a wide array of interactions between plants and insects, including pollination, herbivory and indirect defence by attracting the natural enemies. Over the past two decades, research into the ecological roles, chemical diversity and applied value of plant VOCs has expanded significantly, driven by advances in analytical chemistry, molecular biology and ecological modelling. Despite this growth, the field lacks a systematic bibliometric synthesis to assess global publication trends, key research themes, collaboration networks and knowledge gaps. This review addresses the need by combining thematic analysis with bibliometric mapping to highlight how VOC-related research has evolved, where it is concentrated and which disciplines and technologies are driving its advancement. By identifying core topics, leading contributors and underexplored areas, this bibliometric assessment provides a comprehensive overview of the intellectual structure of plant VOC insect interaction research. It also outlines emerging trends, including interdisciplinary integration with climate science, microbial ecology and digital agriculture. This synthesis aims to support more informed and strategic research planning, foster collaboration and encourage the application of VOC-based innovations in sustainable pest management and ecosystem resilience.

Data collection and analysis

A systematic search was conducted to retrieve relevant publications on plant VOCs and insect interactions (Fig. 1). A well-defined preliminary search strategy was applied across predetermined academic databases, including Scopus, Web of Science, PubMed, Google Scholar and ScienceDirect, yielding 910 publications. A screening process was then applied to ensure relevance and quality. Only journal and conference articles written in English were considered for inclusion. Following this, 548 publications were excluded due to lack of topic relevance, language barriers or absence of peer review, resulting in 362 publications as the final dataset. This filtered collection formed the basis of the bibliometric analysis and data synthesis. The selected articles were further examined to determine publication trends, influential authors and journals, co-authorship networks and thematic developments in the field. This rigorous and transparent process ensured both the validity and reproducibility of the data employed in this bibliometric review.

Annual scientific production

Studies on plant VOCs in plant–insect associations have shown impressive growth since the early 2000s, with a steady increase in the rate of publications (Fig. 2). Between 2007 and 2012, publication rates remained relatively stable, averaging around 10 -15 articles per year. From 2013 onward, however, there was a marked increase, peaking in 2019 with nearly 40 publications, reflecting the growing recognition of VOCs in plant defence and insect behavioural ecology. Although the curve shows a decline

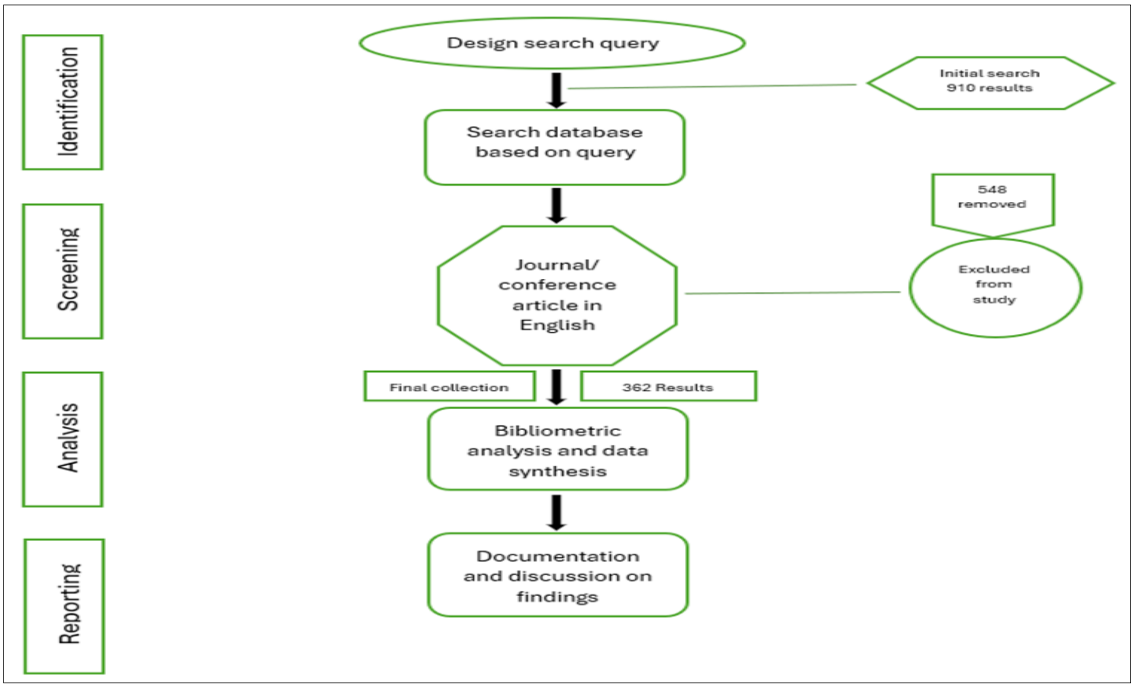

Fig. 1. Workflow of literature selection and bibliometric analysis.

