Biocatalysis and Agricultural Biotechnology 45 (2022) 102502

Contents lists available at ScienceDirect

Biocatalysis and Agricultural Biotechnology

journal homepage: www.elsevier.com/locate/bab

Essential oils and their applications in agriculture and agricultural products: A literature analysis through VOSviewer

Linda Catani [a], Eleonora Grassi [a], Adele Cocozza di Montanara [b], Loretta Guidi [a], Roberto Sandulli [b], Barbara Manachini [c], Federica Semprucci [a,*]

[a] University of Urbino, Department of Biomolecular Sciences (DiSB), 61029 Urbino, Italy
[b] Parthenope University of Naples, Department of Sciences and Technologies, Laboratory of Marine Biology, Naples, Italy
[c] University of Palermo, Department of Agricultural, Food and Forest Sciences (SAAF), 90128 Palermo, Italy

A R T I C L E I N F O

Keywords:
Agriculture
Essential oils
Agriculture target activities
VOSviewer
Bibliometric analysis

A B S T R A C T

In agriculture, more attention has been paid to limit the amount of chemical plant protection products. A potential alternative solution has been found in essential oils (EOs), which appear as promising candidates for their properties (safe, bioactive, biodegradable products) in managing plant diseases in agriculture. Therefore, a co-occurrence analysis was carried out on the available literature on Scopus database, through network maps created by VOSviewer software in order to identify the EOs used in agriculture, agricultural products and their target application. USA and India appeared as the most productive countries in terms of documents and citations followed by Iran and Italy. The co-occurrence analysis revealed eight, more frequently used, EOs in agriculture, in particular, they found more applications as antibacterial and insecticidal agents. On the contrary, any specific EO for nematicidal and acaricidal activity emerged from the analysis. The EOs with the largest applicability were *Thymus* (mainly *T. vulgaris*), *Citrus*, *Rosmarinus officinalis*, *Origanum*, *Lavandula*, *Mentha*, *Ocimum* (mainly *O. basilicum*). Thanks to EOs main features, is possible to invest more in the research, as demonstrated by the increasing trend of documents published in the last decades and the list of high-quality journals interested in this topic. An easier interpretation of the great amount of data enables to identify what has been investigated till nowadays to shape the potential future progression and prospective in this research field.

1. Introduction

The future of the agriculture system will cope with the demand for significant changes: new dietary trends and solutions to reduce environmental impact. So, increasing attention has been devoted to the research of natural products in food safety and environmental protection. Since the interest in organic and, zero-mile agriculture has considerably grown and it is destinated to continue, it is necessary to find a sustainable alternative to synthetic products tipically used in conventional agriculture. To manage plant diseases, pests, and weeds without significantly affecting crop yields, a valid solution is essential oils (EOs) (Isman, 2016). EOs also called essences due to their peculiar odor, are volatile mixtures of different liposoluble organic substances most of which are aromatic. They can be produced directly throughout the plant, or they can be found in organs of the plant itself; in glandular hairs or secretory cavities of the plant cell wall or presented as droplets of fluid in the leaves, flowers, roots, fruits, stems and bark of different plants (Bakkali et al., 2008). The EOs are secondary metabolites produced by plants as a strategy to copy stressors. The aromatic features of EOs

* Corresponding author.
E-mail address: federica.semprucci@uniurb.it (F. Semprucci).

https://doi.org/10.1016/j.bcab.2022.102502
Received 2 August 2022; Received in revised form 18 September 2022; Accepted 26 September 2022
Available online 4 October 2022
1878-8181/

provide various functions for the plants including: repelling insects or attracting pollinators, shielding the plants from environmental stress (heat, cold, etc.), or protecting themselves from pests and/or insects, bacteria and fungi (Dhifi et al., 2016). Nowadays, EOs are widely used in the cosmetic and nutraceutical industry as components or as food or flavoring additives. The use of these natural compounds in agriculture is very interesting for the defense of plants from phytopathogenic fungi and bacteria (Ascrizzi et al., 2021) but also for the control of weeds and crop protection purposes. The main components of EOs are monoterpenoids, regarded as candidates for insecticidal activity (Digilio et al., 2008). Several studies have shown that EOs present antibacterial properties against pathogens, which can cause post-harvest diseases in vegetables and fruits (Alonso-Gato et al., 2021). Recently, even more, research is based on finding and applying selective and biodegradable compounds to solve the problem of persistency and toxicity to mammals

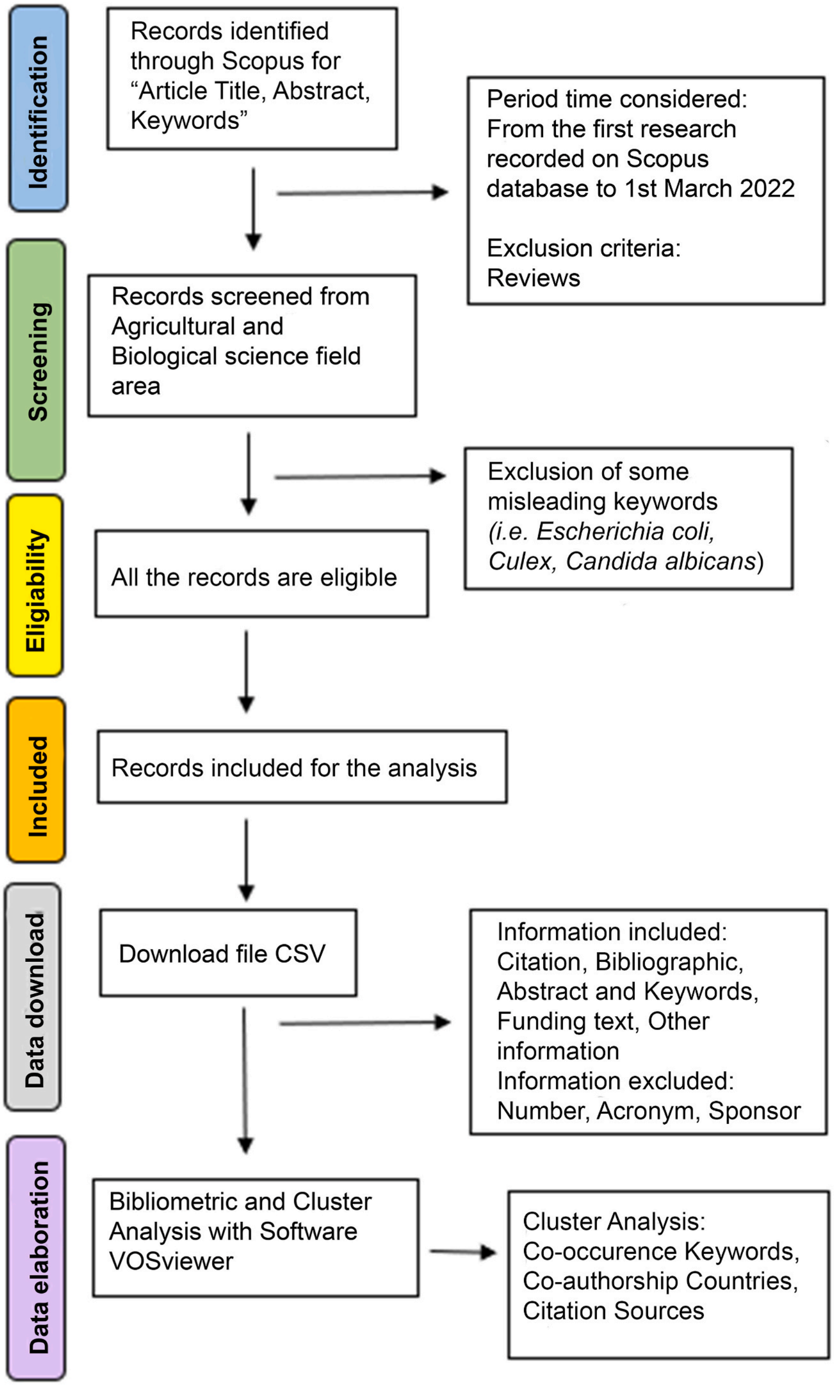

Fig. 1. Flow diagram, criteria for the present research with VOSviewer.

and the environment. Much research on this application of EOs has been carried out *in vitro*, but there are also very promising scientific works in field (*in vivo*). Only a few studies have considered the application of EOs in the field, in the greenhouse or directly on the crop to reduce the use of synthetic pesticides but the topic is arising great interest in the context of environmental protection (Abd-Elgawad et al., 2021; Renčo et al., 2021). One of the main challenges encountered in the development of these biopesticides using volatile molecules is their short persistence (degradation, volatility etc.) in comparison to synthetics. Biopesticides cover a wide spectrum of potential products used as plant protection products (PPPs), in the case of the majority of EOs as biopesticide they can be considered as products based on plant extracts (Europe Parlament and Council of European Union, 2009). In this context, EOs can be considered as botanical active substances that are -with current knowledge- known to be unharmful for humans, animals and the environment and are based on materials with known specifications e.g. food grade. However, it is important to remember that EOs, unless demonstrated the safe use, are active substances which, in accordance with Article 23 (EFSA 2021) of the European Commission Regulation (EC) No 1107/2009, need an application for approval as a 'basic substance' to be used in plant protection as acaricide, insecticide and fungicide following the new adoptation procedures and guidelines (Ockleford et al., 2017). Further investigations need to be performed to completely understand how EOs may be used in sustainable agricultural practices. Since the topic appears to have a bright future, it is important to understand where the research on EOs in agriculture has advanced. In particular, the purpose of this work is to investigate in what ways the EOs have been evaluated during the last decades. The present research is based on collecting all the research available as literature by answering the following questions: 1) where and how have the essential oils (EOs) been applied in agriculture and agricultural products; 2) which are the main essential oils (EOs) target activities in agriculture and agricultural products. The paper proposes a full view by investigating with software that helps to deepen different aspects of research: countries that publish most of the topic, the most used keywords within publications and the journals in which authors publish their works.

