

REVIEW

Essential Oils as Multifunctional Natural Products: Antioxidant, Antimicrobial, Anti-Inflammatory, Antitumor and Technological Applications

Esther Rodrigues Alves dos Reis^{1*} 

¹Undergraduate student in Biological Sciences (B.Sc.), University Estácio de Sá, Belo Horizonte, Minas Gerais, Brazil.

Article history

Received: June 06, 2026

Revised: August 27, 2026

Accepted: September 01, 2026

*Corresponding Author: Esther Rodrigues Alves dos Reis, University Estácio de Sá, Belo Horizonte, Minas Gerais, Brazil.
Email: estherreis2012@gmail.com

Abstract: Essential oils have attracted increasing scientific interest due to their diverse biological activities and expanding technological applications. This systematic review aimed to synthesize current evidence regarding the phytochemical composition, biological properties, and technological potential of plant-derived essential oils. The review followed PRISMA 2020 guidelines and included studies retrieved from the Scopus, Web of Science, and Google Scholar databases. Publications published between 1995 and 2026 were screened according to predefined eligibility criteria, resulting in the inclusion of 55 studies. Antimicrobial activity was the most frequently reported application (69.1%), followed by antioxidant (56.4%), anti-inflammatory (32.7%), antitumor (29.1%), and nanotechnology-related applications (25.5%). The observed biological effects were mainly associated with compounds such as thymol, carvacrol, eugenol, linalool, limonene, and β -caryophyllene. Advances in nanoencapsulation technologies have improved the stability, bioavailability, and efficacy of essential oils, expanding their applicability in pharmaceutical, agricultural, food, cosmetic, and biotechnological sectors. Despite these promising findings, challenges related to phytochemical variability, methodological heterogeneity, limited toxicological and pharmacokinetic data, and scarce clinical evidence remain. Overall, essential oils represent promising multifunctional bioactive resources; however, further standardization, safety assessment, and clinical validation are required to support their practical and commercial implementation.

Keywords: phytochemistry; natural products; bioactive compounds; nanoencapsulation; biodiversity; sustainable biotechnology.

1. Introduction

Natural products have historically played a fundamental role in the discovery of bioactive molecules and the development of therapeutic agents. Among these resources, medicinal and aromatic plants represent an important source of chemically diverse constituents with applications extending beyond human health to agriculture, food preservation, cosmetics, and industrial biotechnology.

In recent decades, increasing concerns regarding antimicrobial resistance, adverse effects associated with synthetic additives, environmental sustainability, and consumer demand for naturally derived products have intensified scientific interest in plant-based bioactive substances (de Sousa et al., 2023; Mohammed et al., 2024).

Within this context, essential oils have attracted considerable attention due to their remarkable phytochemical diversity and wide range of biological

activities. These complex mixtures of volatile secondary metabolites are predominantly composed of terpenes, terpenoids, phenylpropanoids, and related constituents that play important ecological functions in plant defense, signaling, and adaptation to environmental challenges (Jugreet et al., 2020; Elshafie et al., 2023).

The phytochemical composition of essential oils is influenced by multiple factors, including plant genotype, geographical origin, environmental conditions, developmental stage, and extraction procedures, resulting in substantial variability in their biological properties and technological potential (Al-Khayri et al., 2023; Ben Miri, 2025).

The growing scientific interest in essential oils is largely driven by their multifunctional biological activities. Numerous studies have demonstrated their antioxidant potential through the neutralization of reactive oxygen species and the mitigation of oxidative damage associated with aging and several chronic diseases.

Likewise their antimicrobial activity has been extensively investigated due to effectiveness against bacteria, fungi, yeasts, and other pathogenic microorganisms, highlighting their potential as natural alternatives or complementary agents for infection control and food preservation (Pandey et al., 2017; Razzouk et al., 2022; Carvalho-Silva et al., 2024).