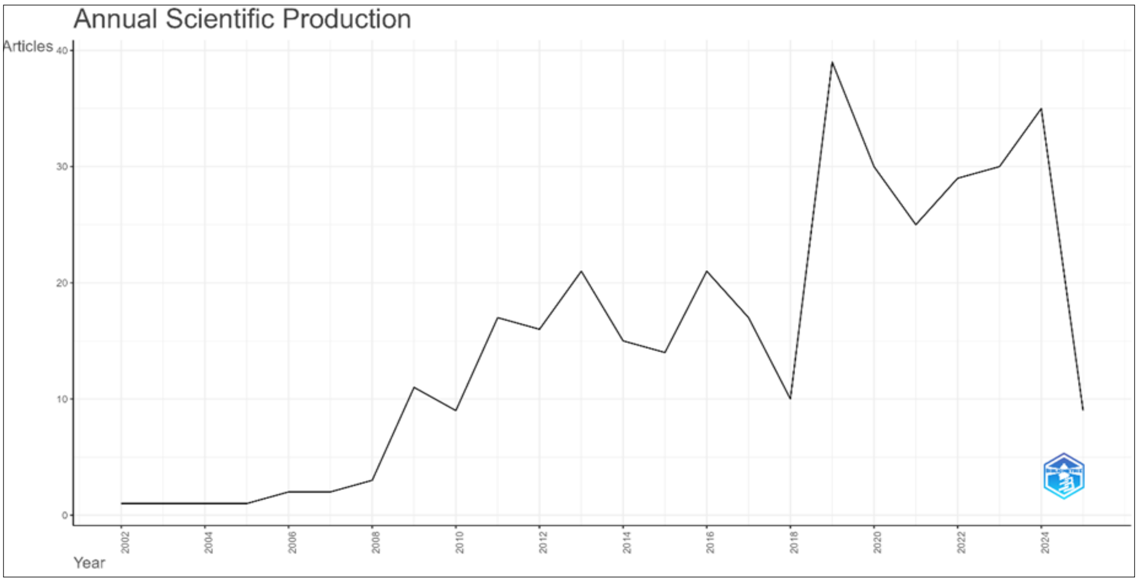

Fig. 2. Annual scientific production of plant VOCs in plant- insect associations.

after 2019, partial recovery occurred between 2021 and 2024, suggesting continued—though somewhat inconsistent research activity. The apparent sharp drop in 2025 should be interpreted cautiously, as it most likely reflects incomplete data collection at the time of analysis rather than a true decline in research output. Overall, the average annual growth rate of publications in this field indicates that research on VOCs has gained significant momentum in the past decade and continues to attract strong scholarly attention, with phases of both expansion and temporary slowdown.

Identification of core literature sources based on Bradford's law

Based on Bradford's law analysis, the most influential journals or core sources that consistently publish research on plant VOCs and their roles in insect interactions shown in Fig. 3. The figure shows bibliometric analysis of the most authoritative journals in the topic of plant VOCs and their response towards insects. According to Bradford's Law, a small number of core journals dominate publication output in this domain.

Among them, Journal of Chemical Ecology (impact factor ~3.1, 2024) stands out as a key platform for advancing chemical ecology research, particularly in VOC-mediated insect behaviour. New Phytologist (impact factor ~8.0, 2024) has also been highly impactful, often cited for its integration of plant physiology and ecological signalling studies. PLOS One (impact factor ~3.7, 2024), though more generalist, has contributed substantially by publishing accessible, open-access research that expands the global reach of VOC studies.

These journals are important for disseminating groundbreaking research findings on the use of VOCs and their effect on insect behaviour, pollination manipulation, pest reduction and plant defence strategies. It is worth noting that other journals including, Frontiers in Plant Science (impact factor ~6.4, 2024) and Plants (impact factor ~4.5, 2024), have also contributed significantly, publishing peer-reviewed articles that further innovate our understanding of the chemical interaction between the insects and plants.

These major sources are important to researchers and professionals to have a good basis to study ecological and evolutionary effects on plant-insect interactions with VOCs. Recognizing these core sources allows researchers to focus on high-impact platforms for staying updated and disseminating findings effectively.

Most relevant authors in plant VOCs in plant-insect interactions

Fig. 4 highlights the most influential writers in the study of plant VOCs. Among them, M. Dicke (21 publications) and T.C.J. Turlings (13 publications) stand out as the most prolific contributors, particularly in advancing our understanding of VOC-mediated insect behaviour and multitrophic interactions.

In terms of the biochemical and ecological functions of VOCs, J. Gershenzon (12 publications) and B.T. Weldegergis (11 publications) have played central roles, offering valuable insights into plant defence mechanisms and the chemical composition of volatiles. Similarly, S.B. Unsicker and R. Gols, each with about 8 publications, have contributed significantly to exploring plant–insect chemical signalling in ecological contexts.

On the applied side of research, authors such as J.A. Pickett, J.J.A. Van Loon, J.D. Blanche and M. Erb (7–10 publications each) have focused on insect olfaction, multitrophic VOC-mediated interactions and plant protection strategies. This author ranking not only identifies central figures in the literature but also illustrates distinct thematic clusters of expertise, helping to map the collaborative networks and intellectual hubs that drive progress in the field.

Word cloud of dominant themes in VOC mediated plant-insect interaction literature

The word cloud illustrates the most frequently occurring keywords in literature concerning plant VOCs and their roles in insect interactions, offering a snapshot of dominant research themes (Fig. 5). Frequently appearing terms such as "volatile organic compounds," "herbivory," "animals" and "insect" reflect the central focus of the field on the chemical interactions between plants and herbivores. The presence of words like