2. Methodological approach

2.1. Data sources and research method

To ensure the scientific integrity of the data source, this research literature is derived from the core collection of The Elsevier® Scopus library services Metabase (www.scopus.it), that was chosen for its wide coverage. During the research on Scopus the association of two keywords was used to reply to the two questions reported above. The keywords used for the first question are the combination of "essential oil" and "agriculture". While for the second question it has considered the association of "essential oil" with the biotic adversities in plants such as bacteria, fungi, nematodes, insects and mites. All the keywords were searched using Boolean operators AND. Fig. 1 shows the PRISMA procedure adopted in the research for articles collection. The period considered for each research began from the evidence of the first document available on the Scopus database to the March 1, 2022.

2.2. Bibliometric network analysis

VOSviewer software version 1.6.8 was used to perform all the analyses (van Eck and Waltman, 2010; Gradus et al., 2017). The maps created are composed of nodes or items linked by connections. The node size is directly proportional to the number of documents it represents. The visualization approach is based on the distance between nodes, therefore, a short distance between nodes reveals a closer relationship between them. To sum up the main technical terms, they are listed and explained in Table S1.

The data exported have been analyzed in both cluster and overlay visualization for the research of the co-authorship among countries, the co-occurrence of keywords and cited scientific journals. The overlay visualization where the maps are weighted on the average number of citations and average year of publication. Especially for the co-occurrence of keywords in each research, it has been created a thesaurus file, which aims to avoid the repetitions and synonyms among the keywords and allows the unification of terms (e.g. essential oil/essential oils were unified in the singular form essential oil), making the network map more readable (Table S2).

3. Results and discussion

The number of publications that address issues related to EOs, as reported in the next sections, is very high, which makes it difficult to gain a general perspective of the development of research in this area of knowledge. This section provides a bibliometric analysis of the publications related to the agriculture sector and pathogens and pests of agricultural plants.

3.1. Where and how have the essential oils (EOs) been applied in agriculture and agricultural products?

The combination of "essential oil" AND "agriculture" terms produced on Scopus 1044 documents, that after the exclusion process described in Fig. 1 decreased to 487 documents. The documents resulted included in the temporal span between 1973 and 2022 (Fig. S1). Although the research counts 50 years, it is notable a production gap in documents until the 1990s. The number of research papers was on the rise by the end of the nineteen century. However, the topic has gained a larger increase in publishing since 2018 and 2021 and exactly this latter resulted the most productive year with a total of 60 documents (Fig. S1).

3.1.1. Countries involved

Based on the author's cooperation relationship, VOSviewer is used to analyze the cooperation and influence of the country and research institutions. The research on essential oils (EOs) and agriculture covered 75 countries, a minimum of five documents per country was set as the threshold and 28 countries met this criterium. The countries were divided into eight main clusters. India resulted as the leader country in several documents (70) followed by the United States (63) and Iran (58) (Fig. 2a). The ranking for citations and links with other countries is headed by the United States (2032 citations, 36 links) and Italy (1484 citations, 25 links), while India revealed a marginal collaboration with other countries (only 10 links) as appeared in Fig. 2b.

3.1.2. Frequency of keywords

The keywords analysis allowed us to discover the most used terms and their relationships, from which the main research topics related to the analyzed field can be derived. The results permit to evaluate trending topics of current research. The number of co-occurrence of keywords in the publications is 4526, in which at least 5 keywords occur together in the title, abstract, or keywords list. This number was reduced to 4237 after the production of a thesaurus file. Forty-six keywords met the thresholds and they resulted grouped into 5 clusters (Fig. 3). The sub-division in clusters reveals five possible application fields of the EOs, cluster: 1. is principally focused on the types of EOs and their applications in the field as revealed keywords such as "plant leaf", "manure", "seed" and "soil" (cited EOs are *Origanum*, *Ocimum basilicum*, *Thymus vulgaris* and *Mentha*); 2. relates to compounds present in EOs and their possible application (e.g. cited EO is *Citrus)*; 3. handles with activities needed to tackle fungi and bacteria; 4. composed of two EOs extracted from flower petals *Lavandula* and *Cymbopogon*; 5. is composed of three items referred to how humans perceive and analyze EOs (Fig. 3). The most recent keywords used in publications can be distinguished into two groups in Fig. S2, there are keywords referred to the soil as "manure", "irrigation" and "arbuscular mycorrhiza" (soil microorganism). Regarding the number of average citations, the highest number is correlated to "antifungal agent", "anti-infective agent", "insecticide", "insect repellent" and again "nanoparticle". "*Cymbopogon*" appears as the most cited EO (Fig. S2). As recognizable from Figs. S2a and b, phytopathogenic fungi attracted increasing interest because responsable for considerable economic losses in agriculture (Felšöciová et al., 2020). The co-occurrence analysis highlighted the use mainly of seven EOs that find frequent and effective applications in crop production and food preservation (Figs. 3 and 4).

Cymbopogon EO is often used to prevent the attacks of fungi and bacteria during the storage of many types of fruits and vegetables e. g. *Cymbopogon citratus* (rich in citral, thymol and carvacrol) is used in post-harvest decay control (Antunes and Cavaco, 2010). Antonioli et al. (2020) documented as nanocapsules, containing lemongrass citral, protected the apples after harvesting from *Colletotrichum acutatum* and *C. gloeosporioides*. Nanoencapsulation techniques are increasingly becoming a consolidated method for the application of EOs in agriculture offering numerous advantages such as better solubility in water, effective protection against degradation, prevention of evaporation of volatile components and controlled and targeted release. In particular, nanoprecipitation seems to be the most suitable nanoparticle preparation technique for EOs agricultural applications as an antifungal agent, anti-infective, insecticide and insect repellent (Lammari et al., 2020).

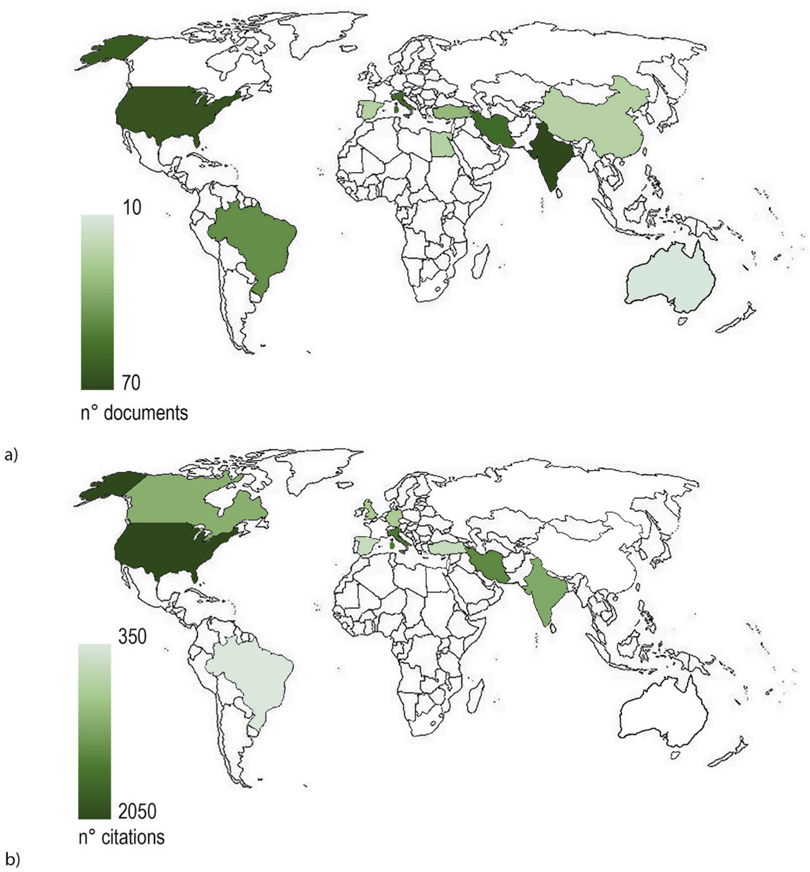

Fig. 2. List of 10 countries ranking by number of (a) documents and (b) citations, Co-authorship analysis of countries. Thresholds were set as a minimum of 5 documents per country in co-authorship among countries. Each country is coloured according to the number of documents referred to the scale bar.

