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REVIEW

Minthostachys mollis: Chemical composition, biological activities and potential applications in a systematic and bibliometric review

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Abstract

Minthostachys mollis, commonly known as muña, is an aromatic medicinal plant widely distributed in the Andean region and traditionally used to treat various conditions. In recent years, scientific interest in this species has increased due to its chemical composition, biological activities, and potential applications in different sectors. The objective of this study was to systematically and bibliometrically analyze the scientific literature on *Minthostachys mollis* in order to synthesize the available evidence on its phytochemical composition, biological activities, and potential applications. To this end, a systematic search was conducted in the Scopus database from 2005 to 2026. The selection of studies was carried out following the guidelines of the PRISMA protocol. Likewise, a bibliometric analysis was performed to identify research trends. The results showed a progressive increase in the number of publications in recent years, with greater scientific output in countries in the Andean region, particularly Peru and Argentina. Phytochemical studies indicated that the essential oil of *Minthostachys mollis* is mainly composed of monoterpenes such as pulegone, menthone, and limonene. In addition, several studies reported relevant biological activities such as antimicrobial, antifungal, insecticidal, repellent, antioxidant, and pharmacological properties. These findings highlight the potential of this species as a source of bioactive compounds with applications in the pharmaceutical, agricultural, and food sectors. However, challenges remain related to variability in chemical composition, standardization of extracts, and evaluation of safety and efficacy under real-world conditions of use. In this context, future research should focus on phytochemical standardization, the development of innovative formulations, and the validation of their applications through more advanced experimental studies.

Keywords: muña; natural products; essential oils; thematic evolution; Latin American flora.

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1. Introduction

Medicinal plants have traditionally been used as an important source of bioactive compounds with various applications in human health, agriculture, and the food industry (Chaachouay & Zidane, 2024; Murphy, 1999). In recent decades, scientific interest in natural plant-derived products has increased considerably due to their potential for the discovery and development of new drugs, as well as their use as natural alternatives to synthetic compounds (Ghafouri et al., 2025; Latif & Nawaz, 2025; Tian-Liang et al., 2025). This growing interest is largely due to the presence of secondary metabolites, such as terpenoids, phenolic compounds, and alkaloids, which have been shown to have various biological activities, including antimicrobial, antioxidant, insecticidal, and pharmacological properties (Atanasov et al., 2021; Benites et al., 2018).

Within this context, various aromatic species have been investigated due to their high content of essential oils and secondary metabolites with biological potential. Among them is Muña *Minthostachys mollis*, an aromatic plant belonging to the Lamiaceae family, widely distributed in the Andean region of South America, especially in Peru, Bolivia, Colombia, Ecuador, Venezuela, and northern Argentina (Lock et al., 2016; Mora et al., 2009). It has traditionally been used by Andean communities for digestive and respiratory conditions and parasitic infections (Rojas-Armas et al., 2019; Saldaña-Chafloque et al., 2024; Viena et al., 2020).

From a phytochemical point of view, the essential oil of *Minthostachys mollis* is characterized by a predominance of oxygenated monoterpenes, mainly pulegone and menthone, accompanied by other compounds such as limonene, isomenthone, and carvacrol (Gillij et al., 2008; Pellegrini et al., 2017). Several studies have shown that the chemical composition of this specie can vary depending on geographical, ecological, and seasonal factors, which have allowed different chemotypes to be identified in populations from various Andean countries (Olivero-Verbel et al., 2010; Rojas-Molina et al., 2024; Van Baren et al., 2014). These chemical variations have been associated with multiple biological activities, including antimicrobial, antifungal, insecticidal, repellent, and antioxidant properties, demonstrating the potential of *Minthostachys mollis* as a source of bioactive compounds with applications in the pharmaceutical, agricultural, and food sectors (Chavez et al., 2022; Comelli et al., 2024; Navarro-Paredes et al., 2025; Sierra-Quitian et al., 2025; Soto-Cáceres et al., 2022).

Despite the growing number of studies related to *Minthostachys mollis*, the available information is scattered across different areas of research, including phytochemical characterization, evaluation of biological activities, and the development of potential applications in sectors such as agriculture, the food industry, and pharmacology. This diversity of approaches makes it difficult to obtain an integrated view of the scientific potential of this species. In this context, it is necessary to conduct a systematic synthesis of the available evidence to identify the main bioactive compounds, the biological activities evaluated, and the possible applications reported in the scientific literature.

Therefore, the following research question arises: what is the available scientific evidence on the phytochemical composition, biological activities, and potential applications of *Minthostachys mollis* reported in the scientific literature? Based on this question, the overall objective of this study was to systematically and bibliometrically analyze the scientific literature on *Minthostachys mollis* in order to synthesize the existing evidence on its chemical composition, biological activities, and possible applications in different fields. To this end, the following specific objectives were set: (i) To evaluate research trends through bibliometric analysis, (ii) to identify studies describing the phytochemical composition of *Minthostachys mollis*, (iii) to analyze the main biological activities experimentally evaluated in extracts and essential oils of this species, and (iv) to examine the potential applications of *Minthostachys mollis* in the pharmaceutical, food, and agricultural sectors reported in the scientific literature.

2. Methodology

2.1 Search strategy and article selection

In February 2026, studies were collected from the Scopus database, selected for its broad coverage of indexed scientific literature and its relevance for systematic reviews and bibliometric analyses. The search strategy included titles, abstracts, and keywords from articles published between 2005 and 2026. The research question and search strategy were structured using the PIO (Population, Intervention, Outcome) approach, where the population corresponded to the plant species *Minthostachys mollis* (muña), the intervention included plant extracts and essential oils; and the outcomes focused on the evaluation of antimicrobial, antibacterial, antifungal, repellent, and insecticidal activities. The search equation used was: ("*Minthostachys mollis*" OR "*M. mollis*" OR "Minthostachys M" OR "muña") AND ("essential oil" OR "plant extract" OR "composition") AND (antimicrobial OR antibacterial OR antifungal OR repellent OR insecticidal OR pesticide OR antioxidant), which initially identified 308 records. Filters were then applied to include original articles published in scientific journals in English. Reviews, conference proceedings, books, book chapters duplicate documents, studies without experimental evaluation, and publications related to other plant species were excluded, resulting in a total of 231 eligible articles. The selection was made following the PRISMA protocol guidelines. The records were independently evaluated by the authors using the open-access Rayyan software for blind review of titles and abstracts, which allowed the exclusion of irrelevant studies, particularly those that only mentioned the species without evaluating it experimentally. Finally, the sample consisted of 53 articles, which were classified according to the subject area of study (Figure 1).

2.2 Data processing

Two open-access tools were used for bibliometric analysis and data visualisation. The first was Bibliometrix a R-package (Aria & Cuccurullo, 2017) an R package used to evaluate the temporal evolution of scientific production on *Minthostachys mollis*. This tool made it possible to identify the geographical distribution of publications, the most cited articles, and keyword clouds in two periods (2005–2015 and 2016–2025), providing an evolutionary perspective on the thematic focus in the field. The second tool was VOSviewer V.1.6.19 (Van Eck & Waltman, 2010), which was used to construct visualisation maps with the keyword co-occurrence network, the collaboration network between authors, and the thematic evolution over time. These graphical representations facilitated the identification of the main thematic clusters, as well as the connections and patterns of collaboration between researchers and institutions.

3. Results and discussion

3.1 Descriptive analysis

Between 2005 and 2026, scientific production related to *Minthostachys mollis* has shown an upward trend (Figure 2). During the period 2005 to 2016, scientific output was low and irregular, with values ranging from zero to three publications per year, reflecting an incipient and discontinuous interest in the species. From 2017 onwards, there was a progressive increase in scientific output, with a sustained rise reaching a peak in 2024 and 2025 (eight publications per year), indicating growing interest in its biological properties and potential applications. The decline observed in 2026 is probably since the year is still ongoing at the time of the search. The geographical distribution of publications shows a marked concentration of studies in South American countries, particularly in the Andean region, where the species *Minthostachys mollis* is native and widely used. Peru leads scientific production with 76 records, reflecting the high national interest in research on this plant due to its ethnobotanical, medicinal, and agro-industrial importance. Argentina ranks second with 42 publications, followed by Brazil with 12 studies.