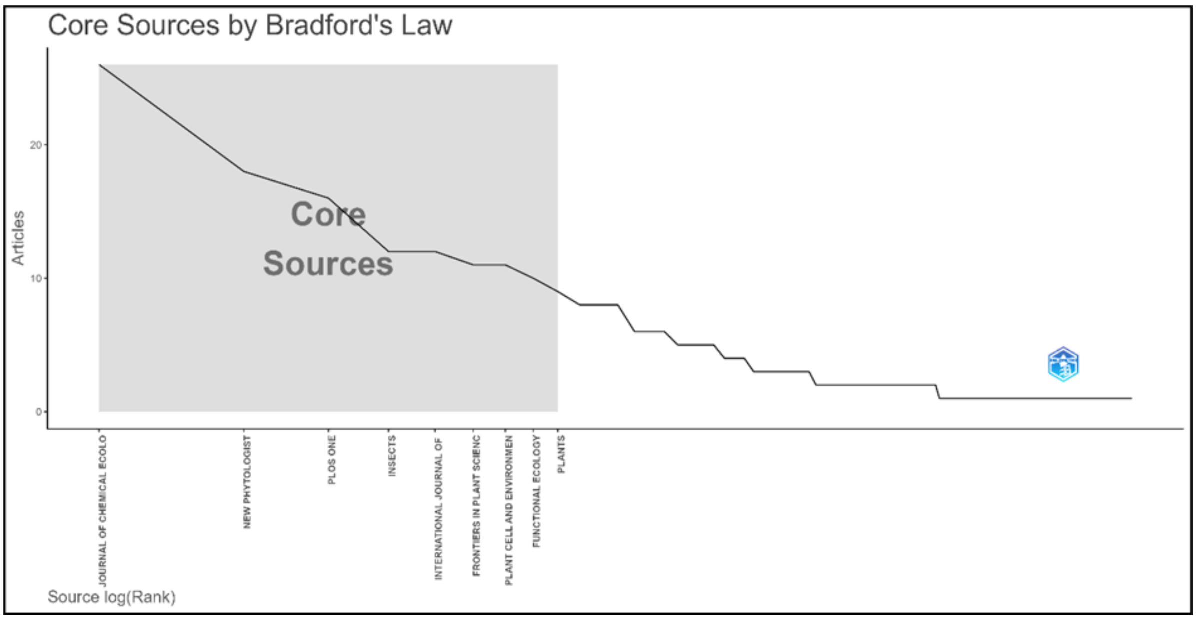

Fig. 3. Influential journals or core sources that consistently publish research on plant VOCs and their roles in insect interactions according to Bradford's Law.

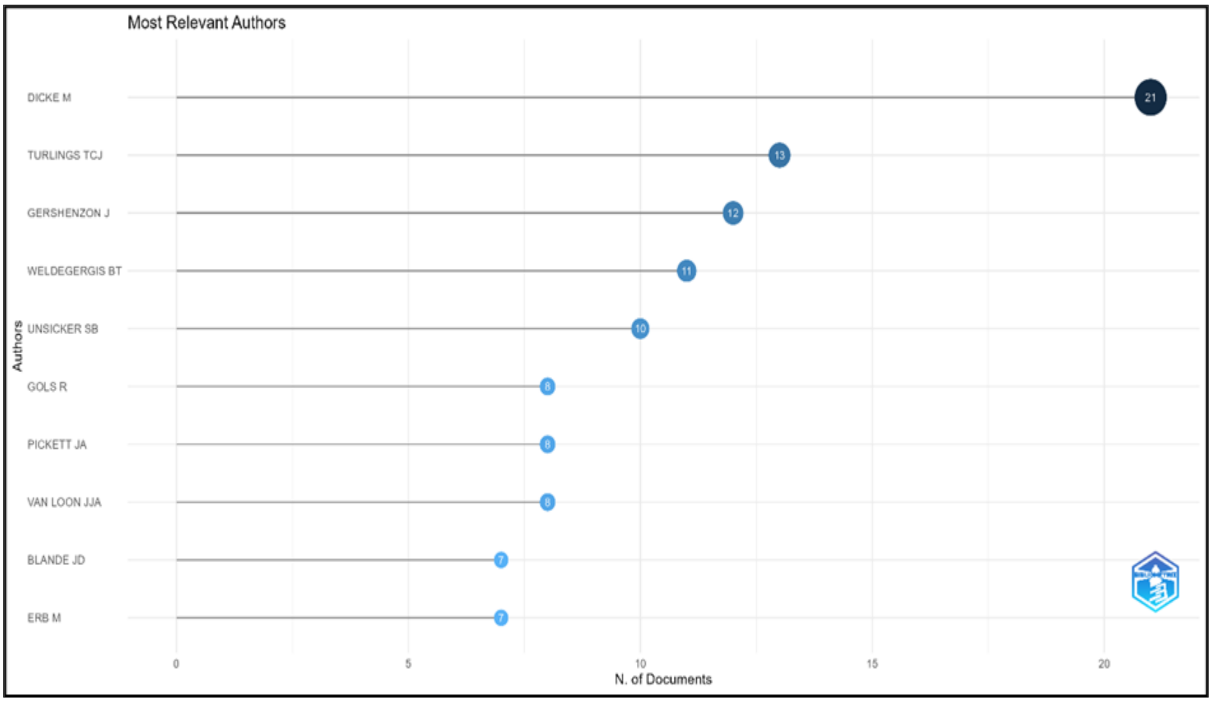

Fig. 4. Most relevant authors in plant VOCs in plant-insect interactions research.

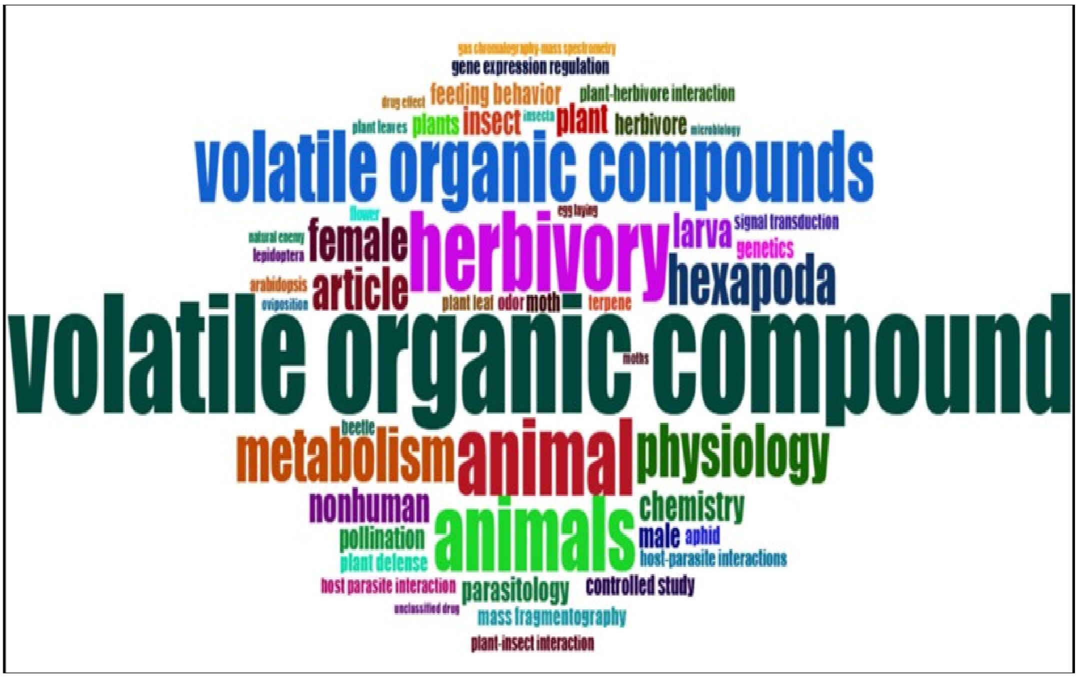

Fig. 5. Word cloud of dominant themes in VOC mediated plant-insect interaction literature.