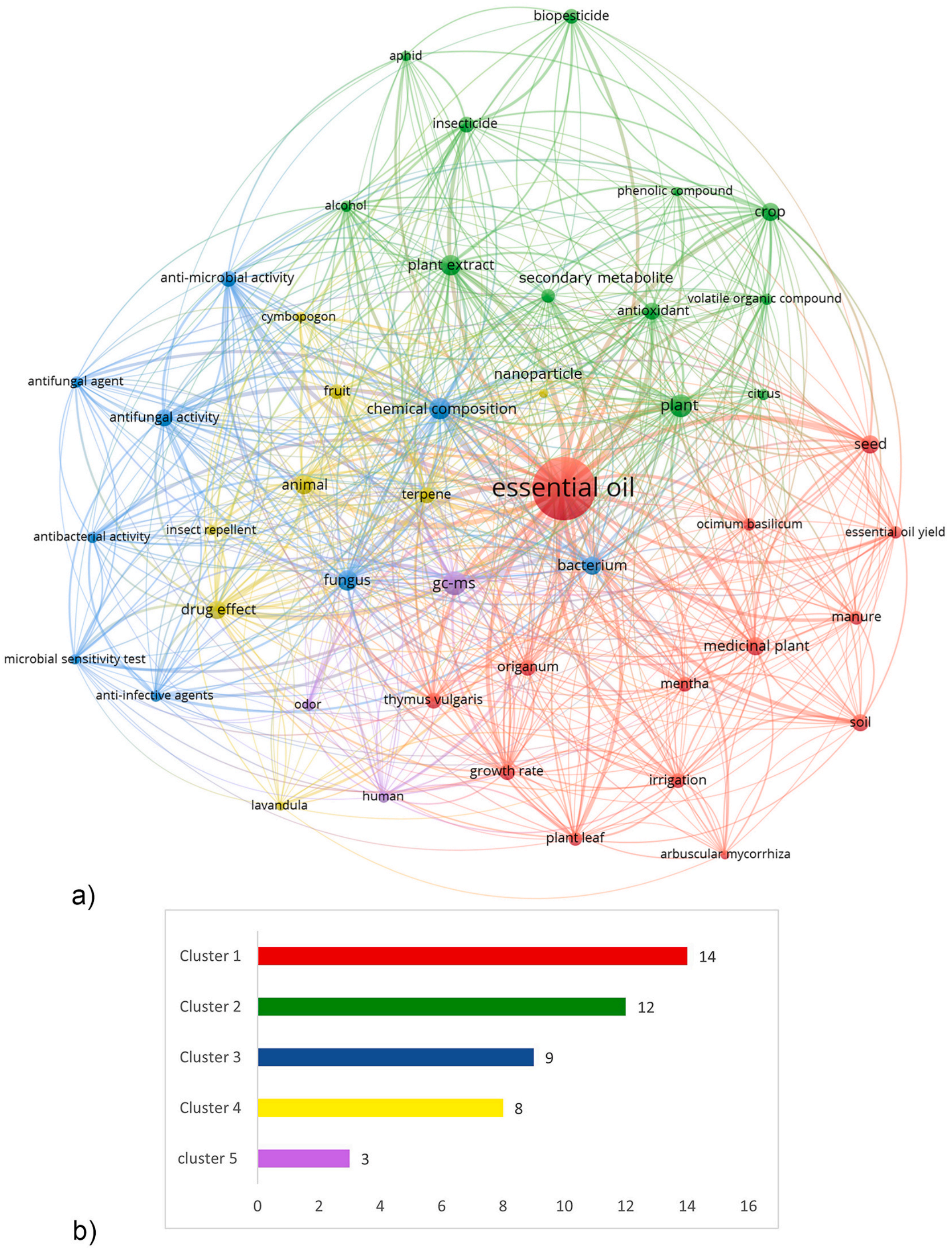

Fig. 3. Network map of keywords co-occurrences for research "essential oil" AND "agriculture" divided in the cluster (a) and number of keywords for each cluster (b) (plot created by VOSviewer software).

3.1.3. Citation analysis for sources

The citation analysis of sources represents the network created by the link between a journal that cites another. The analysis produced an overall number of 239 journals and, among them, only 11 journals met the criterium (i.e. a minimum of 5 documents per journal set as threshold). The results of the analysis underlined 10 specialized journals on the topic (Fig. 5). Industrial Crops and Products is the journal in which a higher number of documents was found (67), followed by the Journal of Agricultural and Food Chemistry (20) and Acta Horticulturae (15). The first two journals lead the ranking for citations too. Exception for Acta Horticulturae, the first five sources occupy the first quartile (Q1), underlining the importance that the scientific community gives to articles on EOs.

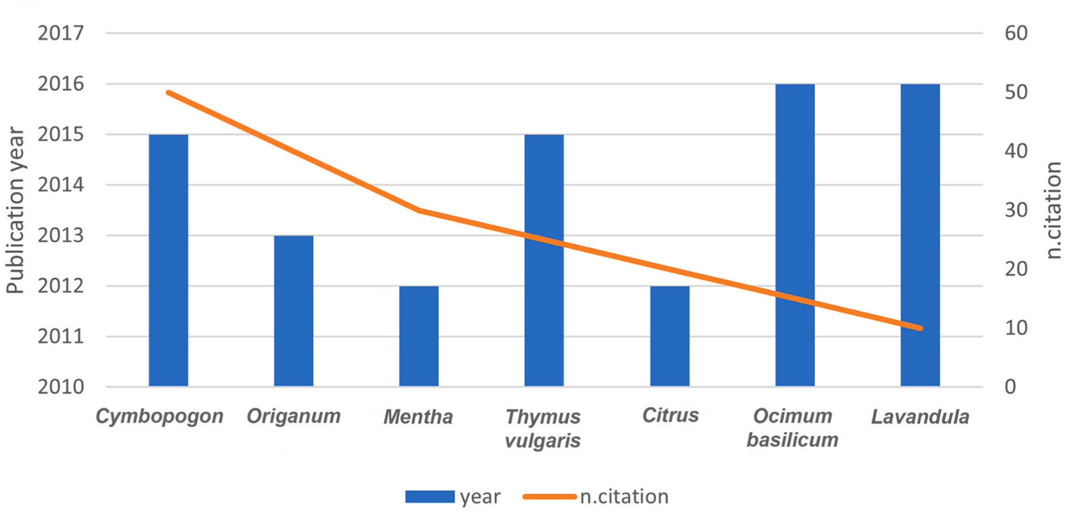

Fig. 4. The essential oils for average publication year and number of citations for the research "essential oil" AND "agriculture".

3.2. *Which are the main essential oils (EOs) target activities?*

For answering the question, six research were done by associating the keyword "essential oil" with one of the main target activity of the EOs (Table S2). In the results below, only the frequency of keywords in cluster and overlay visualization has been represented. The research is listed in descending order according to the number of documents found on Scopus.

3.2.1. *Essential oils (EOs) and antibacterial*

Association between the terms "essential oil" and "antibacterial" produced 1331 documents, which is the highest number when compared with other analyses. Moreover, the period time considered is the largest affirming the importance of the research on the topic within the scientific community. The most productive year is 2021 which goes beyond 200 documents (Fig. S3a). The great number of keywords is reduced to 33 by the thesaurus file for a minimum of 10 occurrences of a keyword. The 4 clusters emphasize thematic divisions, in particular, Cluster 1 includes most of the interrelation between bacteria and EOs and cluster 4 correlates the keyword "fruit" to "antifungal agent" (Fig. 6).

The overlay visualization for average number of citations have a low number (around 9) as shown in Fig. S4. EOs "*Rosmarinus officinalis*" and "*Cinnamon*" stand out for citations nearly to 50 followed by *"Origanum"* and *"Thymus vulgaris"* with nearly 40. Both

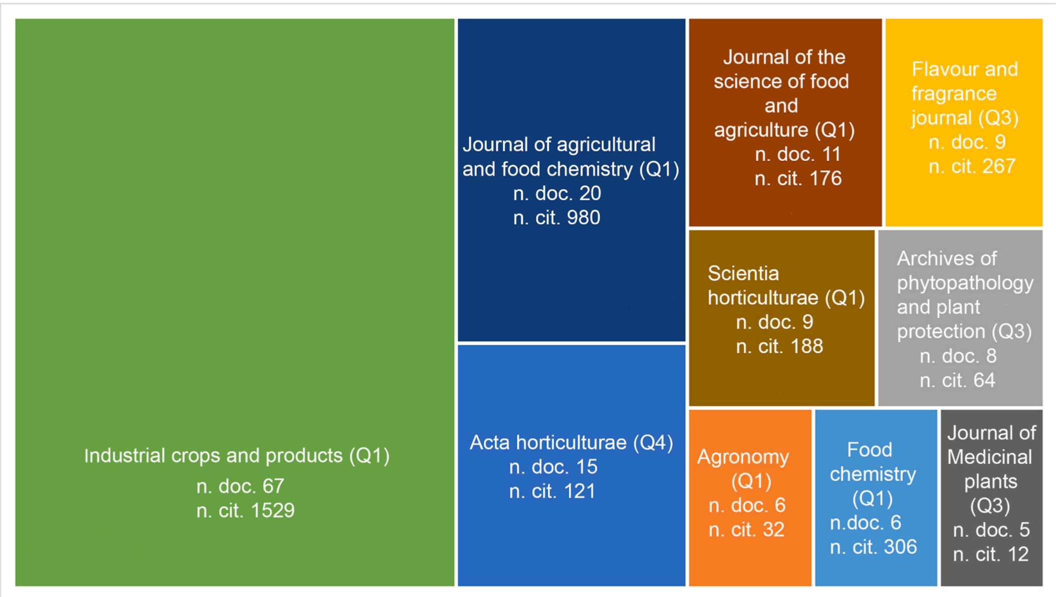

Fig. 5. List of the journals ranked by number of documents from citations-source analysis for research "essential oil" AND "agriculture". Each journal shows the number of documents and citations. In brackets is indicated the Quartile ranking as reported by Journal Citation Reports (JCR).