Other countries with lower participation include Colombia (8 publications), Ecuador (6), Venezuela (5), and Bolivia and Chile with 4 publications each. Finally, Cuba has made a minor contribution with 3 studies. This geographical distribution suggests that research on *Minthostachys mollis* is mainly carried out in countries where the species is part of the native flora and traditional medicine and agriculture systems (Rojas-Molina et al., 2024; Saldaña-Chafloque et al., 2024; Van Baren et al., 2014). It is worth noting that the total number of contributions exceeds the number of unique articles analyzed, as a single study may include authors affiliated with institutions from different countries.

Keyword analysis of articles related to this plant reveals a thematic evolution between the periods 2005 to 2015 and 2016 to 2025. In the first decade, the predominant terms included essential oil, *Minthostachys mollis*, Lamiaceae, chemical composition, and medicinal plant, reflecting that initial research focused mainly on the phytochemical characterization of the species and the identification of its volatile compounds. These studies focused on determining the chemical composition of essential oils and their main metabolites, such as pulegone and menthone, compounds characteristic of the species (Benites et al., 2018; Mora et al., 2009).

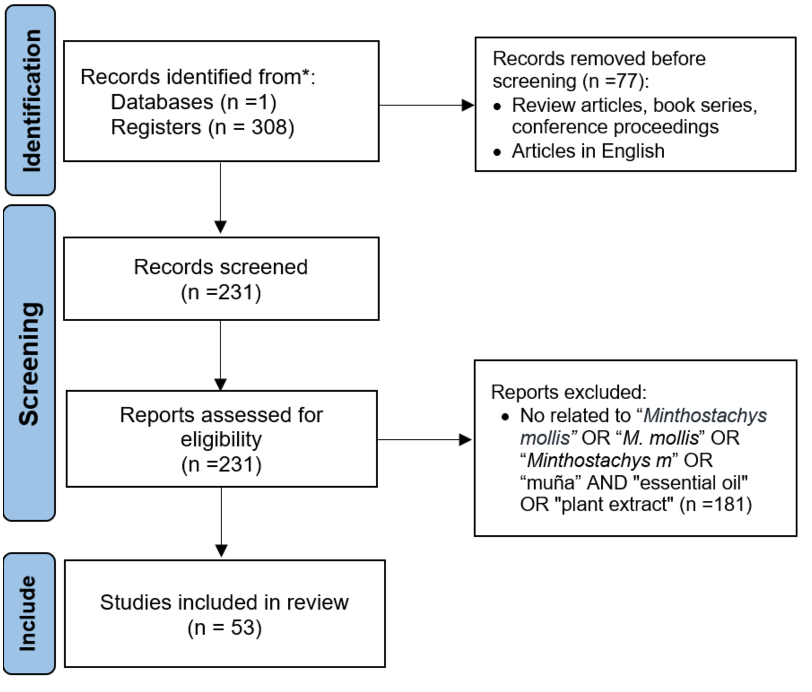

Figure 1. Selection of papers for review, adapted from the PRISMA (Page et al., 2021).

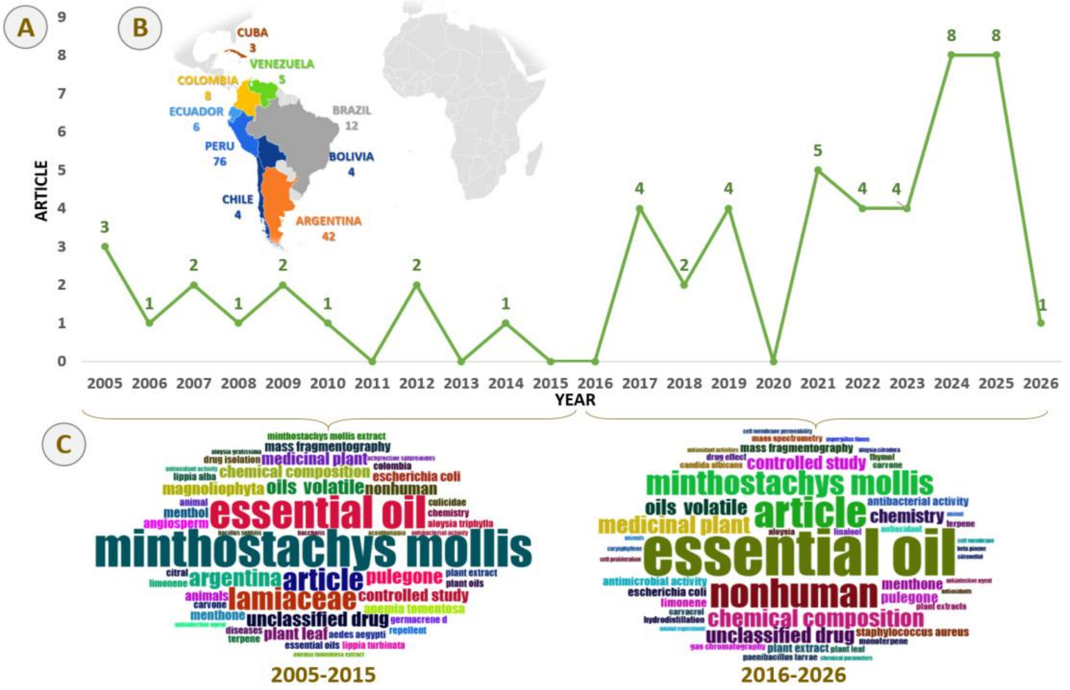

Figure 2. Scientific production on *Minthostachys mollis* de 2005 a 2026: (A) annual number of publications, (B) top contributing countries, and (C) keyword evolution.

Likewise, during this period, terms associated with biological activities appeared, particularly antimicrobial activity, as well as microorganisms of interest such as Escherichia coli, which shows an early interest in the antimicrobial potential of the species' essential oils (Navarro-Paredes et al., 2025; Pellegrini et al., 2017). In the second period 2016 to 2026, there was an increase in the frequency and diversity of terms related to biological and pharmacological applications. In addition to the core terms essential oil and *Minthostachys mollis*, keywords such as chemical composition, antibacterial activity, Staphylococcus aureus, and medicinal plant appeared more frequently. This pattern suggests an evolution in research from descriptive studies of chemical composition to research aimed at evaluating biological applications and potential pharmacological, agricultural, and biotechnological uses of the species (León-Marrou et al., 2023; Paz Soldán et al., 2023; Quispe-Sanchez et al., 2025a).

Scientific citations reflect the impact and visibility of a publication within the academic community, but they also constitute an indirect indicator of the relevance of the topic addressed. The analysis of the most cited articles on *Minthostachys mollis* focuses on research into essential oils with applications in health, bee health and vector control. Table 1 shows the eight most cited articles, with values ranging from 32 to 273 citations, with the study by Gillij et al. (2008), on repellent activity against *Aedes aegypti* being the most referenced. There is interest in exploring natural alternatives to synthetic compounds, reinforcing the importance of continuing to research this native Andean species.

3.2 Researcher collaboration network

Figure 3 shows a co-authorship network among researchers who have worked with *Minthostachys mollis*, highlighting the collaborative structure surrounding this line of research. The nodes represent individual authors, while the links indicate co-authorship in scientific publications.

The red cluster brings together authors who have investigated the chemical differences and antibacterial activity of essential oils from *Minthostachys mollis* extracted from different parts of the plant (Fernández et al., 2017). The yellow cluster, where authors focused on studying how physical damage or insect damage modifies the chemical composition of *Minthostachys mollis* essential oil, with an emphasis on its commercial impact (Banchio et al., 2005a, 2005b, 2007).

The green cluster focuses on evaluating the antimicrobial activity of *Minthostachys mollis* essential oil, primarily targeting oral pathogens (Sánchez-Tito et al., 2021a; Sánchez-Tito et al., 2021b; Sánchez-Tito & Collantes-Díaz, 2021c). The purple cluster addresses research on the use of *Minthostachys* *mollis* in the oxidative stabilization of vegetable oils, such as sacha inchi oil (Chavez et al., 2022). Finally, the blue cluster groups together studies related to the bioactive properties of *Minthostachys* mollis as a natural agent, highlighting its antioxidant and antimicrobial potential (Juncos et al., 2024; López et al., 2022).