"animal physiology," "metabolism" and "plant-herbivore interaction" emphasizes the physiological aspects of these chemical signals and their role in influencing insect behaviour.

Additionally, "plant defence," "terpene," "beetle" and "pollination" highlight the ecological and evolutionary significance of VOCs in plant protection and pest control. Terms like "aphid," "larva" and "hexapoda" suggests frequent exploration of insect behaviour, sex-based response variability and specific pest targets in ecological studies. Meanwhile words such as "chemistry," "genetics" and "signal transduction" point to the biochemical and molecular processes underlying plant-insect communication.

The visibility of "parasitology," "host-parasite interaction" and "plant-insect interaction" underscores interest in tritrophic interactions, where VOCs influence natural enemy. The interdisciplinary nature of this research integrates fields such as chemistry, ecology and entomology to explore the complex dynamics of plant defence mechanisms and insect behaviour.

Thematic map

Fig. 6 presents a thematic map that organizes the focal importance and developmental strength of keywords within the literature on plant VOCs and plant–insect interactions. In the motor themes quadrant, terms such as "volatile organic compounds" and "animals" appear as well-developed and highly relevant topics, highlighting their central role in research on chemical communication between plants and insects. These themes represent the established core of the field, particularly in relation to insect behaviour and plant defence.

In contrast, the basic themes quadrant includes keywords such as "plant" and "metabolism," which are

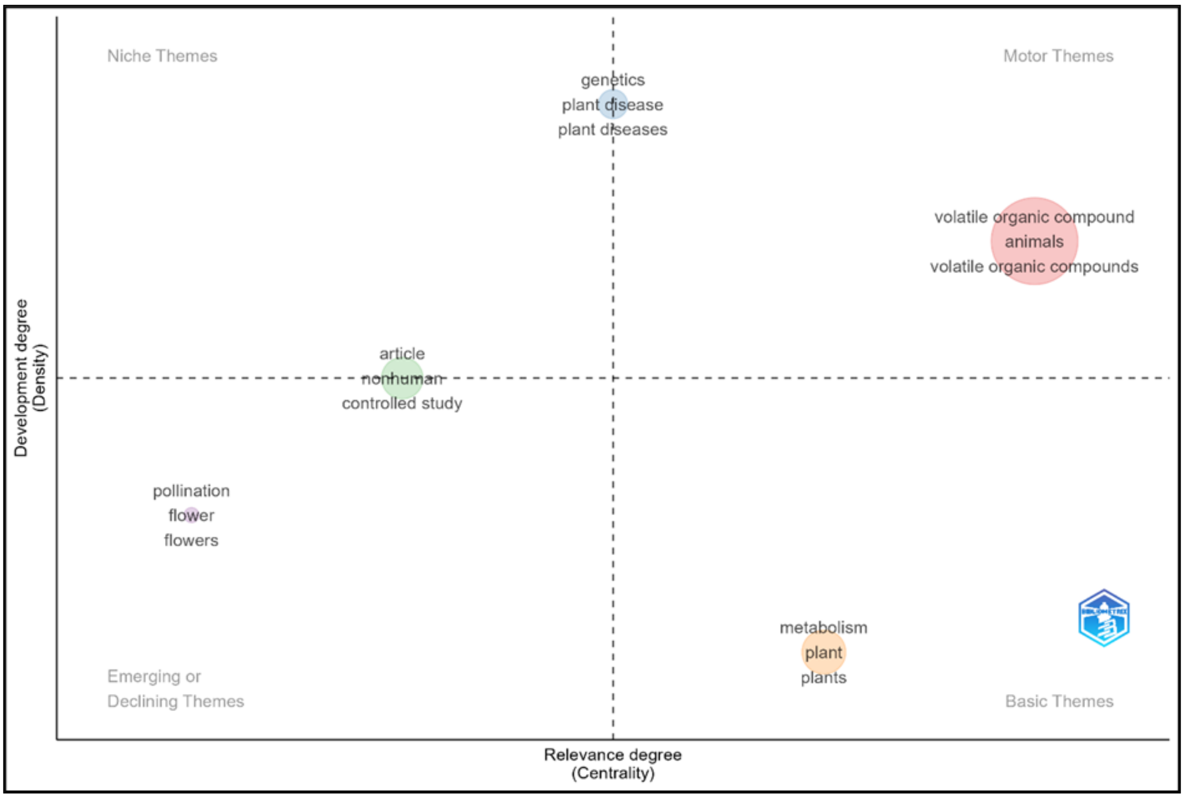

Fig. 6. Thematic map of research on plant volatile organic compounds (VOCs) and plant insect interactions.

fundamental but less developed, indicating the need for further empirical studies to explore the complex links between plant metabolism and insect interactions. The niche themes quadrant features more specialized terms, including “genetics” and “plant diseases.” While narrower in scope, these themes provide opportunities for focused research that could refine our understanding of plant responses to insect herbivory and trees.

Finally, the emerging or declining themes quadrant highlights terms such as “pollination” and “flower,” which may reflect topics that are either in the early stages of scholarly attention or waning in focus. Nevertheless, these areas remain promising, particularly for ecological studies examining the role of VOCs in pollination biology and floral signalling. Overall, the thematic structure underscores the need to further develop central themes around VOCs, insect physiology and plant defenses, while also advancing research into the genetic, microbial and ecological dimensions of VOC production and function.