keywords are related to another well-cited keyword "*Listeria*". This last genus is a bacteria causing foodborne listeriosis, one of the most severe foodborne diseases that is caused mainly by the *L. monocytogenes*. Listeriosis counts from 0.1 to 10 cases per 1 million people per year depending on the countries and regions of the world (World Health Organization). Although it is a rare disease, the high number of death associated with this infection makes it a significant public health concern. In addition, these bacteria survive and multiply at low temperatures usually found in refrigerators. Therefore its control is required at all stages in the food chain (FAO, 2007). So literature regarding the prevention methods to this pathogen is quite huge and EOs are considered as potential ones (FAO, 2007). Indeed, EOs show antibacterial proprieties both against foodborne bacteria and plant pathogen bacteria such as *Xanthomonas* spp., *Clavibacter* spp., *Erwinia* spp. and the species *Agrobacterium tumefaciens* (Raveau et al., 2020). EOs are found to be antibacterials due to their large amount of chemical constituents (i.e. phenolic compounds such as carvacrol, eugenol and thymol (Burt, 2004), whose dispare structures allow them to penetrate inside the lipid bilayer of the bacterial membrane. The EOs action mechanisms depend on targets (Burt, 2004), a mechanism deals with the loss of ions and other cellular content resulting in the death of the bacterial cell, while other mechanism includes degradation of the cell wall, coagulation of the cytoplasm, damage to membrane proteins, reduction of ATP production, etc. (Burt, 2004). Gram-negative bacteria are more resistant to the antibacterial activity of essential oils and their components because of the structure of the cell wall of these bacteria that is more resistant to the entry of hydrophobic molecules than one of Gram-positive (Nazzaro et al., 2013).

3.2.2. Essential oils (EOs) and insecticide

Two keywords "essential oil" and "insecticide" in the research on Scopus produced the second-highest number of documents. Overall, 985 documents were considered after the exclusion from Scopus of some keywords that clearly referred to dangerous insects for humans (e.g. *Culex* and *Aedes*). The terms "insecticides" or "pesticides" are commonly used as a synonym for plant protection products. However, insecticides or pesticides are broader terms that also cover products such as biocides, which are intended for non-plant uses to control pests and diseases and do not fall within the remit of this paper.

The period considered for all documents starts from 1971 to 2022 (Fig. S3b). The maximum pick is reached in 2020 with a production of 107 documents. Compared with other research, this thematic is the most investigated since the 2000s, showing a great interest in the scientific field.

The great number of documents gives above 5k of keywords. A minimum of 10 occurrences has been considered only in this

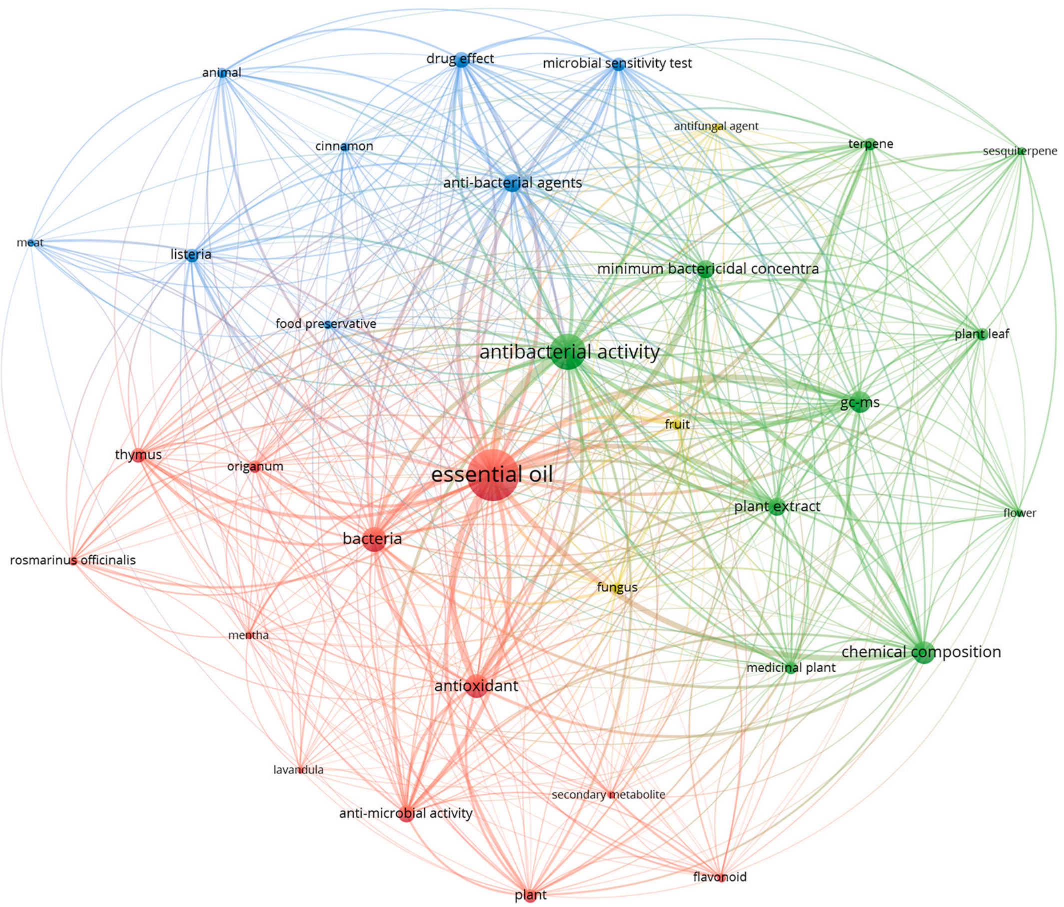

Fig. 6. Network map of keywords co-occurrences for research "essential oil" AND "antibacterial" divided into clusters (plot created by VOSviewer software).

research. The result from the thesaurus file leads to 34 keywords, divided into 5 clusters (Fig. 7). The highest number of keywords belong to red cluster with 14 keywords, 6 of which EOs i.e. *Mentha, Citrus, Lavandula, Origanum, Rosmarinus officinalis, Ocimum basilicum*.

The use of synthetic pesticides is still the principal approach in pest management, although the widespread use has resulted in numerous side effects, such as environmental contaminations, the accumulation of hazardous residues in food and high toxicity to non-target organisms and the resistance of beetles to frequently used chemical pesticides. Indeed, EOs are mainly tested against insect pests of stored food products (Campolo et al., 2018), for this reason, the keyword "*Tribolium*" appeared as one of the most relevant. *Tribolium*, a genus of flour beetles, which includes *T. castaneum* and *T. confusum*, is one of the most common infestants in home and grocery stored products (flours, bread, rice, seeds, corns, dry legumes).

The EOs above mentioned have insecticidal and insect-repellent properties: e.g. the EO extracted from plants of the genus *Citrus* showed insecticidal activity against *T. castaneum* and *Rhyzopertha dominica* (Coleoptera: Bostrichidae) when used in stored wheat (Kumar and Pandey, 2021) as well as *Lavandula* oils were effective against the beetles *Callosobruchus maculatus* (Coleoptera: Chrysomelidae) (El Abdali et al., 2022). Thyme, rosemary and basil EOs also showed insecticidal and insect repellent activity against *T. confusum* and the rice weevil *Sitophilus oryzae* L. (Coleoptera: Curculionidae) a stored product pest which attacks seeds of several crops, including, rice, wheat and maize (Saroukolai and Meshkatalsadat, 2010; Caballero-Gallardo et al., 2011; Al-Harbi et al., 2021).

According to the overlay visualizations for both average citation and publication year, it is notable that even if the thematic is deeply investigated, publications and citations on the topic are seasoned, as demonstrated in Fig. S5, where blue color is predominant. The newest published keywords include "antioxidant", "beetle", "biopesticide", "monoterpene" and "moth" (Fig. S5b): two of them are insects that can infest crops or stored products, "monoterpene" is a class of terpenes in the EOs extracted from plants, "antioxidant" is referred to a substance. The proximity between the keyword "biopesticide" to the others (such as *Mentha, Citrus, Origanum, Lavandula, Rosmarinus officinalis*) might suggest that some essential oils are used as biopesticides. While the number of citations is average 25 for