This analysis not only allows us to identify the main themes surrounding *Minthostachys mollis*, but also to visualize how authors are grouped according to disciplinary approaches and specific applications. It also reveals opportunities to foster greater collaboration between currently isolated lines of research, thereby strengthening the integration of scientific knowledge about this species.

3.3 Keyword co-occurrence network

Figure 4 shows a co-occurrence network of terms extracted from titles and abstracts of scientific publications related to *Minthostachys mollis*. Each node represents a key term, and the size of the node is proportionally related to the frequency of occurrence.

Table 1
Eight articles with the highest number of citations

Title	Journals	Citations	Main Findings	Authors
Mosquito repellent activity of essential oils of aromatic plants growing in Argentina	Bioresource Technology	281	Essential oils from Argentine plants, including *Minthostachys mollis*, showed repellency against Aedes aegypti. Efficacy varied according to origin and composition, with limonene and camphor standing out as the main active compounds.	(Gillij et al., 2008)
LD50 and Repellent Effects of Essential Oils from Argentinian Wild Plant Species on Varroa destructor	Journal of Economic Entomology	111	Essential oils from native Patagonian species, including *Minthostachys mollis*, were evaluated against Varroa destructor. Some showed significant acaricidal effects and high selectivity with respect to Apis mellifera. The oils of *Minthostachys mollis*, Lippia turbinata, and L. junelliana exhibited repellent properties, with no attractive effects on the mites.	(Ruffinengo et al., 2005)
Chemical composition and antioxidant activity of essential oils isolated from Colombian plants	Brazilian Journal of Pharmacognosy	57	Thirteen essential oils from Colombian plants, including *Minthostachys mollis*, were evaluated for their cytotoxicity and antioxidant activity. Five oils showed high cytotoxicity (LC_{50} <10 μg/mL), while those from Ocotea sp., Tagetes lucida, and Lippia alba (geranial chemotype) exhibited the highest antioxidant capacities. The oil from *Minthostachys mollis* did not exhibit significant antioxidant activity (EC_{50} >1000 μg/mL).	(Olivero-Verbel et al., 2010)
Anti-quorum sensing activity of essential oils from Colombian plants	Natural Product Research	49	Essential oils from Colombian plants, including *Minthostachys mollis* (rich in pulegone), were characterized and evaluated for their anti-quorum sensing (QS) activity. Several showed inhibitions of the short-chain QS system in E. coli, with Lippia alba standing out. Some compounds such as carvone, citral, and α-pinene showed moderate activity at high concentrations. These results suggest a potential QS modulator in Colombian flora.	(Jaramillo-Colorado et al., 2012)
Chemical Composition, Antimicrobial Activity, and Mode of Action of Essential Oils against Paenibacillus larvae, Etiological Agent of American Foulbrood on Apis mellifera	Chemistry & Biodiversity	35	Essential oils from eight species, including *Minthostachys mollis*, showed antibacterial activity against Paenibacillus larvae, and most caused membrane disruption. This activity was associated with compounds such as pulegone, carvone, and limonene, suggesting them as natural alternatives for controlling American foulbrood.	(Pellegrini et al., 2017)
Effects of Mechanical Wounding on Essential Oil Composition and Emission of Volatiles from *Minthostachys mollis*	Journal of Chemical Ecology	33	Mechanical damage to *Minthostachys mollis* caused a temporary increase in menthone and pulegone in the essential oil of damaged leaves, with no response in adjacent leaves. Pulegone emission also increased, suggesting inducible chemical changes with potential commercial implications.	(Banchio et al., 2005a)
Quantitative Variations in the Essential Oil of *Minthostachys mollis* (Kunth.) Griseb. in Response to Insects with Different Feeding Habits	Journal of Agricultural and Food Chemistry	32	In *Minthostachys mollis*, herbivory by insects with different feeding habits induced a decrease in menthone and an increase in pulegone in the essential oil, both in damaged and undamaged leaves, indicating a systemic response. These changes, consistent across damage types, could be related to the defensive role of pulegone and have potential implications for its commercial exploitation.	(Banchio et al., 2005b)

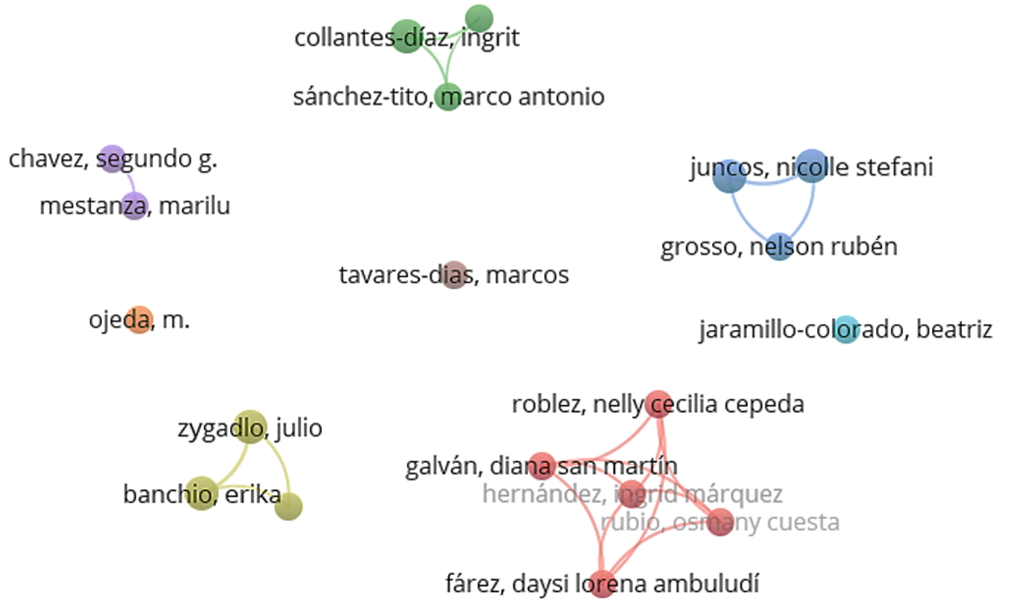

Figure 3. Research collaboration map of authors working on *Minthostachys mollis* in Scopus indexed publications from 2005 to 2026, obtained with Vosviewer using the minimum number of documents by an author two.

The green cluster, centered on the term "essential oil," represents the most dominant theme in the network. This group includes keywords related to plant extracts, volatile compounds, terpenes, and insecticidal or repellent activities, indicating a strong interest in the study of *Minthostachys mollis* essential oils and their application in the control of insects and agricultural pests. Within this cluster, terms such as plant extract, repellent activity, insecticides, and Aedes aegypti appear, evidencing applications in both agriculture and public health. Several studies have shown that the essential oils of this species have repellent and insecticidal activity against insects of agricultural and health importance (Guerra et al., 2007; Sierra-Quitian et al., 2025; Soto-Cáceres et al., 2022).

The blue cluster is mainly associated with the antimicrobial activity of the species. This group includes microorganisms frequently evaluated in experimental studies, such as *Staphylococcus aureus*, *Escherichia coli*, *Candida albicans*, *Enterococcus faecalis*, and *Pseudomonas aeruginosa*. Likewise, methodological terms such as minimum inhibitory concentration and in vitro study appear, reflecting the predominant experimental approach in research on the plant's antibacterial and antifungal potential. Several studies have reported the antimicrobial activity of *Minthostachys mollis* essential oil against pathogenic bacteria and fungi, attributing these effects to terpenic compounds present in the plant (Huamaní et al., 2021; Pellegrini et al., 2017; Sánchez-Tito et al., 2021b).

The red cluster relates to the chemical characterization and bioactive properties of the compounds present in the plant. This group includes terms such as chemical composition, antioxidant activity, hydrodistillation, gas chromatography, and various terpenic compounds such as thymol, citral, geraniol, and β-pinene. These results reflect that a significant proportion of studies focus on identifying secondary metabolites responsible for the reported biological activities. Previous research has identified major compounds such as pulegone, menthone, limonene, and eucalyptol, which are related to the antioxidant and antimicrobial properties of the essential oil (Mora et al., 2009; Olmedo et al., 2018; Rojas-Molina et al., 2024). Finally, the yellow cluster groups terms related to the botany, taxonomy, and phytochemical characteristics of the species, including Lamiaceae, monoterpene, plant leaves, and aromatic plants. This group reflects research aimed at understanding the chemical variability of the plant, its ecology, and its importance within the Lamiaceae family, one of the most studied botanical families due to its richness in bioactive secondary metabolites (Ali et al., 2025; Linares Otoya, 2020).