In addition to antioxidant and antimicrobial properties, essential oils have demonstrated promising anti-inflammatory activity through the modulation of cytokines, inflammatory mediators, and intracellular signaling pathways. Increasing evidence also supports their antitumor potential, including the induction of apoptosis, inhibition of cell proliferation, suppression of tumor progression, and modulation of molecular pathways involved in carcinogenesis (Sharma et al., 2022; Montalvão et al., 2023).

Collectively, these findings have stimulated growing interest in the incorporation of essential oils into pharmaceutical products, functional foods, cosmetic formulations, and innovative therapeutic approaches (Mohamed & Alotaibi, 2023; Elshafie & Camele, 2023).

Recent advances in nanotechnology have further expanded the applicability of essential oils by addressing some of their major physicochemical limitations. Various nanoencapsulation strategies, including nanoemulsions, nanocapsules, lipid nanoparticles, and liposomal systems, have been

developed to improve stability, aqueous dispersion, bioavailability, and controlled release of bioactive constituents.

These technological innovations have created new opportunities for the application of essential oils in pharmaceutical, agricultural, food, and cosmetic sectors while enhancing their functional performance and commercial viability (Pezantes-Orellana et al., 2024).

Brazil represents a particularly relevant setting for essential oil research due to its exceptional biodiversity. As one of the most biologically diverse countries in the world, Brazil harbors a vast array of aromatic and medicinal plant species distributed across ecosystems such as the Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampa.

This rich botanical heritage constitutes an important source of essential oils with unique phytochemical profiles and promising biological activities, reinforcing the importance of continued phytochemical, pharmacological, and technological investigations (Santana de Oliveira et al., 2023; Santos et al., 2024).

Despite the rapid expansion of scientific research in this field, the available evidence remains fragmented across different disciplines and areas of application. Many studies focus on individual plant species, isolated constituents, or specific biological properties, whereas numerous review articles address only a single activity or application domain.

Consequently, a comprehensive synthesis integrating current knowledge regarding phytochemical composition, biological activities, and emerging technological applications of essential oils remains necessary. This fragmentation limits a broader understanding of their multifunctional nature and hinders the identification of research gaps, translational challenges, and future development opportunities.

Accordingly, the present systematic review was guided by the following research question: What is the current scientific evidence regarding the phytochemical composition, biological activities, and technological applications of plant-derived essential oils, and how do these characteristics support their utilization in pharmaceutical, agricultural, food, cosmetic, and biotechnological sectors?

Based on the premise that the multifunctional properties of essential oils are closely associated with their phytochemical diversity and that recent technological advances have expanded their practical applicability, this review aimed to systematically

evaluate and synthesize the available scientific evidence concerning the antioxidant, antimicrobial, anti-inflammatory, and antitumor activities of essential oils, as well as their emerging technological applications.

Additionally, the review seeks to identify current research trends, methodological limitations, knowledge gaps, and future perspectives that may contribute to the development, standardization, and sustainable utilization of these natural products.

2. Material and Methods

2.1 Study Design

This study was conducted as a systematic literature review following the recommendations established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020). The objective was to systematically identify, evaluate, and synthesize the available scientific evidence regarding the phytochemical composition, biological activities, and technological applications of plant-derived essential oils.

2.2 Search Strategy

The literature search was conducted in April 2026 using the Scopus, Web of Science Core Collection, and Google Scholar databases. These databases were selected because of their extensive coverage of peer-reviewed publications in phytochemistry, natural products chemistry, pharmacology, biotechnology, agriculture, food science, and environmental sciences.

The search strategy was developed using a combination of controlled vocabulary terms and free-text keywords related to essential oils, their phytochemical constituents, biological activities, and technological applications. Boolean operators (AND and OR) were employed to maximize the retrieval of relevant studies.