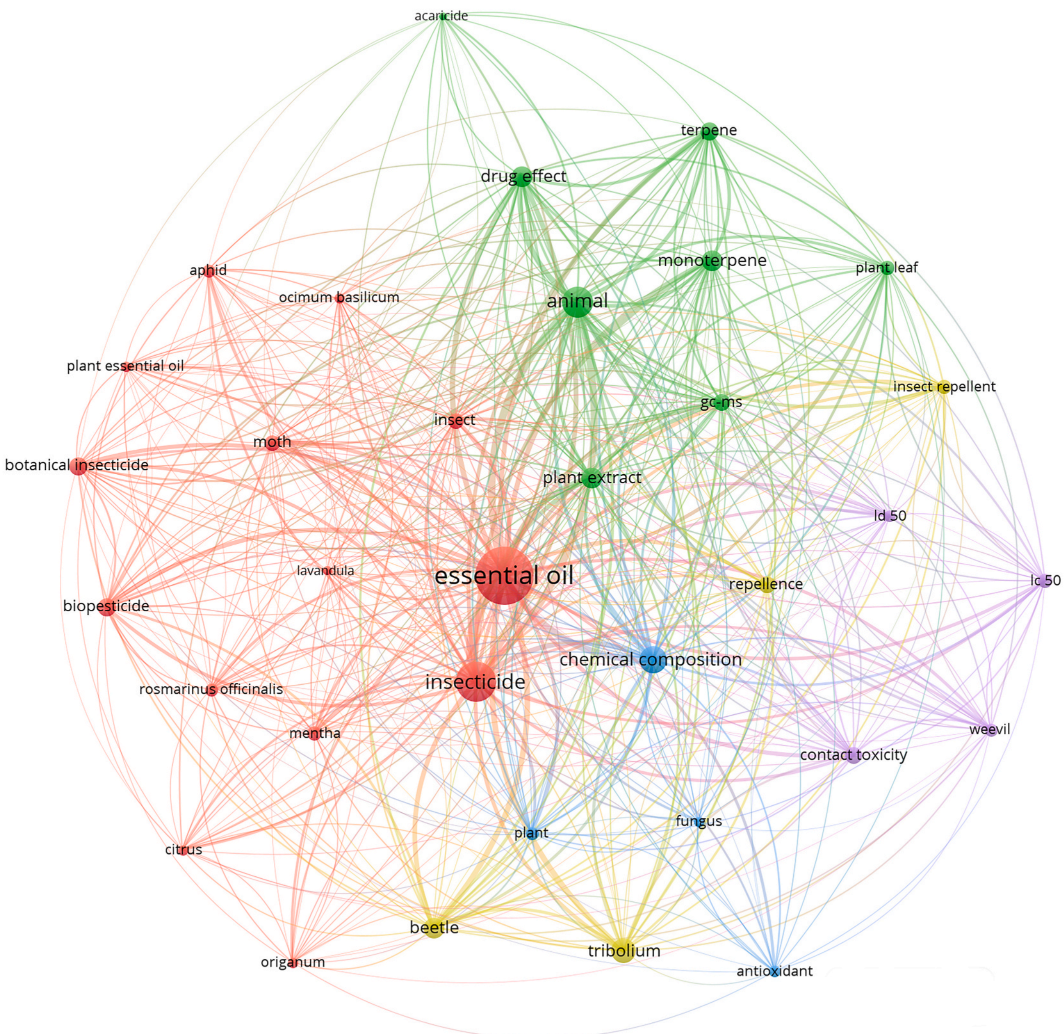

Fig. 7. Network map of keywords co-occurrences for research "essential oil" AND "insecticidal" divided into clusters (plot created by VOSviewer software).

all keywords on the map, exception of “plant essential oil”, “insect” and “aphid”, which reach the top of 50 citations (Fig. S5a). Currently, EOs and their components, mostly monoterpenes (linalool, thymol, eugenol, menthol, etc), can be PPPs.

Despite the promising results, there are still few authorized commercial EO-based insecticide formulations available on the market (Isman, 2020).

3.2.3. Essential oils (EOs) and fungicidal

The combination between the keywords “essential oil” and “fungicidal” produced 318 documents. The research is deeply investigated by the scientific community since the period goes from 1961 to nowadays, however, a gap in production from the 60s to the 80s was observed. The year 2021 is targeted as the most productive one, with 42 documents published (Figure S6a). Out of 2326 keywords in total for all documents published, 209 met the threshold of a minimum of 5 occurrences per document. After the thesaurus file, the total number decreased to 2140. The map is composed of 22 keywords grouped in 4 clusters (Fig. 8).

As for the bacteria, the majority of the literature is regarding fungi that cause diseases linked to food. The figure shows that the attention was paid more to the type of EOs rather than the fungal species. However several studies were carried out on plant-pathogen fungi such as *Alternaria* spp. *Aspergillus* spp. and *Botrytis* spp. (Raveau et al., 2020).

In the overlay visualization weighted on average publication year, it is notable that most of the keywords in the map are recently used since the network tents to the yellow color (Figure S7a). The oldest ones, i.e. “plant extract”, are referred to aromatic plants as “*O. basilicum*”, “*Thymus vulgaris*” and “*Origanum*” which are the most cited. Among the most cited keywords stands out “aflatoxin” and “food preservation”(Figure S7b). Despite the moderate antifungal activity of the EO of *Origanum vulgare*, its main components, i.e. carvacrol and thymol, have shown great application potential as natural fungicides for the prevention and control of plant diseases caused by the gray mold, *Botrytis cinerea* (Hou et al., 2020). *B. cinerea* has developed resistance to many fungicides making necessary to find new compounds that are safe and effective. Again carvacrol and thymol together with eugenol, show to inhibit infestation of infected orange fruits with a suspension of *Penicillium digitatum* and *Geotrichum candidum* spores or a mixture of both, using strains resistant to chemical fungicides. The presence of keyword “fruit” is linked to this treatment that demonstrated to be effective in reduction or inhibition of fruits decay development. Some components of EOs have potential as active compounds for the formulation of natural preparations to use as alternatives to synthetic fungicides for the management of green, blue and sour rot in citrus fruit (Moussa et al., 2021). For this reason keyword *“Citrus”* has gained attention in the publications of the last years, as reveled its yellow color in Fig. S7a.

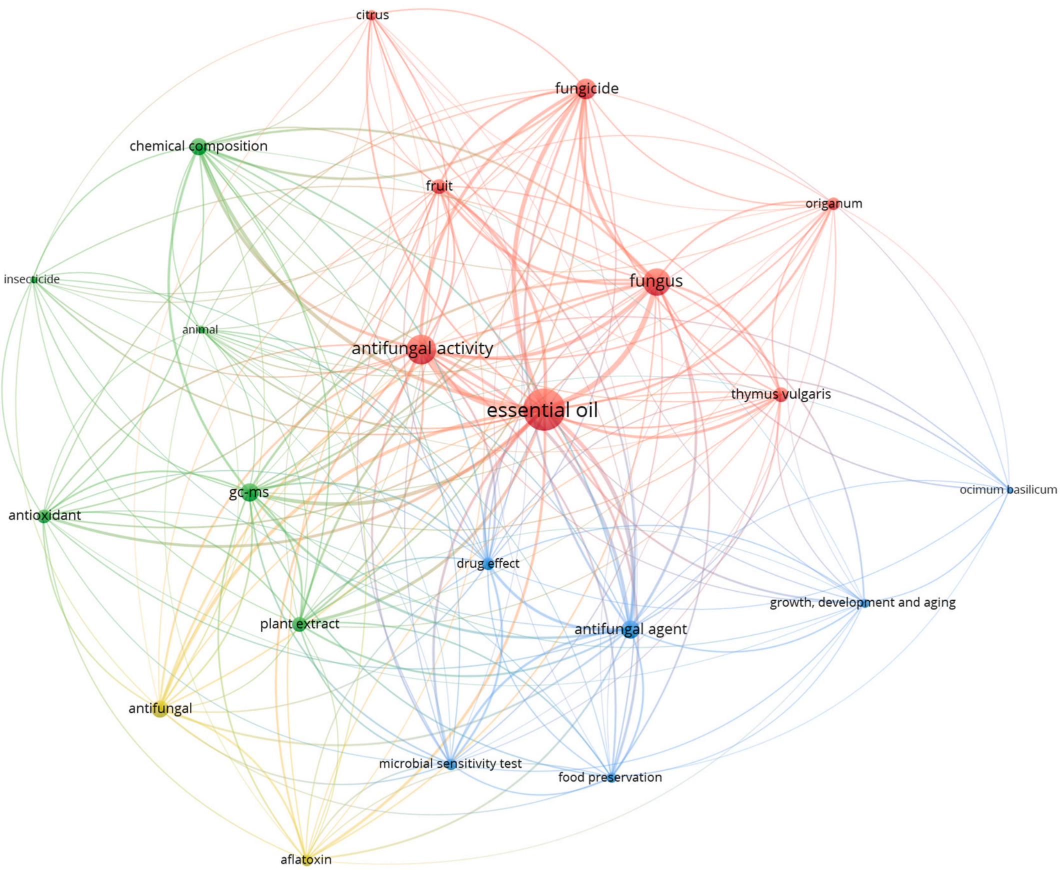

Fig. 8. Network map of keywords co-occurrences for research “essential oil” AND “fungicidal” divided into clusters (plot created by VOSviewer software).