Bibliometric coupling

The collaboration network map visualises the interconnection of the countries in the area of interest, which is plant VOCs in plant-insect interactions (Fig. 7). Countries with larger nodes, such as the United States, the United Kingdom, Germany and China-represent both high research output and centrality in global collaboration networks. The map reveals distinct regional clusters: one led by the United States and its partners (green), another by Germany and Central Europe (red) and cluster linking the UK and Commonwealth nations (purple), another consisting of China and its Asian collaborators (blue) and one representing Latin American partnerships (light green/yellow). Other important contributers, including France, Italy and the Netherlands, also form significant groups.

Importantly, emerging contributors such as Brazil, India, South Africa and Turkey are increasingly integrated into global collaborations, suggesting a growing international interest and diversification of research capacity in this field. Bibliometric coupling reveals the nature of the interactions in curbing the process of sharing knowledge and research findings in plant-insect interactions mediated by VOCs. This map serves as a useful tool to locate the most active countries in the field and provide insights into future collaborative trajectories. It underscores where international cooperation may be strengthened to enhance the study of ecological and chemical processes of plant-insect interactions.

Keyword co-occurrence network in plant VOC–insect research

Fig. 8 illustrates the keyword co-occurrence network, highlighting thematic connections within plant-insect VOC research. The network reveals several clusters of interrelated terms, reflecting the diversity of research topics in this area, such as plant defence mechanisms, HIPVs, chemical signalling and resistance pathways. The main cluster-denoted by large green and red nodes—revolves around core research topics, including "volatile organic compound", “plant defence” and “plant-insect interaction”. This indicates that much of the research is focused on the protective roles of VOCs and their influence on insect behaviour.

Adjacent to this central cluster are small nodes representing related areas that help contextualize the biochemical and ecological processes underlying VOC production. These include topics such a sustainable chemistry, primary metabolism and plant diseases. Other significant clusters include such as “insects”, “hexapoda” and “parasitoid”, which underscore the importance of insect diversity and specificity in herbivory ecology. The appearance of keywords like "genetics," "gene expression" and "genomic DNA" reflects a rising interest in molecular and genetic approaches to understand how VOCs are produced in response to insect attack.

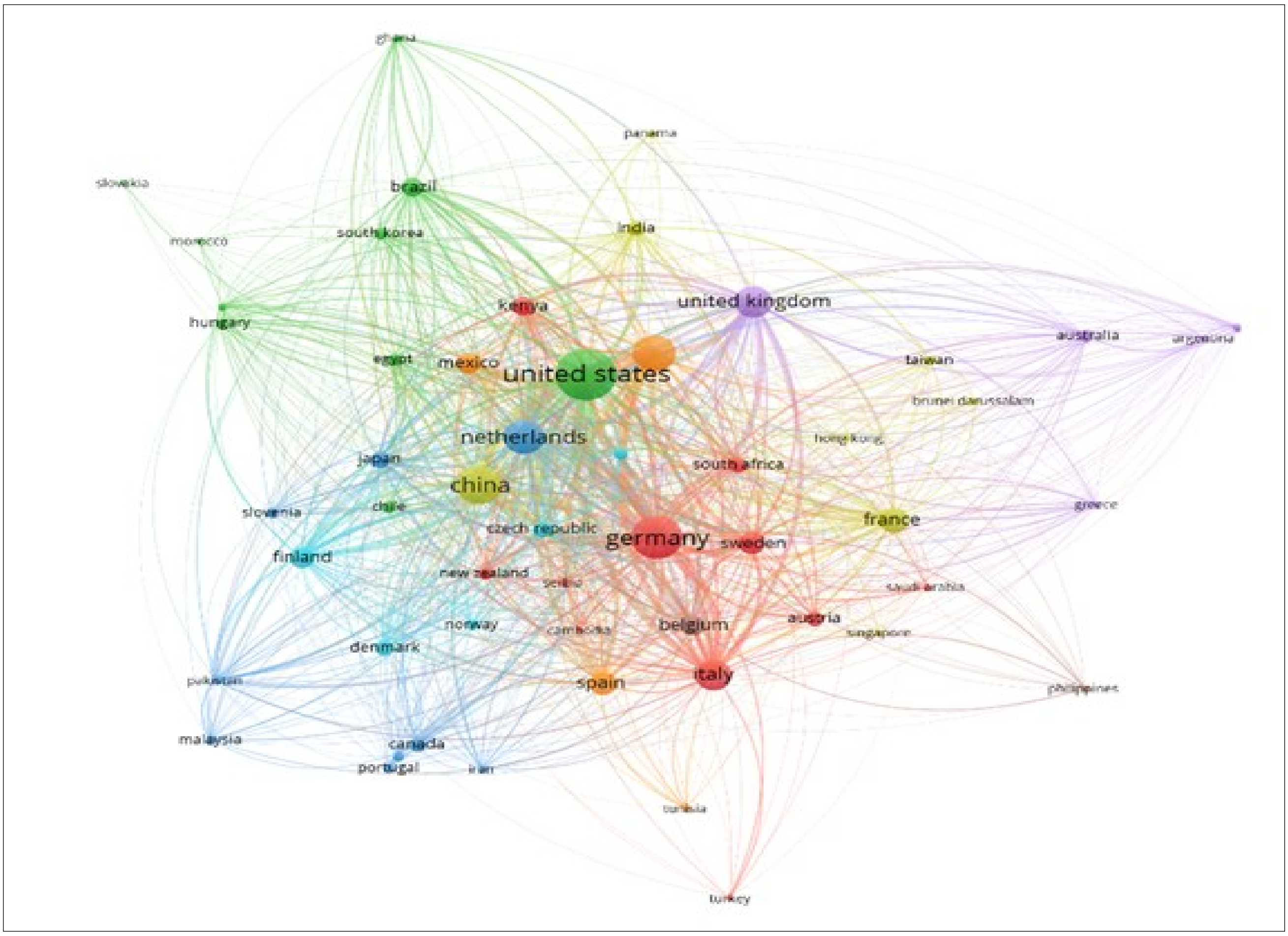

Fig. 7. Collaboration network map of nations.