3.4 Topic areas and main findings

The studies were classified into nine thematic areas according to the type of biological activity or experimental approach evaluated. This classification made it possible to identify the main lines of research developed around *Minthostachys mollis*.

Figure 5 shows the distribution of studies according to the thematic areas identified in the scientific literature. Most of the research focused on evaluating antimicrobial activity (26%), followed by studies related to antioxidant properties in food (19%), insecticidal or biopesticidal activity (17%), phytochemical characterization (13%) and, to a lesser extent, research on antifungal activity (9%), antiparasitic activity, post-harvest preservation, and toxicological safety. These results show that the antimicrobial potential of *Minthostachys mollis* has been one of the main areas of interest in recent scientific research.

3.4.1 Antimicrobial activity

Table 2 presents the studies that evaluated the antimicrobial activity of *Minthostachys mollis*. Most of the research used essential oils obtained by hydrodistillation, while some studies used complementary techniques such as ultrasound, maceration, or microencapsulation to improve the stability or yield of the extract. The predominant chemical compounds in the extracts were mainly monoterpenes, among which pulegone, menthone, carvacrol, and eucalyptol stand out.

The studies mainly evaluated clinically important pathogenic bacteria, such as *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*, as well as oral pathogens and some fungi. Overall, the results report significant antimicrobial activity, mainly attributed to the presence of monoterpenes in the essential oil, which can interfere with the integrity of the microbial cell membrane and limit the growth of microorganisms. The results suggest that *Minthostachys mollis* essential oil has significant potential as a natural antimicrobial agent, with possible applications in the pharmaceutical, food, and agricultural sectors.

3.4.2 Food antioxidant

Several studies have evaluated the antioxidant potential of *Minthostachys mollis* and its possible application in food systems and experimental trials. This research has focused mainly on the use of essential oil and plant extracts obtained through different extraction methods, analyzing their ability to inhibit oxidation processes and improve the stability of food matrices. Likewise, some studies have evaluated antioxidant activity through in vitro chemical tests and experimental models, considering the influence of the chemical composition of the essential oil and its variability according to the geographical origin of the plant. Table 3 summarizes the studies that analyze the antioxidant activity and food applications of *Minthostachys mollis*, including the type of extract used, the extraction or preparation method, the food matrix or system evaluated, and the main findings reported.

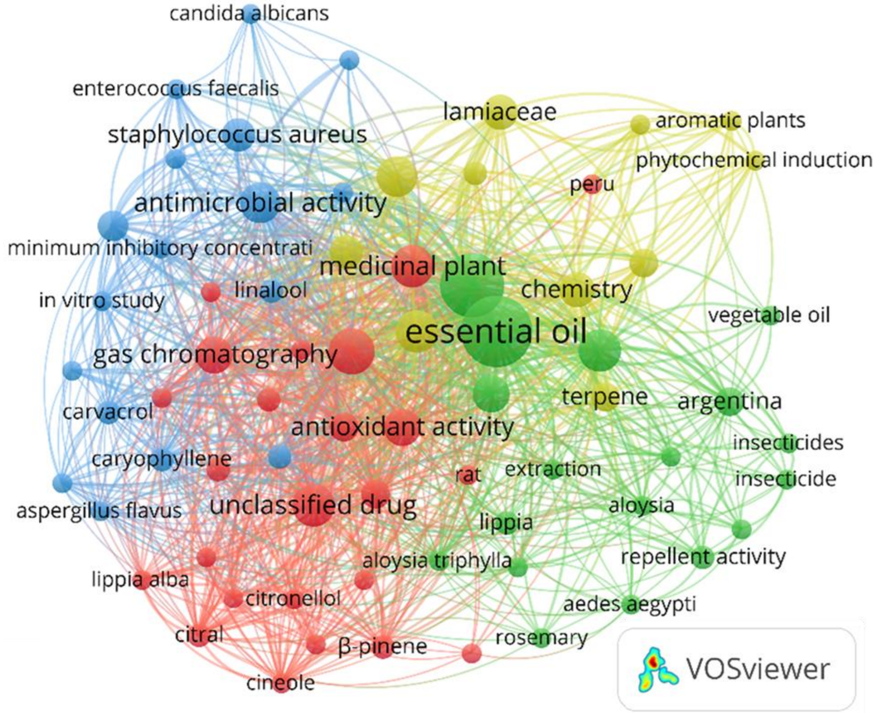

Figure 4. Keyword co-occurrence network in scientific articles between 2005 to 2026, obtained with Vosviewer using the minimum number of documents by author three.

Table 2
Studies on the antimicrobial activity of *Minthostachys mollis* reported between 2005 and 2026

Type of extract	Extraction or preparation method	Main chemical composition	Microorganisms evaluated	Main findings	Reference
Essential oil (EO)	Hydrodistillation	Pulegone (55.2%), trans-menthone (31.5%)	*Bacillus. subtilis, Salmonella typhi*	MIC approximately 4 μg/mL High antibacterial activity associated with monoterpenes	(Mora et al., 2009)
Essential oil	Optimized distillation	Carvacryl acetate (44.01%), carvacrol (16.51%), menthone (8.20%)	*P. aeruginosa, S. enterica, E. coli, S. aureus.* Pathogenic bacteria (in vitro) and antioxidant assays	Antimicrobial activity against pathogenic bacteria and moderate antioxidant capacity; extraction optimization	(Rojas-Molina et al., 2024)
Essential oil	Ultrasound and Hydrodistillation	High total phenols	*S. aureus, E. coli, P. aeruginosa*	Extraction optimization; significant biological activity Ultrasound improves extraction kinetics	(Navarro-Paredes et al., 2025)
Ethanolic extract	Maceration	Phenols, flavonoids, triterpenes	*Staphylococcus aureus* *S. aureus*	Bacterial sensitivity observed, phenols and flavonoids associated with antibacterial activity	(Campo et al., 2017)
Essential oil fractions	Fractionation	cis-menthone, thymol, α-terpineol	Oral bacteria (*S. mutans, L. acidophilus, E. faecalis, P. gingivalis,*) and *Candida albicans*	Highly active organic fractions; MIC 0.2-3.2 ug/mL	(Sánchez-Tito & Collantes-Díaz, 2021c)
Essential oil	Distillation	Menthone (32.9%), eucalyptol (28.06%)	*S. mutans, L. acidophilus*	Approximate halos 19 mm, significant inhibition of cariogenic bacteria	(Sánchez-Tito et al., 2021a)
Essential oil	Distillation	Menthone, eucalyptol	*Enterococcus faecalis, Porphyromonas gingivalis, Candida albicans*	Halos 15–21 mm, *Candida albicans* was the most sensitive microorganism	(Sánchez-Tito et al., 2021b)
Essential oil	Distillation	Pulegone (30.17%), menthone (16.55%)	*S. aureus, P. gingivalis, C. albicans*	Halos 8–10 mm, greatest effect at 24 hours	(Paucar-Rodriguez et al., 2021)
Free and microencapsulated essential oil	Microencapsulation with β-cyclodextrin	Oxygenated monoterpenes	*E. coli, S. aureus, Botrytis cinerea*	High antimicrobial activity; microencapsulation improves stability and controlled release, 100% inhibition	(Quispe-Sanchez et al., 2025b)
Essential oil	Distillation	Dominant monoterpenes	*Paenibacillus larvae*	Membrane disruption, leakage of cytoplasmic components	(Pellegrini et al., 2017)
Plant extract	With and without maceration; organic solvents vs. aqueous	Not applicable	Pathogenic enterobacteria	Greater activity with organic solvents	(Mijail et al., 2019)
Extract and essential oil	Essential oil yield 1.19%	Not applicable	*S. aureus, Proteus spp., K. pneumoniae, E. coli, P. aeruginosa, E. faecalis, Enterobacter spp.*	Greater efficacy of essential oil; superior to antibiotics, effective against *Enterobacter spp.* and *E. faecalis*	(Negrete et al., 2024)
Ethanolic extract	Extracts at different concentrations	Not applicable	*S. aureus*	Bactericidal activity muña and Argemone at 1000 mg/mL; low toxicity,	(López et al., 2024)
Essential oil	Hydrodistillation of plant material; chemical analysis by gas chromatography coupled with mass spectrometry (GC-MS)	Predominance of monoterpenes. In sample Mp1: neomenthol (32.34%), pulegone (28.42%), menthone (19.32%). In sample Mp2: geraniol (24.93%) and citronellol (14.84%)	*Staphylococcus aureus*	The essential oil showed antibacterial activity in vitro, evidenced by inhibition halos against S. aureus. The differences in chemical composition between samples are attributed to intrinsic and environmental factors of the plant.	(Fernández et al., 2017)