3.2.4. Essential oils (EOs) and acaricide

Keywords "essential oil" and "acaricide" gave 138 documents, here some misleading keywords referred to mites of veterinary interest were excluded (i.e. cattle, cattle disease, cattle tick, ixodida). The application of EOs as acaricide is relatively recent, considering the first document in 1998, and not particularly explored since the number of documents is on average 9 per year. The maximum production is reached in 2021 with 22 documents (Fig. S6b). Out of 1225 keywords, 100 composed the network, however, the thesaurus file reduced the keywords to 1140 which decreases keywords in the network map to 15. The keywords are grouped in 3 clusters (Fig. 9). Among the EOs compounds, carvacrol has been shown to have excellent acaricidal activity thanks to its toxicity to mites even at low concentrations. Monoterpene 1,8-cineole, from plants of the *Eucalyptus* genus, Myrtaceae family, showed powerful acaricidal activity (Xu, 2019). The hypothesized mechanism of action is that these substances may act by inhibiting cytochrome P450 enzymes or interfering in the nervous system, damaging biochemical and physiological functions of ectoparasites (Camilo et al., 2017). The overlay visualization of the network map is weighted on the average year of publication, from 2010 to 2014. The most relevant and newest published keywords (Fig. S9a) are "Tetranichidae", one of the most abundant mite family in agriculture, followed by the keywords "mite" and "honey bee". This last keyword is closely linked to "Varroidae", a parasitic mite family, to which belong *Varroa destructor* one of the major pest of honey bees. EOs and their components appear as candidates used mainly to control the population of the *Varroa destructor* instead of synthetic acaricide (Conti et al., 2020; Hýbl et al., 2021). In the network map (Fig. 9), any EOs appear in association with the most frequently used keywords. However, various EOs were tested and recorded to have acaricidal activity against agricultural mite pest such as *Tetranychus urticae* (Han et al., 2010; Araújo et al., 2012; Attia et al., 2011; Laborda et al., 2013). Regarding the citation's number for each keyword, the range is between 20 and 40. The citations reach the maximum only for the keywords "plant extract" and "insecticide", while immediately behind appears "Tetranichidae" (Fig. S9b).

3.2.5. Essential oils (EOs) and nematicidal

Only 93 documents appeared for the search using "essential oil" and "nematicidal". The word "nematicidal" has been chosen because with nematocidal, nematocide or nematicide the results on Scopus were less than ten, sustaining not trustable research. The aim of the search is not to use specific keywords but rather to investigate how inquired are some topics. The nematicidal activity linked to EOs is not much investigated yet. The thematic counts barely above ten documents per year. This is the first research that does not give results in publications for the current year 2022 (Fig. S8). In 93 results researched, there were found 978 keywords of which only 53 met the threshold and after thesaurus, the keywords were reduced to 933 and were divided into 2 clusters: one composed of 3 (animal, antinematodal agent, terpene) and the other of 5 keywords (i.e. nematode, essential oil, *Bursaphelencus*, *Meloidogyne*, plant extract). According to overlay visualization (Fig. S10) weighted for the average year of publication, it is observable how predominant are the two keywords in yellow "essential oil" and "*Meloidogyne*" over the others. Indeed, this phytoparasite nematode genus is known as root-knot nematode and it is considered one of the key pests of several important crops (Ralmi et al., 2016), causing damages and

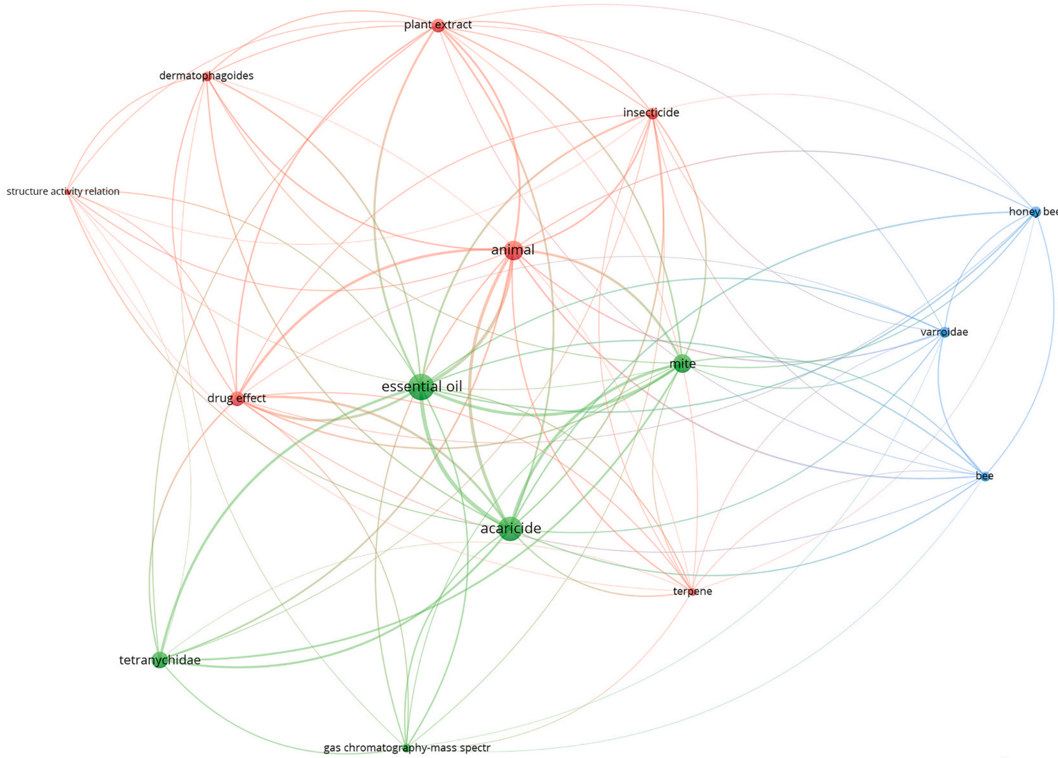

Fig. 9. Network map of keywords co-occurrences for research "essential oil" AND "acaricide" divided in the cluster (plot created by VOSviewer software).

losses of 2–5 billion dollars per year (Richard et al., 2021). There are several species of *Meloidogyne* and their management and control are often difficult, even with chemical nematocides. In addition, considering the adverse effect of chemical pesticides and the reduced number of active compounds registered as nematocides, alternative control methods are still advisable. EOs are considered as potential control methods, especially as nematode static.

In this case the citation scale reached for the first time 55. The most cited keyword are "*Bursaphelencus*" and "antinematodal agent". *Bursaphelencus* genus counts 125 species, several of them are obligate and facultative plant-parasitic nematodes. Most species have a phoretic relationship with insects, especially bark beetles and wood borers, and are associated with dead or dying conifers, for example *B. xylophilus*, one of the most dangerous forest pathogen in the world causes devastating pine forest deaths with considerable economic losses. Alternative nematocides control methods should bet on EOs, thanks to their successful activity against the major plant feeders nematodes (Oka et al., 2000; Faria et al., 2021; Ardakani and Hosseininejad, 2022) and their absence of side effects on natural environments (Mohan et al., 2011).

4. Concluding remarks

The bibliometric quantitative analysis has taken hold in the recent years and VOSviewer is regarded as one of the most promising software to analyze large spectra of data for title, keywords, word frequency, citation information, authors, countries etc … (Zhou et al., 2021). This method can process large numbers of documents from many analysis angles at the same time (e.g. research status, research institutions, and research hotspots, possible future application fields), and the analysis results have high reliability and can be easly visualized with network maps (Zong and YuanShen, 2012).

From the VOSviewer co-occurrence analysis on the keywords, some EOs resulted mainly associated with particular target activities as summarized in Fig. 10. According to this schematization, the highest number of EOs is primarily associated with antibacterial and insecticidal activities (6 out 8 EOs are included), both activities comprise EOs of *Rosmarinum officinalis*, *Origanum*, *Lavandula* and *Mentha*. Investigations on these activities are associated with the increased interest in finding a sustainable alternative that can minimize the damages produced by pesticides (health problems and economic losses). It has been demonstrated that the use of toxic synthetic insecticides (mainly composed of pyrethroids and organophosphates), offers only partial control and by time has resulted in the loss of efficacy and consequently development of resistance in insects populations. The spread of pathogens resistant to synthetic products pose one of the most serious threats to the successful treatment of microbial diseases in agriculture.

However, some EOs probably have further activities that those here reported from VOSviewer. For instance, *Cinnamon* emerged only for antibacterial activity (Fig. 10), but it is recognized in literature even as active EO against phytopathogenic fungi (Kowalska et al., 2020; Bisht et al., 2021) and insects (Liu et al., 2014). *Thymus*, which appeared able to contrast bacteria and fungi, is also proven to be effective against insects (Pavela and Sedlák, 2018; Selçuk et al., 2020), in addition to their antibacterial and insecticidal activities, *Lavandula* and *Mentha* exploit fungicidal action (Yakhlef et al., 2020; El Abdali et al., 2022). An interesting information emerges from the total number of publications: EOs in agriculture have arisen the interest in scientific community as demonstrated by the increasing number of documents published in the last decades and last studies are focused on the EOs of *O. basilicum* and *Lavandula.*

Instead, the results found for acaricidal and nematocidal activities revealed a lower number of documents (138 and 93, respectively) when compared to antibacterial, insecticidal and fungicidal activities (1331, 985, 318, respectively). These results allow to argue that the use of EOs against nematodes and acari was less developed and, likely for this reason, any specific EOs come out by VOSviewer plot (see Fig. 9 and S10). However, an increasing interest in the last years (see Figs. S6b and S8a) as well as promising results were found against them (e.g. Marcic, 2012; Fierascu et al., 2020; Kong et al., 2006; Kim et al., 2008; D'Addabbo and Avato, 2021).