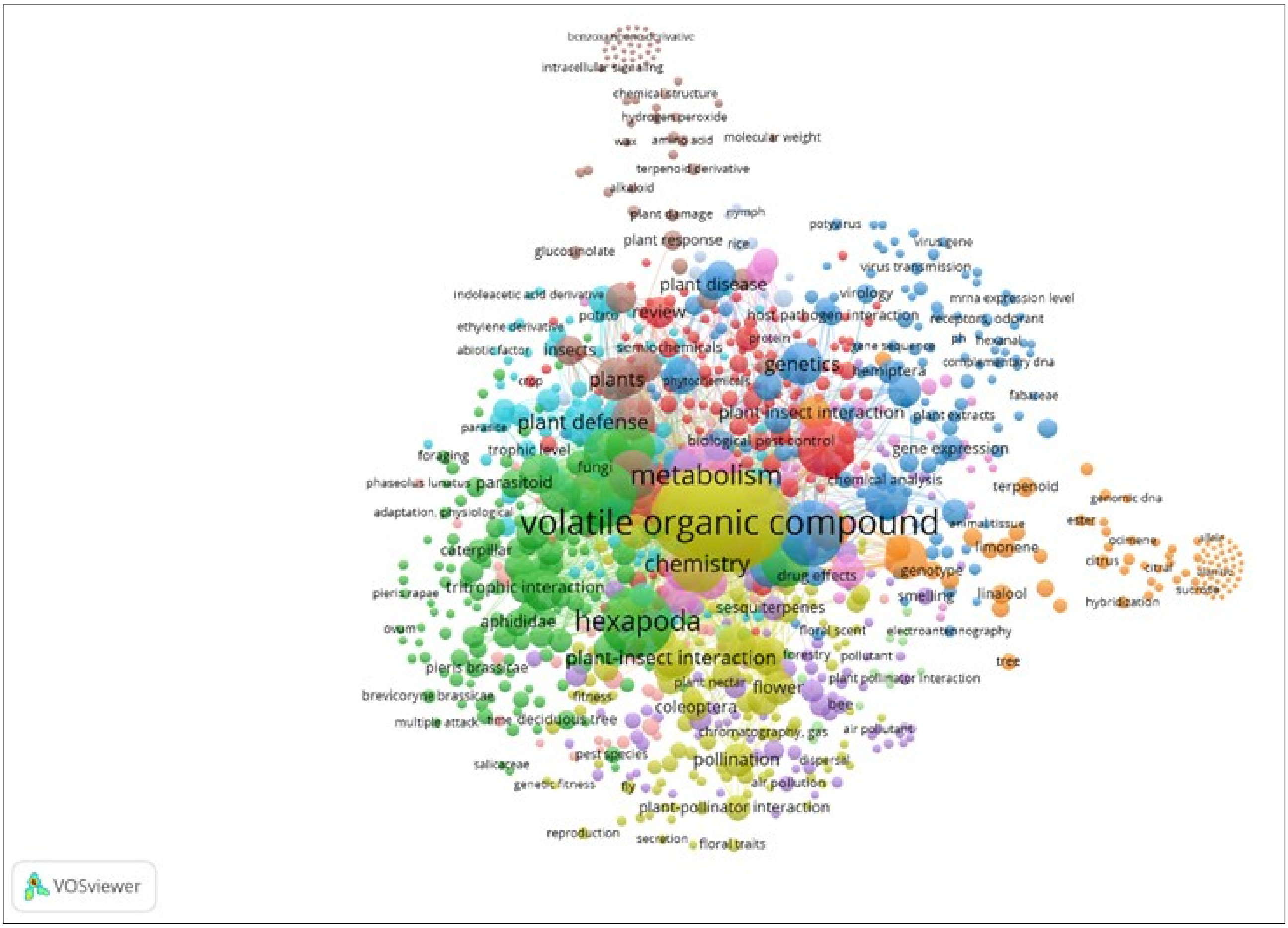

Fig. 8. Coupling the author’s keywords bibliographically. Source: Utilizing the VOS viewer's analysis, the author drew.

A separate cluster of keywords such as “pollination”, “flower” and “bee” indicate the overlap between VOC research and pollination ecology, highlighting how VOCs also influence plant-pollinator interactions. This map emphasizes the interdisciplinary and evolving nature of VOCs research. It reveals how themes from chemical ecology, molecular biology, insect physiology and applied plant science are tightly integrated. The dense network of nodes and strong interconnections illustrates not only topic diversity but also high cohesion and collaboration among subfields.

Ultimately, the co-occurrence network confirms the richness of this research domain and the need for continued exploration, particularly in areas such as pollination dynamics, genetic mechanisms and multi-trophic interactions. This thematic integration supports the broader goal of advancing ecological knowledge and sustainable agricultural practices through VOC-based research.

Tree map

Fig. 9 presents a tree map illustrating keyword frequency in VOC-related plant-insect literature. The largest block-representing “volatile organic compound”- is by far the most important topic in the field. Other frequently occurring terms, like “herbivory”, “animal” and “metabolism” are also highly prominent and contribute substaintially to the research landscape. The theme of the plant-eating insects is emphasized by the use of the term "herbivory" (204 hits), while the influence of VOC on insect physiology and biochemistry is reflected in the use of term “animal” (193 hits) and “metabolism” (138 hits). Other significant keywords—"hexapoda," "female," “larva” and "beetle—appear in smaller blocks, illustrating the diversity of the insect species represented in studies of VOC-mediated interactions. These terms disclose the emphasis on particular insect groups and relations with plants due to the emissions of VOC. Lower on the map, the term like “pollination”, “food behaviour”, "odor" and “plant defence” remind the greater ecological scenarios under which the VOCs act, beyond herbivory into the pollinator-plant relationship and chemical protection.