Table 3
Studies on the antioxidant activity and food applications of *Minthostachys mollis*

Type of extract	Extraction or preparation method	Food matrix or system evaluated	Main findings	Reference
Essential oil	Dietary supplementation (0-1.5%)	*Brycon amazonicus* fish	Increased protein content in fillets; moderate doses do not affect growth; high doses alter physiological parameters	(Fernández-Mendez et al., 2024)
Essential oil	Distillation and incorporation into food matrix	Dark chocolate	Greater oxidative stability and physicochemical changes	(Quispe-Sanchez et al., 2023)
Essential oil	Distillation and addition to oil	Sacha inchi oil	Doses of 1–4 g/kg stabilize lipid oxidation for up to 10 days with efficacy comparable to BHT	(Chavez et al., 2022)
Essential oil (blend)	Blend with oregano oil	Sunflower oil	Reduction in lipid oxidation; no significant synergistic effect detected	(Juncos et al., 2024)
Essential oil	Hydrodistillation	Sunflower oil	Natural additives with antioxidant capacity comparable to BHT	(Olmedo et al., 2018)
Essential oil	Hydrodistillation and GC-MS	DPPH Chemical Assay	Antioxidant activity varies depending on the place of cultivation	(Castro-Alayo et al., 2019)
Essential oil	Hydro-distillation and microwave-assisted hydro-distillation	α-pinene, estragole, geranial (depending on the species) Rat liver microsomes	Some oils showed significant antioxidant activity; however, the essential oil of *Minthostachys mollis* did not show relevant antioxidant activity (EC50 >1000 µg/mL), demonstrating variability in antioxidant potential among aromatic species.	(Olivero-Verbel et al., 2010)
Essential oil	GC-MS and accelerated oxidation	Sunflower oil	Combination with BHT improves oxidative stability; allows for reduced use of synthetic antioxidants.	(Cravero Ponso et al., 2025)
Aqueous plant extracts	Aqueous extraction	Model: In vitro chemical assays	Extracts with antioxidant capacity; *Minthostachys mollis* included among species evaluated. Significant relationship between phenolic content and antioxidant capacity	(Dadé et al., 2009)

Table 4
Experimental studies on the insecticidal, repellent, and biopesticidal activity of Minthostachys mollis

Type of extract	Extraction or preparation method	Organisms	Design or dosage	Main findings	Reference
Essential oil	Distillation by stripping	*Tribolium castaneum, Sitophilus zeamais*	Fumigant (LC50) and contact (LD50) tests; comparison of EO vs. compounds	High fumigant and contact toxicity; active monoterpenes EO from *Minthostachys mollis*: T. castaneum LC50 4.8 µL/L air; LD50 6.5 µg/insect. S. zeamais LC50 7.0 µL/L air; LD50 5.81 µg/insect. Preliminary SAR: carbonyl + conjugated double bonds in cyclic monoterpenes associated with insecticidal potency	(Sierra-Quitian et al., 2025)
Essential oil (12 species)	GC–MS and models	*Carpophilus dimidiatus, Oryzaephilus mercator*	Lab tests with 12 EOs	Most bioactive: A. gratissima var., M. verticillata, L. junelliana (ER ≥70%); proposes action by inhalation; promising for stored nuts	(Comelli et al., 2024)
Essential oil and dried plant	Coverage with buds; "no-choice" bioassay	Potato moth	Rustic warehouse and lab bioassay	Buds reduce damage (5% vs. 12%). EOs reduce oviposition ≈80%. Genetic variation in the pest suggests possible evolution of resistance	(Guerra et al., 2007)
Essential oil mixed with wax in repellency	Full exposure; wax tubes	*Varroa destructor*	0.1–25 µL, cage; 24, 48, and 72 h; attraction and repellency	Repellent activity in wax matrices	(Ruffinengo et al., 2005)

Aqueous, ethanolic and hexane extracts	10% and 20% extracts; 24–72 h	Pest: *Tetranychus urticae*	10–20%; NOEC/LOEC; RCRS	Aqueous M. mollis 20%: 28.9% mortality in T. urticae. Ethanolic M. mollis: high toxicity in C. externa (75.7% at 72 h). Aqueous extracts without toxicity in C. externa (48 h)	(Alegre et al., 2017)
Essential oil and DEET 10%	Topical application on sedated *Rattus rattus* (bait)	*Aedes aegypti* (adult mosquito)	125–1000 mg/mL; 0.1 mL	Best oils: C. citratus, E. globulus, L. glutinosa, M. piperita (up to 180 min). DEET: 173 min. *M. mollis* evaluated but not among the best	(Soto-Cáceres et al., 2022)
Essential oil	Geographic origin evaluated	*Aedes aegypti*	Different concentrations (90%, 12.5%)	*M. mollis* oil showed repellent activity; efficacy varied according to geographic origin. Variation by origin. At 12.5% longer time: B. spartioides, R. officinalis, A. citriodora. Associated components: limonene and camphor	(Gillij et al., 2008)
Aqueous/ethanolic extracts and essential oils	Insecticide/biocide	*Aedes aegypti* (adult)	Biocide tests on adults (NR dose/time)	Extracts and EOs from the three species showed a biocidal effect on adults; chemical profiles characterized and quality parameters "according to standards"; eco-friendly alternative proposed with lower risk of resistance Biocidal activity against mosquito vectors; potential natural alternative	(Paz Soldán et al., 2023)

Table 5

Experimental Phytochemistry and chemical characterization

Material or Product	Extraction or preparation method	Analytical techniques	Main chemical composition reported	Main findings	Reference
Essential oil of M. mollis and seven other species	NR	Raman and GC-MS	Detects 224 compounds (terpenoids predominate). Reports overall major constituents: cis,cis-nepetalactone (30.16%), β-caryophyllene (≤18.26%), citronellol (10.92%), citral, linalool	Integrates structure-composition; differences in proportion of oxygenated compounds (citral, linalool, geraniol) vs. hydrocarbons (β-caryophyllene, limonene, β-pinene). Reports cis,cis-nepetalactone in M. mollis for the first time	(Granda-Santos et al., 2025)
Essential oils and foods	Solvent MeOD/$CHCl_3$ 1:1; extraction requireded for food; steam distillation > UAE	NMR (chemical analysis)	Development of ^{1}H NMR method to detect pulegone	High pulegone in pennyroyal and muña oil; proposes tool for quality control and regulatory compliance; includes toxicological evaluation with no adverse effects on intake	(Yu et al., 2024)
Essential oil	Water-steam distillation by co-distillation	GC-MS	Variation in composition depending on storage, Fresh: 42 compounds (notably carvacryl acetate, trans-caryophyllene, germacrene D). Stored: 24 compounds (notably trans-caryophyllene, sabinene)	Higher yield with medium humidity. Storage reduces diversity (42 to 24 compounds) and changes profile	(Moreno et al., 2019)
Essential oil and 6 other spp	Hydrodistillation	GC-MS	In M. mollis: cis-dihydrocarvone, carvone, cis-piperitone epoxide (≥10% relative intensity). Limonene and linalool present in all EOs evaluated (wide ranges)	Presence of carvone and piperitone epoxide	(Vaca Meza et al., 2024)
Essential oil	Exposure to herbivores; measurement at 24 and 48 h	Variable evaluated: Essential oil composition	Dominant monoterpenes: pulegone and menthone	Menthone generally low; pulegone increases in all treatments; changes also in adjacent leaves.	(Banchio et al., 2005b)
M. mollis leaves	Bites; monitoring at 24/48/120 h; emissions at 24/48 h	NR	Pulegone and menthone (dominant)	Increase in pulegone and decrease in menthone (first 48 h).	(Banchio et al., 2007)
M. mollis leaves	Perforación; seguimiento 24/48/120 h; emisiones 24/48 h	NR	Pulegone and menthone (dominant)	Increase in pulegone and menthone in first 24 h; no systemic response	(Banchio et al., 2005a)