The countries which lead the research on topic, ranking by number of documents published, are India and USA followed by Iran and Italy, while by the citations the top countries are USA and Italy. Addictionally, journals which publish most are known for their importance and reputation among scientific community. Indeed, Industrial Crops and Products and Journal of Agricultural and Food Chemistry belong to the first quartile as highlight of their the prestige in the scientific community. This data emphasizes and provides evidence of the interest in this topic's research. The antimicrobial property of EOs appears as the most recently investigated and future progression can bet on this activity.

In conclusion, although VOSviewer software is not always able to pick up EOs associated to specific pests, it allows a visualization of the primary research trends and possible gaps that can be useful to obtain a comprehensive overview of the application of the EOs in agriculture and agricultural products. Therefore, it might be regarded as a potential tool to understand which research activities might be implemented in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Activities	*Rosmarinus officinalis*	*Cinnamon*	*Thymus (mainly T. vulgaris)*	*Origanum*	*Lavandula*	*Mentha*	*Ocimum (mainly O. basilicum)*	*Citrus*
Antibacterial	X	X	X	X	X	X	-	-
Insecticidal	X	-	X	-	X	X	X	X
Fungicidal	-	-	X	X	-	-	X	X
Acaricidal	-	-	-	-	-	-	-	-
Nematicidal	-	-	-	-	-	-	-	-

Fig. 10. Summary of the main target activities evaluated using VOSviewer and the primary essential oils (EOs) found through the research on available literature. "x" indicates the association between activity and EOs.

Acknowledgements

Linda Catani's PhD grant was supported by MUR, PON "Ricerca e Innovazione" 2014–2020, Axis IV "Istruzione e ricerca per il recupero" Action IV.4 "Dottorati e contratti di ricerca su tematiche dell'innovazione" and Action IV.5 "Dottorati su tematiche green". DM 1061/2021 (DOT19MJNRL CUP H31B21009680003) in collaboration with SOCIETA' AGRICOLA PAIARDINI DI PAIARDINI TINO & C. S.A.S. This research was partially funded also by the project UNIPA–PRJ-0510-35161. We are grateful to the referee who gave constructive comments to improve the quality of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bcab.2022.102502.

References

Abd-Elgawad, A., M., El Gendy, A.E.-N.G., Assaeed, A.M., Al-Rowaily, S.L., Alharthi, A.S., Mohamed, T.A., Nassar, M.I., Dewir, Y.H., Elshamy, A.I., 2021. Phytotoxic effects of plant essential oils: a systematic review and structure-activity relationship based on chemometric analyses. Plants 10 (1), 1–16. https://doi.org/10.3390/plants10010036.

Al-Harbi, Awad, N., Al Attar, N.M., Hikal, D.M., Mohamed, S.E., Latef, A.A.H.A., Ibrahim, A.A., Abdein, M.A., 2021. Evaluation of insecticidal effects of plants essential oils extracted from basil, black seeds and lavender against *Sitophilus oryzae*. Plants 10 (5). https://doi.org/10.3390/plants10050829.

Alonso-Gato, M., Astray, G., Mejuto, J.C., Simal-Gandara, J., 2021. Essential oils as antimicrobials in crop protection. Antibiotics 10 (1), 1–12. https://doi.org/10.3390/antibiotics10010034.

Antonioli, G., Fontanella, G., Echeverrigaray, S., Longaray Delamare, A.P., Pauletti, G.F., Barcellos, T., 2020. Poly(Lactic acid) nanocapsules containing lemongrass essential oil for postharvest decay control: in vitro and in vivo evaluation against phytopathogenic fungi. Food Chem. 326, 126997 https://doi.org/10.1016/j.foodchem.2020.126997. April.

Antunes, M.D.C., Cavaco, A.M., 2010. The use of essential oils for postharvest decay control. A review. Flavour Fragrance J. 25 (5), 351–366. https://doi.org/10.1002/ffj.1986.

Araújo, M.J.C., Câmara, C.A.G., Born, F.S., Moraes, M.M., Badji, C.A., 2012. Acaricidal activity and repellency of essential oil from *Piper aduncum* and its components against *Tetranychus urticae*. Exp. Appl. Acarol. 57 (2), 139–155. https://doi.org/10.1007/s10493-012-9545-x.

Ardakani, A.S., Hosseininejad, S.A., 2022. Identification of chemical components from essential oils and aqueous extracts of some medicinal plants and their nematicidal effects on *Meloidogyne incognita*. J. Basic. Appl. Zool. 83 (1) https://doi.org/10.1186/s41936-022-00279-6.

Ascrizzi, R., Flamini, G., Bedini, S., Tani, C., Giannotti, P., Lombardi, T., Conti, B., Fraternale, D., 2021. *Ferulago campestris* essential oil as active ingredient in chitosan seed-coating: chemical analyses, allelopathic effects, and protective activity against the common bean pest *Acanthoscelides obtectus*. Agronomy 11 (8). https://doi.org/10.3390/agronomy11081578.

Attia, S., Grissa, K.L., Lognay, G., Heuskin, S., Mailleux, A.C., Hance, T., 2011. Chemical composition and Acaricidal properties of *Deverra scoparia* essential oil (Araliales: Apiaceae) and blends of its major constituents against *Tetranychus urticae* (Acari: Tetranychidae). J. Econ. Entomol. 104 (4), 1220–1228. https://doi.org/10.1603/EC10318.

Bakkali, F., Averbeck, S., Averbeck, D., Idaomar, M., 2008. Biological effects of essential oils - a review. Food Chem. Toxicol. 46 (2), 446–475. https://doi.org/10.1016/j.fct.2007.09.106.

Bisht, D., Saroj, A., Durgapal, A., Chanotiya, C.S., Samad, A., 2021. Inhibitory effect of Cinnamon (*Cinnamomum tamala* (Buch.-Ham.) T.Nees & Eberm.) essential oil and its aldehyde constituents on growth and spore germination of phytopathogenic fungi. Trends Phytochem. Res. 5 (2), 62–70. https://doi.org/10.30495/tpr.2021.1914085.1184.

Burt, S., 2004. Essential oils: their antibacterial properties and potential applications in foods - a review. Int. J. Food Microbiol. 94 (3), 223–253. https://doi.org/10.1016/j.ijfoodmicro.2004.03.022.

Caballero-Gallardo, K, Olivero-Verbel, G, Stashenko, E., 2011. Repellent activity of essential oils and some of their individual constituents against *Tribolium castaneum* herbst. J. Agric. Food Chem. 59 (5), 1690–1696. https://doi.org/10.1021/jf103937p.

Camilo, C.J., de Fatima Alves Nonato, C., Galvão-Rodrigues, F.F., et al., 2017. Acaricidal activity of essential oils. Trends Phytochem. Res. 1 (4), 183–198.

Campolo, O., Giunti, G., Russo, A., Palmeri, V., Zappalà, L., 2018. Essential oils in stored product insect pest control. J. Food Qual. https://doi.org/10.1155/2018/6906105, 2018.

Conti, B., Bocchino, R., Cosci, F., Ascrizzi, R., Flamini, G., Bedini, S., 2020. Essential oils against *Varroa destructor*: a soft way to fight the parasitic mite of *Apis mellifera*. J. Apicult. Res. 774–782. https://doi.org/10.1080/00218839.2020.1790790. Bee management.

D'Addabbo, T., Avato, P., 2021. Chemical composition and nematicidal properties of sixteen essential oils—a review. Plants 10 (7), 1368. https://doi.org/10.3390/plants10071368.

Dhifi, W., Bellili, S., Jazi, S., Bahloul, N., Mnif, W., 2016. Essential oils' chemical characterization and investigation of some biological activities: a critical review. Medicines 3 (4), 25. https://doi.org/10.3390/medicines3040025.

Digilio, M.C., Mancini, E., Voto, E., De Feo, V., 2008. Insecticide activity of mediterranean essential oils. J. Plant Interact. 3 (1), 17–23. https://doi.org/10.1080/17429140701843741.

FAO, 2007. Guidelines on the Application of General Principles of Food Hygiene to the Control of *Listeria monocytogenes* in Foods. Food and Agriculture Organization. CAC/GL 61, ".

Faria, J.M.S., Barbosa, P., Vieira, P., Vicente, C.S.L., Figueiredo, A.C., Mota, M., 2021. Phytochemicals as biopesticides against the pinewood nematode *Bursaphelenchus xylophilus*: a review on essential oils and their volatiles. Plants 10 (12). https://doi.org/10.3390/plants10122614.

Felšöciová, S., Vukovic, N., JeAowski, P., Kačániová, M., 2020. Antifungal activity of selected volatile essential oils against *Penicillium* sp. Open. Life. Sci. 15 (1), 511–521. https://doi.org/10.1515/biol-2020-0045.

Fierascu, R.C., Fierascu, I.C., Dinu-Pirvu, C.E., Fierascu, I., Paunescu, A., 2020. The application of essential oils as a next-generation of pesticides: recent developments and future perspectives. Z. fur Naturforsch. - C J. Biosci. 75 (7–8), 183–204. https://doi.org/10.1515/znc-2019-0160.

Gradus, R.H.J.M., Nillesen, P.H.L., Dijkgraaf, E., van Koppen, R.J., 2017. A cost-effectiveness analysis for incineration or recycling of Dutch household plastic waste. Ecol. Econ. 135, 22–28. https://doi.org/10.1016/j.ecolecon.2016.12.021.