Further, keywords such as the term “genetics”, "signal transduction” and "moth" indicate that an increasing importance is being placed at the molecular and genetic routes of VOC production and even signal mechanism in plants as well as insects. The tree map effectively conveys the complexity of this field, highlighting a balanced focus on ecological, biochemical and genetic dimensions of VOC-mediated interactions. This visualization helps to define the most studied domains and provide the information about the probable ways of the future research development in this lively sphere.

Co-occurrence network

The co-occurrence network highlights dense interlinkages among core terms such as "volatile organic compound," "plant defence" and "insect," underscoring their central role in VOC research (Fig. 10). These primary nodes are strongly interconnected, underscoring the focus on how VOCs function as chemical cues in plant defence and insect behaviour. Surrounding these core terms are related keywords like "metabolism," "chemistry," "genetics" and "insect physiology," which further enrich the discussion by linking biochemical pathways and molecular mechanisms involved in VOC production and insect response.

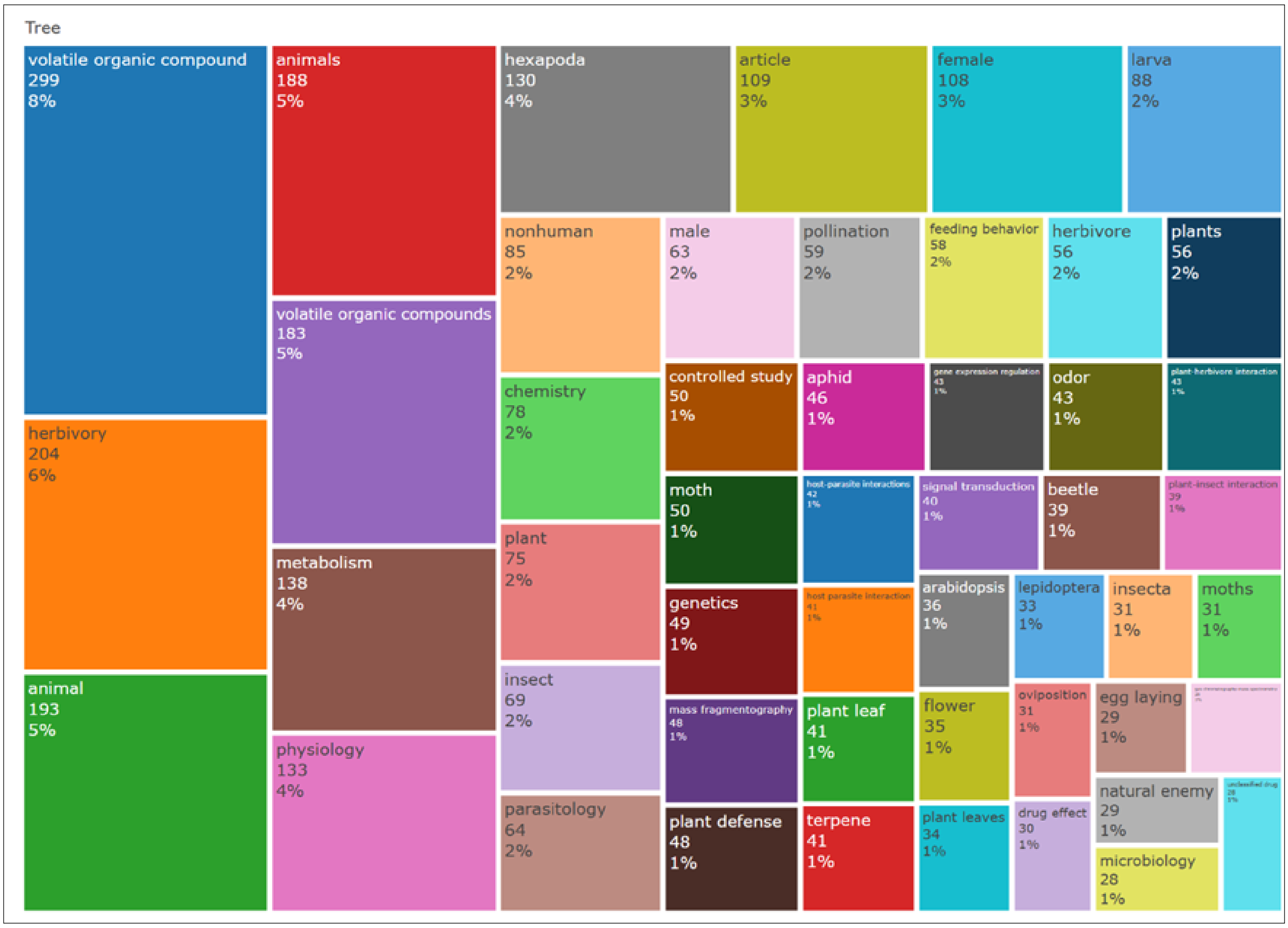

Fig. 9. Tree map.