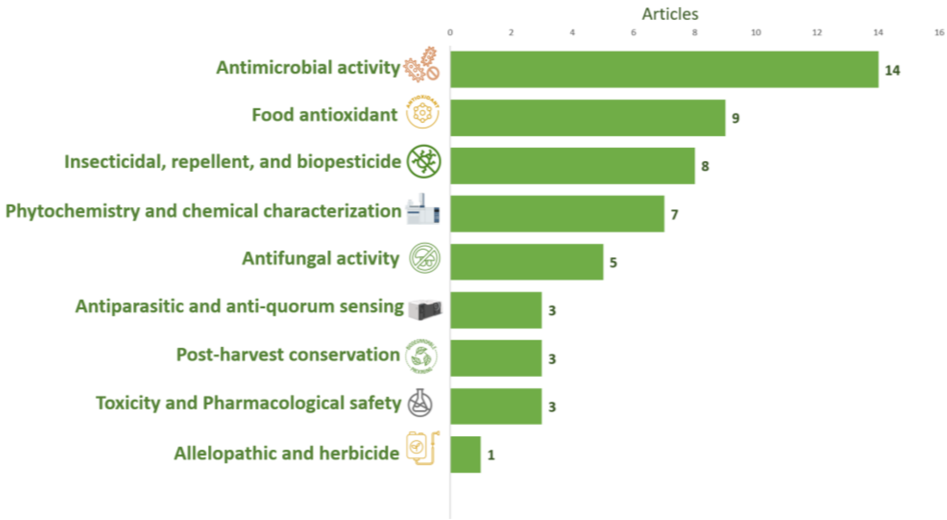

Figure 5. Topic area of *Minthostachys mollis* research.

The studies reviewed indicate that the essential oil and extracts of *Minthostachys mollis* have variable antioxidant potential, which depends mainly on their chemical composition, the extraction method used, and the matrix evaluated. In food applications, the incorporation of essential oil has been shown to contribute to the reduction of lipid oxidation and the improvement of oxidative stability in different products and vegetable oils. Likewise, some studies report that its antioxidant effect may be comparable to that of synthetic antioxidants or act in a complementary manner when used in combination.

On the other hand, chemical tests carried out in in vitro systems show that antioxidant activity can vary between samples due to factors such as the content of phenolic compounds and monoterpenes, as well as the environmental and geographical conditions where the plant grows. Taking together, these results suggest that *Minthostachys mollis* has significant potential as a source of natural antioxidant compounds with possible applications in the food industry.

3.4.3 Insecticidal, repellent, and biopesticidal activity

Studies have evaluated the potential of *Minthostachys mollis* as a source of bioactive compounds with insecticidal, repellent, and biopesticidal activity against different species of insects and mites of agricultural and sanitary importance. This research has mainly used essential oils and plant extracts obtained through different extraction methods, evaluating their effect on stored grain pests, phytophagous mites, and mosquito vectors. The experimental trials include contact and fumigation toxicity tests, repellency bioassays, and evaluations of biocidal activity under different concentrations and experimental conditions. Table 4 summarizes the studies reporting the insecticidal, repellent, and biopesticidal activity of *Minthostachys mollis*, including the type of extract, the method of extraction, the organisms evaluated, the experimental design, and the main findings reported.

In general, the studies reviewed show that the essential oil and extracts of *Minthostachys mollis* have significant activity against various insects and arthropods of agricultural and health interest. The monoterpenes present in the essential oil, such as pulegone and menthone, have been found to be associated with toxic effects through contact and fumigation, as well as repellent properties against several pest species. Likewise, some studies highlight its effectiveness against insects that affect stored grains and against mosquito vectors, suggesting its potential as a natural alternative for pest and vector control.

Furthermore, the results indicate that biological efficacy may vary depending on factors such as the concentration used, the method of application, and the target species evaluated. Taken together, these findings support the potential of *Minthostachys mollis* as a source of natural compounds with applications in integrated pest management strategies and in the development of plant-based biopesticides.

3.4.4 Phytochemistry and chemical characterization of *Minthostachys mollis*

The phytochemical characterization of *Minthostachys mollis* has been extensively studied due to the presence of volatile compounds and secondary metabolites responsible for their biological properties. Various studies have analyzed the chemical composition of the essential oil and different parts of the plant using analytical techniques such as gas chromatography coupled with mass spectrometry (GC-MS), Raman spectroscopy, and nuclear magnetic resonance (NMR). These studies have mainly identified monoterpenes and other volatile compounds that vary according to factors such as geographical origin, the physiological state of the plant, and storage conditions or damage by herbivory. Table 5 presents the studies that report the phytochemical composition and chemical characterization of *Minthostachys mollis*, including the plant material analyzed, the extraction or preparation method, the analytical techniques used, and the main compounds identified.

Studies agree that the essential oil of *Minthostachys mollis* is dominated by monoterpenes, with pulegone and menthone being the major compounds reported in different populations of the plant. However, the chemical composition may vary depending on environmental factors, geographical origin, and storage conditions of the plant material. Likewise, some studies have shown that processes such as herbivory or mechanical damage can induce changes in the proportion of these compounds, evidencing chemical defense responses in the plant.

In addition, the development of advanced analytical techniques has improved the identification and quantification of metabolites present in the essential oil, facilitating the understanding of its chemical variability and its relationship with the biological activities reported for this species.

3.4.5 Antifungal activity of *Minthostachys mollis*

These studies have mainly analyzed essential oil and different types of plant extracts obtained through methods such as hydrodistillation or aqueous extraction, evaluating their ability to inhibit the growth of phytopathogenic fungi and yeasts. Likewise, some studies have explored their effect on mycotoxin production, which broadens their potential application in the control of fungal contaminants in agricultural and food systems. Table 6 summarizes the studies reporting the antifungal activity of *Minthostachys mollis*, considering the type of extract used, the method of extraction, the organisms evaluated, and the main findings reported.

Several studies have observed that the monoterpene compounds present in essential oil, such as pulegone and menthone, could be associated with the inhibition of mycelial growth and the reduction of the viability of the microorganisms evaluated. Likewise, some studies suggest that extracts from the plant may interfere with metabolic processes related to mycotoxin production, providing evidence of possible additional mechanisms of antifungal action. These results highlight the potential of *Minthostachys mollis* as a source of natural compounds with applications in the control of fungal diseases in agriculture and in the development of sustainable alternatives to the use of synthetic fungicides.

3.4.6 Antiparasitic and anti-quorum sensing activity

In recent years, some studies have explored other biological activities of *Minthostachys mollis* related to the interaction between microorganisms and parasitic organisms. Among these activities, the inhibition of the bacterial quorum sensing system, a cellular communication mechanism that regulates the expression of virulence factors, as well as antiparasitic activity against organisms that affect aquatic species of economic importance, stand out. This research has mainly evaluated the plant's essential oil, characterized by its high monoterpene content, using different experimental bioassays to determine its effect on microorganisms and parasites. Table 7 summarizes the studies reporting on the antiparasitic and anti-quorum sensing activity of *Minthostachys mollis*.

The studies reviewed show that *Minthostachys mollis* essential oil can interfere with key biological processes in various microorganisms and parasites. It has been observed that some of its monoterpene components can inhibit bacterial communication systems based on quorum sensing, reducing the expression of factors associated with virulence without directly affecting microbial growth. Likewise, dose-dependent toxic effects have been reported against parasites that affect aquatic organisms, suggesting their potential application in biological control strategies in aquaculture systems. These results indicate that the metabolites present in *Minthostachys mollis* could represent a promising source of natural compounds for the development of therapeutic alternatives or biological control strategies targeting microorganisms and parasites.

3.4.7 Post-harvest preservation and food materials

The essential oil of *Minthostachys mollis* has been evaluated in different food systems and biodegradable materials, particularly in edible coatings, nanoemulsions, and active films. These approaches seek to improve the microbiological and physicochemical stability of foods, as well as prolong their shelf life during storage. Table 8 presents the studies in this subject area.