Han, J., Choi, B.R., Lee, S.G., Kim, Soon Il, Ahn, Y.J., 2010. Toxicity of plant essential oils to Acaricide-susceptible and -resistant *Tetranychus urticae* (Acari: Tetranychidae) and *Neoseiulus californicus* (Acari: phytoseiidae). J. Econ. Entomol. 103 (4), 1293–1298. https://doi.org/10.1603/EC09222.

Hou, H., Zhang, X., Zhao, T., Zhou, L., 2020. Effects of *Origanum vulgare* essential oil and its two main components, carvacrol and thymol, on the plant pathogen *Botrytis cinerea*. PeerJ 8, 1–25. https://doi.org/10.7717/peerj.9626.

Hýbl, M., Bohatá, A., Rádsetoulalová, I., Kopecký, M., Hoštičková, I., Vaníčková, A., Mráz, P., 2021. Evaluating the efficacy of 30 different essential oils against *Varroa destructor* and honey bee workers (*Apis mellifera*). Insects 12 (11), 1–12. https://doi.org/10.3390/insects12111045.

Isman, M.B., 2016. Pesticides based on plant essential oils: phytochemical and practical considerations. ACS (Am. Chem. Soc.) Symp. Ser. 13–26. https://doi.org/10.1021/bk-2016-1218.ch002, 1218 (June).

Isman, M., 2020. Bioinsecticides based on plant essential oils: a short overview. Z. fur Naturforsch. - C J. Biosci. 75 (78), 179–182. https://doi.org/10.1515/znc-2020-0038.

Kim, J., Seo, S.M., Shin, S.C., Park, I.K., 2008. Nematicidal Activity of Plant Essential Oils and Components from Coriander (*Coriandrum sativum*), Oriental Sweetgum (*Liquidambar orientalis*), and Valerian (*Valeriana wallichii*) Essential Oils against Pine Wood Nematode (*Bursaphelenchus xylophilus*), 56. J. Agric. Food. Chem., pp. 7316–7320

Kong, Ok, J., Lee, S.M., Moon, Y.S., Lee, S.G., Ahn, Y.J., 2006. Nematicidal activity of plant essential oils against *Bursaphelenchus xylophilus* (Nematoda: Aphelenchoididae). J. Asia Pac. Entomol. 9 (2), 173–178. https://doi.org/10.1016/S1226-8615(08)60289-7.

Kowalska, J., Tyburski, J., Krzymińska, J., Jakubowska, M., 2020. Cinnamon powder: an in vitro and in vivo evaluation of antifungal and plant growth promoting activity. Eur. J. Plant Pathol. 156 (1), 237–243. https://doi.org/10.1007/s10658-019-01882-0.

Kumar, R., Pandey, P.S., 2021. Insecticidal Activity of Essential Oils against Three Stored Product Beetles in Stored Wheat, vol. 9, pp. 387–389, 1.

Laborda, R., Manzano, I., Gamón, M., Gavidia, I., Pérez-Bermúdez, P., Boluda, R., 2013. Effects of *Rosmarinus officinalis* and *Salvia officinalis* essential oils on *Tetranychus urticae* koch (Acari: Tetranychidae). Ind. Crop. Prod. 48, 106–110. https://doi.org/10.1016/j.indcrop.2013.04.011.

Lammari, N., Louaer, O., Meniai, A.H., Elaissari, A., 2020. Encapsulation of essential oils via nanoprecipitation process: overview, progress, challenges and prospects. Pharmaceutics 12 (5), 1–21. https://doi.org/10.3390/pharmaceutics12050431.

Liu, X.C., Cheng, J., Zhao, N.N., Liu, Z.L., 2014. Insecticidal activity of essential oil of *Cinnamomum cassia* and its main constituent, trans-cinnamaldehyde, against the booklice, *Liposcelis bostrychophila*. Trop. J. Pharmaceut. Res. 13 (10), 1697–1702. https://doi.org/10.4314/tjpr.v13i10.18.

Marcic, D., 2012. Acaricides in modern management of plant-feeding mites. J. Pest. Sci. 85 (4), 395–408. https://doi.org/10.1007/s10340-012-0442-1.

EFSA, Member States, 2021. Consultation on the basic substance application for approval of lemon essential oil to be used in plant protection as an Acaricide. Insecticide and Fungicide in Fruit Trees (Citrus) 18 (10). https://doi.org/10.2903/sp.efsa.2021.en-6873.

Mohan, M.S., Zafar Haider, S., Andola, H., Purohit, V.K., 2011. Essential oils as green pesticides: for sustainable agriculture. Engineering. ID: 111229168.

Moussa, H., El Omari, B., Chefchaou, H., Tanghort, M., Mzabi, A., Chami, N., Remmal, A., 2021. Action of thymol, carvacrol and eugenol on *Penicillium* and *Geotrichum* isolates resistant to commercial fungicides and causing postharvest citrus decay. J. Indian Dent. Assoc. 43 (1) https://doi.org/10.1080/07060661.2020.1767692.

Nazzaro, F., Fratianni, F., De Martino, L., Coppola, R., De Feo, V., 2013. Effect of essential oils on pathogenic bacteria. Pharmaceuticals 6 (12), 1451–1474. https://doi.org/10.3390/ph6121451.

Ockleford, C., Adriaanse, P., Berny, P., Brock, T., Duquesne, S., Grilli, S., Hernandez-Jerez, A.F., 2017. Scientific opinion addressing the state of the science on risk assessment of plant protection products for in-soil organisms. EFSA J. 15 (2) https://doi.org/10.2903/j.efsa.2017.4690.

Oka, Y., Nacar, S., Putievsky, E., Ravid, U., Yaniv, Z., Spiegel, Y., 2000. Nematicidal activity of essential oils and their components against the root-knot nematode. Phytopathology 90 (7), 710–715. https://doi.org/10.1094/PHYTO.2000.90.7.710.

El Abdali, Y., Agour, A., Allali, A., Bourhia, M., El Moussaoui, A., Eloutassi, N., Salamatullah, A.M., et al., 2022. *Lavandula dentata* L.: phytochemical analysis, antioxidant, antifungal and insecticidal activities of its essential oil. Plants 11 (3). https://doi.org/10.3390/plants11030311.

Europe Parlament and Council of European Union, 2009. EC) No 1107/2009. Off. J. Eur. Union 309 (1), 1–50. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0001:0050:en:PDF.

Pavela, R., Sedlák, P., 2018. Post-application temperature as a factor influencing the insecticidal activity of essential oil from *Thymus vulgaris*. Ind. Crop. Prod. 113, 46–49. https://doi.org/10.1016/j.indcrop.2018.01.021. August 2017.

Ralmi, N.H.A., Khandaker, M.M., Mat, N., 2016. Occurrence and control of root knot nematode in crops: a review. Aust. J. Crop. Sci. 10 (12), 1649–1654. https://doi.org/10.21475/ajcs.2016.10.12.p7444.

Raveau, R., Fontaine, J., Lounès-Hadj Sahraoui, A., 2020. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: a review. Foods 9 (3). https://doi.org/10.3390/foods9030365.

Renčo, M., Čerevková, A., Homolová, Z., 2021. Nematode communities indicate the negative impact of *Reynoutria japonica* invasion on soil fauna in ruderal habitats of tatra national park in Slovakia. Glob. Ecol. Conserv. 26 https://doi.org/10.1016/j.gecco.2021.e01470.

Richard, A.S., Desaeger, J., Molendijk, L., 2021. Integrated nematode management. State-of-the-Art and Visions for the Future. https://doi.org/10.1079/9781789247541.0000.

Saroukolai M., T., Meshkatalsadat, H., 2010. Insecticidal properties of *Thymus persicus* essential oil against *Tribolium castaneum* and *Sitophilus oryzae*. J. Pest. Sci. 83 (1), 3–8. https://doi.org/10.1007/s10340-009-0261-1.

Selçuk, K., Tel-Çayan, G., Duru, M.E., Kesdek, M., Öztürkc, M., 2020. Chemical composition and insecticidal activities of the essential oils and various extracts of two *Thymus* species: *Thymus cariensis* and *Thymus cilicicus*. Toxin Rev. 40 (4), 1461–1471. https://doi.org/10.1080/15569543.2020.1731552, 2021.

van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84 (2), 523–538. https://doi.org/10.1007/s11192-009-0146-3.

World Health Organization. n.d. WHO-Leishmaniasis. https://www.who.int/health-topics/leishmaniasis#tab=tab_1.

Xu, C., 2019. Trends in phytochemical research. J. Food Biochem. 43 (6), 12913 https://doi.org/10.1111/jfbc.12913.

Yakhlef, G., Hambaba, L., Pinto, D.C.G.A., Silva, Artur M.S., 2020. Chemical composition and insecticidal, repellent and antifungal activities of essential oil of *Mentha rotundifolia* (L.) from Algeria. Ind. Crop. Prod. 158, 112988 https://doi.org/10.1016/j.indcrop.2020.112988. October.
Zhou, M., Wang, R., Cheng, S., Xu, Y., Luo, S., Zhang, Y., Kong, L., 2021. Bibliometrics and visualization analysis regarding research on the development of microplastics. Environ. Sci. Pollut. Control Ser. 28 (8), 8953–8967. https://doi.org/10.1007/s11356-021-12366-2.
Zong, Q.J., Yuan, Q.J., Shen, H.Z., 2012. Research Focus of China Library Science in 2010 Based on VOSviewer, vol. 4. Library, pp. 88–90.