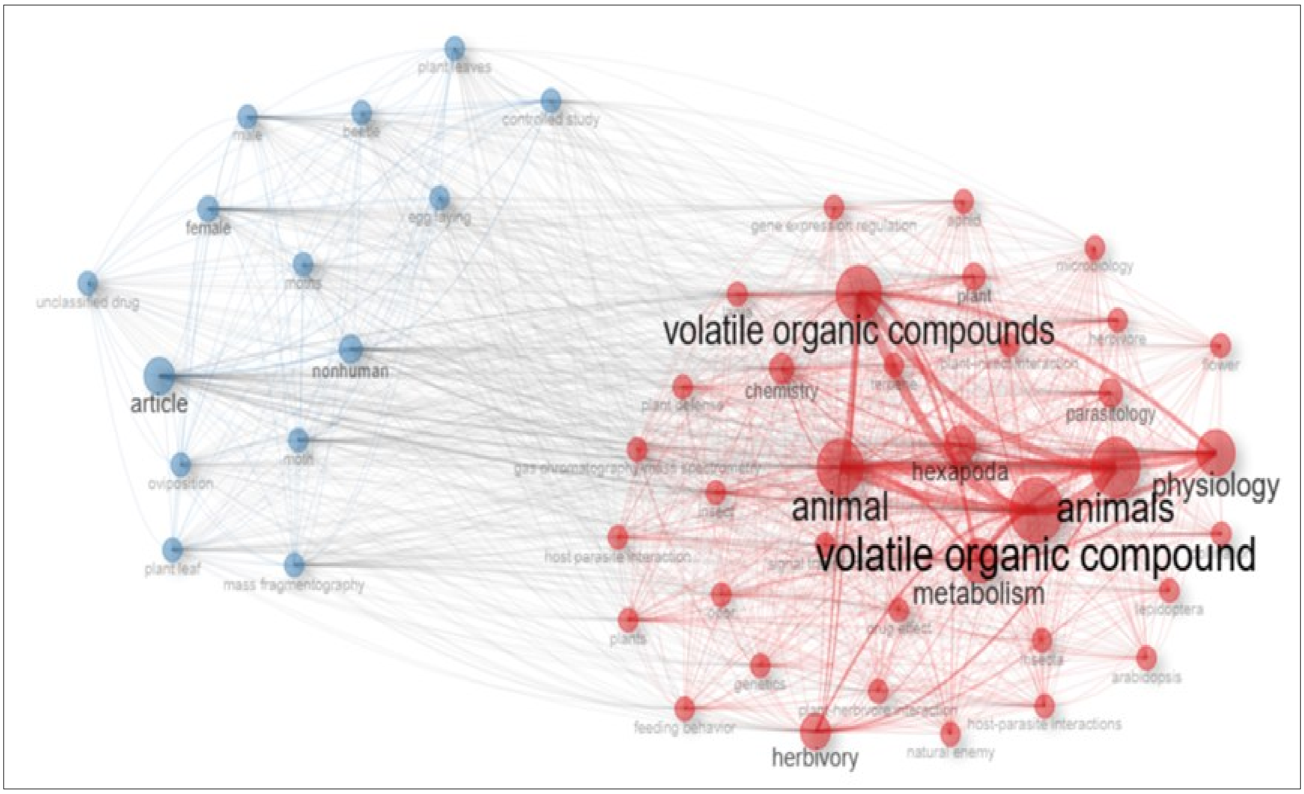

Fig. 10. Co-occurrence network of keywords.

The presence of terms such as "hexapoda," "beetle" and "aphid" highlights the diversity of insect species studied in relation to VOCs, emphasizing the broad spectrum of herbivores and pollinators involved in these interactions. The network also reveals clusters related to "pollination," "odor," and "plant-insect interaction," indicating the broader ecological significance of VOCs in plant-pollinator dynamics, not just plant defence. The interconnections between these terms suggest a growing interest in exploring how VOCs mediate various ecological interactions, from herbivory to pollination and beyond. This co-occurrence network provides valuable insights into the structure of current research on VOCs in plant-insect interactions, identifying both well-established areas of study and emerging themes. It highlights the interdisciplinary nature of the field, where chemistry, ecology and genetics intersect to deepen our understanding of plant-insect relationships.

Challenges and limitations in plant VOC-insect interaction research

Despite the growing interest in understanding plant VOCs and their influence on insect associations, several research gaps continue to limit ecological knowledge and practical applications. One major limitation is the lack of macroevolutionary studies investigating how VOC traits and insect sensory systems have co-evolved over long evolutionary times. The chemical diversity observed in plants remains unexplained by phylogeny, underscoring the need for broader evolutionary perspectives (12).

Another overlooked area is the role of non-volatile metabolites, which may exert substantial effects on insect behaviour and multitrophic interactions, particularly through root-mediated and rhizosphere-based processes (40). The impact of invasive plant species on native VOC communication networks is also a pressing issue, as such disruptions can interfere with host-finding signals in native insects and alter biocontrol dynamics. For instance, it was demonstrated that the invasive plant *Jacobaea vulgaris* emits VOCs that disrupt the ability of the native parasitoid *Microplitis croceipes* to locate its host *Helicoverpa armigera*, thereby weakening tritrophic interactions and reducing biological control success (41). Belowground VOC interactions remain even more complex, since volatile signalling between plants and fungi is still poorly understood due to technical challenges in sampling and analysing VOC emissions in soil environments (42). Finally, considerable uncertainty exists regarding how VOCs behave under variable field conditions, including fluctuating climates and dynamic insect communities. Addressing these gaps is critical for unlocking the full ecological and agricultural potential of VOCs.

Conclusion

This bibliometric review provides an integrated analysis of research progress on plant VOCs in plant–insect interactions, combining quantitative mapping with scientific interpretation. The upward trend in scientific output shows the growing importance of VOCs in fields like chemical ecology, sustainable pest control and molecular plant biology. Our analysis shows that while considerable work has focused on aboveground tritrophic interactions, including HIPVs and their role in attracting parasitoids or pollinators, other dimensions remain understudied. Notably, research on belowground VOC signalling and non-volatile metabolites is still limited, despite evidence that they play critical roles in rhizosphere communication and multitrophic interactions.

In addition, VOC-mediated interactions are increasingly shaped by climate-driven stressors and invasive species, which can disrupt native chemical signalling and ecological balance. The diversity and specificity of VOCs also reflect deep evolutionary relationships, although macroevolutionary studies exploring these patterns remain scarce. Technological advances in VOC detection, such as GC × GC-MS, transcriptomics and online sensors, have improved functional understanding, but real-time field validation and long-term ecosystem-scale studies are still lacking. Overall, this review maps the current structure of VOC–insect research and identifies critical directions for future study. At the same time, it underscores the need for interdisciplinary integration, ecological validation and broader methodological frameworks to unlock the full potential of VOCs in both basic science and agricultural innovation.

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Authors' contributions

AV conceptualized the topic, collected the literature and wrote the manuscript. MA supervised and edited the manuscript. AP has supervised in collecting the literatures and guided in writing manuscript. AS, PSS, MM, SV, PAS, KS, DA, SP and VB assisted in manuscript editing and reviewing. All authors read and approved the final version.

Compliance with ethical standards

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