Table 6
Studies of Antifungal activity in *Minthostachys mollis*

Type of extract	Extraction or preparation method	Chemical composition or main metabolites	Organisms evaluated	Main findings	Reference
Plant extract	In vitro evaluation and field control	General identification of metabolites: flavonoids, tannins, steroids, triterpenoids, alkaloids, leucoanthocyanidins, coumarins, and saponins	Botrytis cinerea, Lasiodiplodia theobromae, Fusarium sp.; control of Erysiphe necator (field); phytotoxicity in wheat seeds	The most effective extracts included Minthostachis mollis (among others). Pimpinella anisum stood out in tomatoes against B. cinerea. Extracts (e.g., Ambrosia artemisiifolia) showed phytotoxicity in wheat. Proposes extracts as alternatives to synthetic fungicides.	(Iparraguirre et al., 2025)
Essential oil	Oil collection	For the most active oils: GC-MS/GC-FID. In M. mollis: pulegone (MEO1) and cis-piperitone epoxide (MEO2) as main	Fusarium oxysporum, *Trichophyton rubrum* and *T. mentagrophytes*	High antifungal activity in most samples. Minthostachys mollis oil showed strong activity against all fungi evaluated.	(Tangarife-Castaño et al., 2012)
Essential oil	Distillation (plant dried in the shade at 21 °C; EO obtained by distillation)		*Candida albicans* ATCC 10231 (oral)	MEO 100% was the most effective among the EO groups (18.9; 18.2; 17.0 mm), but fluconazole was superior (27.9; 27.5; 23.7 mm). Significant differences between concentration and controls	(Huamaní et al., 2021)
Essential oil	Hydro-distillation of aerial parts of the plant	Predominance of monoterpenes, mainly pulegone and menthone (characteristic compounds of muña essential oil)	*Botrytis cinerea*	The essential oil of M. mollis showed significant antifungal activity against Botrytis cinerea, inhibiting mycelial growth and demonstrating potential as a natural alternative for the control of phytopathogens in agricultural crops	(León-Marrou et al., 2023)
Aqueous extract	Aqueous extracts	Links activity to polyphenols/antioxidants in some extracts; for M. mollis, suggests a different mechanism (low DPPH activity)	Inhibition of Aflatoxin B1 (AFB1) synthesis produced by Aspergillus flavus/parasiticus	*M. mollis* inhibited ≈89% of AFB1 production despite low antioxidant activity (IC50 DPPH > 400 mg/L), suggesting another route of inhibition. First report of anti-AFB1 effect for these extracts	(Cadenillas et al., 2023)

Table 7
Studies of Antiparasitic and anti-quorum sensing activity in *Minthostachys mollis*

Type of extract	Extraction method	Main chemical composition	Organisms evaluated	Experimental method	Main findings	Reference
Essential oil	Hydrodistillation	Predominant monoterpenes such as pulegone, α-pinene, carvone, and citral	*Escherichia coli* and *Pseudomonas putida*	Quorum sensing inhibition assay using AHL biosensor systems	Showed inhibition of the bacterial signaling system, suggesting their potential as quorum sensing modulators without directly affecting bacterial growth	(Jaramillo-Colorado et al., 2012)
Essential oil	Hydrodistillation	Characteristic monoterpenes such as pulegone and menthone	Chromobacterium violaceum, Escherichia coli, Listeria innocua, Staphylococcus aureus	Violacein inhibition and broth microdilution assay	The essential oil of M. mollis reduced violacein production by up to 90%, demonstrating strong inhibition of quorum sensing at sublethal concentrations (0.02% v/v).	(Pellegrini et al., 2014)
Essential oil	Hydrodistillation	Volatile monoterpenes (mainly pulegone and menthone)	Monogeneans: Anacanthorus spathulatus, Anacanthorus penilabiatus, Mymarothecium viatorum	In vitro exposure tests at different concentrations	Showed a dose-dependent lethal effect on Amazonian fish monogeneans, eliminating them in less time than other oils evaluated.	(Gonzales et al., 2022)

Table 8
Use of *Minthostachys mollis* in post-harvest conservation and food materials

Type of extract	Type of formulation	Food matrix	Variables evaluated	Main findings	Reference
Essential oil	Coating with muña essential oil, black maca flour, and montmorillonite	Minimally processed melon	Weight loss, firmness, pH, water activity, microbiology	Treatment with 0.1% essential oil reduced weight loss, maintained firmness, and decreased mold and yeast growth, extending shelf life.	(Pacheco-Torreblanca et al., 2025)
Essential oil	Coating with essential oil, amaranth flour, and montmorillonite	Minimally processed mango	pH, water activity, weight loss, texture, microbial load	The coatings reduced weight loss and microbial growth during storage at 5 °C, improving fruit preservation.	(Pillco Ramos et al., 2025)
Essential oil (nanoemulsion)	Essential oil nanoemulsion incorporated into starch films	Biodegradable films	Drop size, zeta potential, mechanical properties, permeability	Optimized nanoemulsions (5.24% EO) generated 48.6 nm drops and increased film stiffness, improving their stability and potential for active biodegradable packaging.	(Flores-Bao et al., 2026)

Table 9
Toxicity pharmacological properties and toxicological safety

Type of extract	Experimental model	Dose or concentration	Parameters evaluated	Main findings	Reference
Essential oil	In vivo trials in rats	Single doses of 300 and 2000 mg/kg and repeated doses of 100–500 mg/kg/day for 28 days	Mortality, histopathological changes, liver enzymes (AST and ALT), body weight	The essential oil showed moderate acute toxicity and dose-dependent toxic effects, including liver and lung alterations, indicating the need to carefully evaluate its safety before therapeutic applications.	(Rojas-Armas et al., 2019)
Leaf extract and infusion	In vivo trial in rats (Rattus norvegicus)	Infusion and extracts administered experimentally	Acetic acid-induced convulsions (analgesic activity) and ethanol-induced gastric lesions	The infusion showed 81.4% analgesic activity and up to 60–69.6% gastroprotective activity, demonstrating greater efficacy than the isolated extracts.	(Velarde-Negrete et al., 2022)
Essential oil	Human cell lines (T24, DU-145, MCF-7) and HEK-293 cells	Approximate IC_{50} ≈ 0.2 mg/mL in tumor cell lines	Chemical composition by GC and GC-MS; cytotoxic activity by MTT assay; antioxidant activity by DPPH assay	The essential oil showed cytotoxic activity in tumor cells with IC50 values close to 0.2 mg/mL, while antioxidant activity was very low, suggesting a mechanism of action independent of free radical neutralization.	(Benites et al., 2018)

The studies reviewed show that incorporating *Minthostachys mollis* essential oil into different food formulations can help improve the preservation of fresh and processed products. In particular, the use of edible coatings and biodegradable matrices has shown positive effects in reducing weight loss, controlling microbial growth, and extending the shelf life of foods during storage. Likewise, the development of nanoemulsions has improved the stability and functionality of the essential oil, facilitating its incorporation into active materials for applications in biodegradable packaging. These results suggest that *Minthostachys mollis* has significant potential as a natural ingredient for the development of innovative food preservation technologies and active packaging systems.

3.4.8 Pharmacological activity and toxicological evaluation of *Minthostachys mollis*

Three experimental studies have analyzed the impact of extracts and essential oils from these species using in vivo and in vitro models, with the aim of determining their possible therapeutic effects and the risks associated with their use. The activities evaluated include analgesic, gastroprotective, and cytotoxic properties, as well as the assessment of acute and subchronic toxicity in animal models. Table 9 summarizes the studies investigating the pharmacological properties and toxicological safety of *Minthostachys mollis*.

Analgesic and gastroprotective effects have been reported in association with the use of infusions and leaf extracts. Likewise, in vitro research has demonstrated cytotoxic activity against certain tumor cell lines, suggesting possible applications in the study of compounds with therapeutic potential. However, some studies have also pointed to the presence of dose-dependent toxic effects in experimental models, especially associated with essential oil, highlighting the importance of carefully evaluating its safety before considering pharmacological or therapeutic applications. Taken together, these results underscore the need for additional research to establish safe doses and better understand the mechanisms of action of the compounds present in this species.