The following search string was used and adapted according to the indexing requirements of each database:

- (“essential oil*” OR “volatile oil*” OR “plant essential oil*” OR “aromatic oil*”) AND (“phytochemical composition” OR phytochemical* OR “bioactive compound*” OR terpene* OR terpenoid* OR phenolic*) AND (“biological activit*” OR antioxidant* OR antimicrobial* OR antibacterial* OR antifungal* OR antiviral* OR anti-inflammatory OR antitumor OR cytotoxic*) AND (“technological application*” OR nanotechnology OR nanoencapsulation* OR nanoemulsion* OR biotechnology OR agriculture OR “food

preservation” OR cosmetic* OR pharmaceutical*)

Only studies published between 1995 and April 2026 were considered. No geographical restrictions were applied. Additionally, the reference lists of all eligible studies were manually screened to identify potentially relevant publications not retrieved through the electronic database searches.

2.3 Eligibility Criteria

The eligibility criteria were established before the screening process. Studies were included when they investigated plant-derived essential oils and reported biological activities, such as antioxidant, antimicrobial, anti-inflammatory, or antitumor effects, or described technological applications related to food preservation, agriculture, cosmetics, pharmaceuticals, or nanotechnology. Only peer-reviewed articles published in English, Portuguese, or Spanish and available in full-text format were considered.

Conference abstracts, editorials, letters to the editor, dissertations, theses, book chapters, duplicate records, and studies lacking sufficient methodological information were excluded. Articles whose primary focus was not related to essential oils or that did not provide relevant experimental evidence were also excluded.

2.4 Study Selection Process

The study selection process followed the PRISMA 2020 guidelines and comprised four sequential stages: identification, screening, eligibility assessment, and inclusion. All records retrieved from the selected databases were exported to reference management software, where duplicate entries were identified and removed.

The review protocol was not prospectively registered in PROSPERO or the Open Science Framework (OSF). Nevertheless, all methodological procedures, eligibility criteria, search strategies, and data extraction methods were predefined before the initiation of the review and conducted according to PRISMA 2020 recommendations.

Study screening, eligibility assessment, and data extraction were conducted by a single reviewer following predefined eligibility criteria and a standardized data extraction protocol. To minimize potential selection bias and enhance methodological consistency, all records were screened according to eligibility criteria established prior to the review process. Full-text articles were reassessed whenever uncertainties arose, and inclusion decisions were verified against the review protocol and PRISMA 2020 recommendations. Although independent duplicate

screening was not feasible, these procedures were adopted to improve consistency, transparency, and reproducibility throughout the study selection process.

A total of 1,137 records were initially identified through database searches, including 462 records from Scopus, 318 from Web of Science, and 357 from Google Scholar. After removing 284 duplicate records, 853 studies remained for title and abstract screening.

During the screening phase, 708 records were excluded because they were unrelated to the objectives of the review, focused on topics other than essential oils, lacked relevance to biological activities or technological

applications, or failed to meet the predefined eligibility criteria.

Subsequently, 145 full-text articles were assessed for eligibility. After detailed evaluation, 90 studies were excluded due to insufficient methodological information, lack of direct relevance to the research question, incomplete reporting of results, duplication of data across publications, or failure to satisfy the inclusion criteria.

Ultimately, 55 studies fulfilled all eligibility criteria and were included in the qualitative synthesis. The complete study selection process is illustrated in the PRISMA 2020 flow diagram (Figure 1).