In general, analgesic and gastroprotective effects have been reported in association with the use of infusions and leaf extracts. Likewise, in vitro research has shown cytotoxic activity against certain tumor cell lines, suggesting possible applications in the study of compounds with therapeutic potential. However, some studies have also pointed to the presence of dose-dependent toxic effects in experimental models, especially associated with essential oil, highlighting the importance of carefully evaluating its safety before considering pharmacological or therapeutic applications. Taken together, these results underscore the need for additional research to establish safe doses and better understand the mechanisms of action of the compounds.

Finally, the study by Alonso-Amelot et al. (2006) evaluated the effects of the essential oil of this species on the germination and initial growth of different plants, including *Lactuca sativa*, *Solanum lycopersicum*, *Cucumis sativus*, and *Bidens pilosa*. The results showed that the essential oil completely inhibited seed germination even at low concentrations, demonstrating a marked allelopathic effect. It was also observed that shoot elongation was more affected than root elongation, with differences in sensitivity among the species evaluated, *Solanum lycopersicum* being one of the most sensitive, while *Bidens pilosa* showed greater resistance. These findings suggest that the volatile compounds present in the essential oil of *Minthostachys mollis* could play a role in the ecological interactions of the plant and in the regulation of the growth of competing plant species.

4. Current and future challenges

Despite growing scientific interest in *Minthostachys mollis* and numerous studies evaluating its chemical composition and biological activities, several challenges remain for its use in pharmaceutical, agricultural, and food applications. Studies have shown that its essential oils and extracts contain bioactive metabolites with antimicrobial, insecticidal, antioxidant, and pharmacological properties; however, most of these studies have been conducted under preliminary experimental conditions, which limits their application on a larger scale. Future research should focus on developing scientific and technological strategies that allow the biological potential of this species to be exploited in a sustainable manner.

4.1 Phytochemical standardization and variability of bioactive compounds

One of the main challenges in studying *Minthostachys mollis* is the variability in the chemical composition of its essential oils and plant extracts. Various factors, such as geographical region, climatic conditions, the phenological state of the plant, and the extraction method used, can significantly influence the concentration of the major compounds, such as pulegone, menthone, and limonene (Bakkali et al., 2008; Benites et al., 2018). This variability can affect the reproducibility of biological results and the standardization of products derived from this species.

In this regard, it is necessary to develop more standardized phytochemical characterization strategies, including the use of advanced analytical techniques such as gas chromatography coupled with mass spectrometry (GC-MS) and Raman spectroscopy for the accurate identification of metabolites (Granda-Santos et al., 2025). The standardization of plant extracts will ensure the quality, safety, and efficacy of potential products derived from *Minthostachys mollis*.

4.2 Safety assessment and advanced pharmacological studies

Another important challenge is the limited availability of toxicological and pharmacological studies in advanced models. Although some research has evaluated the toxicity of *Minthostachys mollis* essential oil in animal models, showing adverse effects at high doses (Alegre et al., 2017; Rojas-Armas et al., 2019), most studies on its biological activities have been conducted in vitro or in preliminary experimental models. Therefore, future research should focus on conducting more comprehensive pharmacological studies, including in vivo evaluations, bioavailability studies, and clinical trials to validate the therapeutic potential of the bioactive compounds present in this species. This type of research is essential for the development of new pharmaceutical products derived from medicinal plants (Atanasov et al., 2021).

4.3 Development of sustainable agricultural applications

The potential of Minthostachys mollis as a source of biopesticides and natural repellents has been widely reported in studies evaluating the insecticidal activity of its essential oils against different species of insect pests. However, most of this research has been conducted on a laboratory scale, so studies evaluating its effectiveness under real field conditions are still needed (Pavela & Benelli, 2016; Saikumar et al., 2025).

In addition, it is important to investigate the stability of essential oils, their persistence in the environment, and their potential impact on non-target organisms. The development of formulations based on plant extracts could contribute to the design of more sustainable integrated pest management strategies, reducing the use of synthetic pesticides.

4.4 Technological innovations in formulation and industrial applications

Another promising line of research relates to the development of formulation technologies that improve the stability and efficacy of the bioactive compounds present in *Minthostachys mollis*. In recent years, strategies such as nanoencapsulation, nanoemulsions, and the development of active biodegradable films incorporating essential oils have been explored for applications in food preservation and functional materials (Flores-Bao et al., 2026; Gupta et al., 2025). These technologies can improve the stability, bioavailability, and controlled release of bioactive compounds present in essential oils, significantly expanding their potential for application in the food and pharmaceutical industries. Several studies have shown that essential oils contain bioactive metabolites with multiple biological activities, supporting their interest for the development of new natural products (Önder et al., 2024).

Finally, progress in the study of *Minthostachys mollis* requires interdisciplinary approaches that integrate phytochemistry, microbiology, pharmacology, agronomy, and food science in order to better understand the mechanisms of action of its metabolites and facilitate their use in different sectors. In this regard, addressing the challenges identified will strengthen the scientific and technological potential of this species as a natural source of bioactive compounds. Future research should focus on the standardization of extracts, the development of innovative formulations, and the validation of their efficacy under real conditions of application.

Figure 6 summarizes the main lines of future research, highlighting the phytochemical standardization of extracts and essential oils, safety assessment through more advanced pharmacological studies, the development of sustainable agricultural applications, and the implementation of formulation technologies that expand their potential industrial applications.

5. Conclusions

The main research trends related to *Minthostachys mollis* were identified. A progressive increase in the number of scientific publications has been observed in recent years, reflecting a growing interest in the study of this species. Likewise, scientific production is mainly concentrated in countries of the Andean region, especially Peru and Argentina, which coincides with the natural geographical distribution of the plant and its traditional use in these countries.

In relation to phytochemical composition, the studies analyzed show that the essential oils and extracts of *Minthostachys mollis* mainly contain monoterpenes and other secondary metabolites, among which compounds such as pulegone, menthone, and limonene stand out. These compounds have been associated with various biological activities, which explains the growing scientific interest in the bioactive potential of this species.

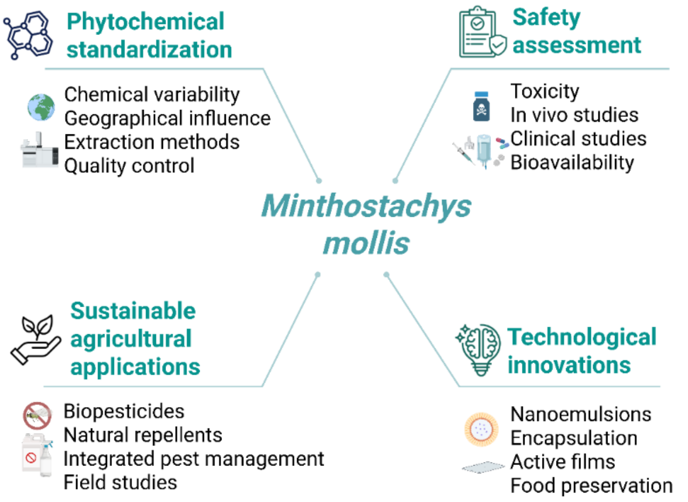

Figure 6. Research gaps and future perspectives in *Minthostachys mollis* studies.

On the other hand, different studies have shown that extracts and essential oils from *Minthostachys mollis* have a wide variety of biological activities, including antimicrobial, antifungal, insecticidal, repellent, antioxidant, and pharmacological properties. These results suggest that this species represents a promising source of natural compounds with potential applications in the pharmaceutical, agricultural, and food sectors.

Some recent studies have explored new technological applications, such as the use of essential oils in food preservation systems and innovative formulations based on nanoemulsions or active coatings. However, challenges remain in terms of phytochemical standardization, safety assessment, and validation of applications under real-world conditions. In this context, future research should focus on the development of more stable formulations, advanced pharmacological studies, and sustainable applications that fully exploit the potential of *Minthostachys mollis*.

Author contributions

K. Eduardo: Writing - review & editing, Writing original draft, Project administration. R. Marchena: Writing - review & editing, Conceptualization. M. Vásquez-Senador: Writing - review & editing, conceptualization.

Declaration of Competing Interest

There are no conflicts to declare.

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