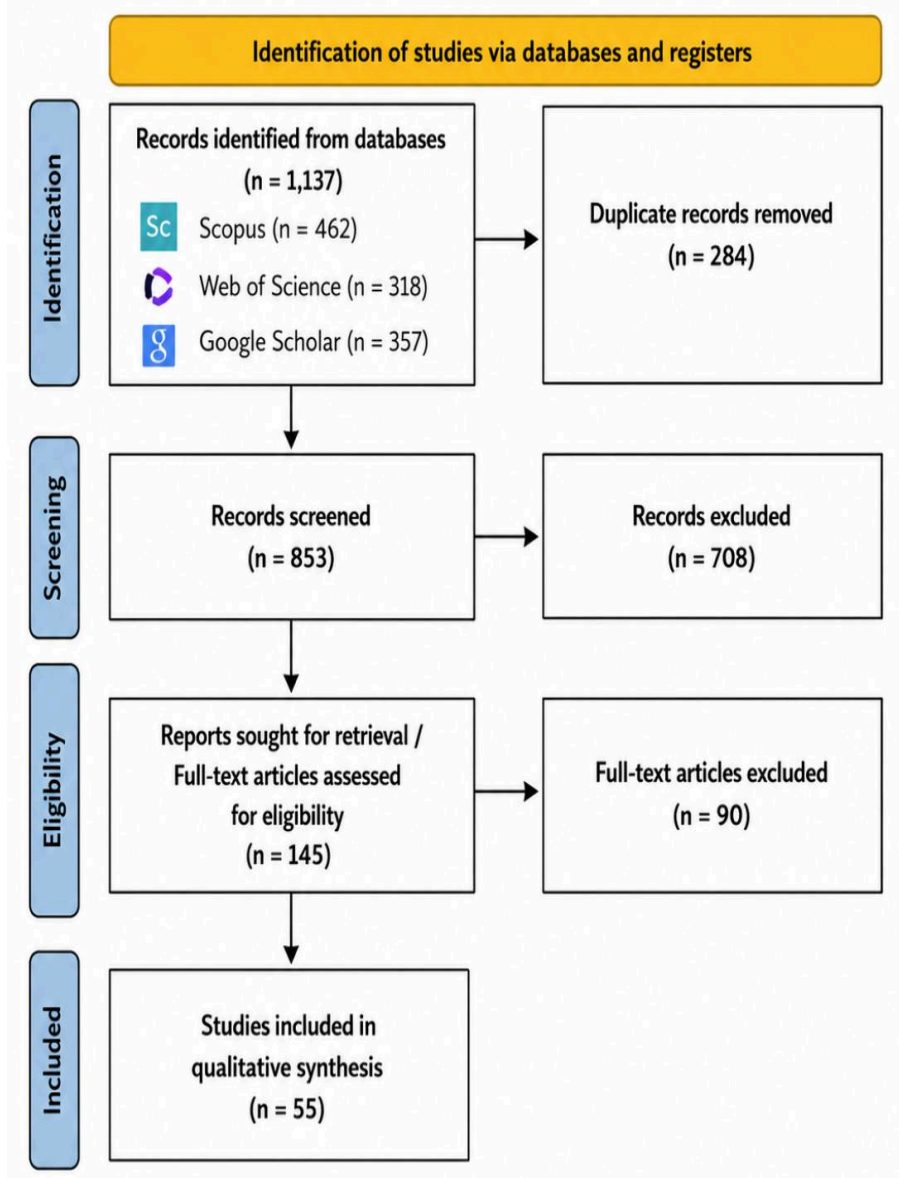


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process for the systematic review of essential oils and their biological and technological applications. Source: Adapted from PRISMA (2021)

2.5 Quality Assessment and Risk of Bias

The methodological quality of the included studies was evaluated using an adapted Joanna Briggs Institute (JBI) critical appraisal framework. The assessment considered the clarity of study objectives, adequacy of methodological design, characterization of essential oils and their phytochemical composition, description of experimental models, transparency of analytical procedures, and completeness of reported results.

Each study was evaluated according to the following criteria:

- Clearly defined objectives;
- Adequate methodological design;
- Detailed characterization of essential oils and major constituents;
- Appropriate description of experimental models and procedures;
- Complete and transparent reporting of results.

Studies fulfilling four or five criteria were classified as presenting a low risk of bias, those fulfilling three criteria were classified as presenting a moderate risk of bias, and studies fulfilling two or fewer criteria were classified as presenting a high risk of bias.

The quality assessment was used to support data interpretation and identify potential methodological limitations across the reviewed literature. Overall, most studies were classified as presenting low to moderate risk of bias, although important sources of heterogeneity were identified, particularly regarding extraction methods, phytochemical characterization, biological assays, and reporting standards.

As illustrated in Figure 2, the overall methodological quality of the included studies was considered satisfactory, with the majority classified as having a low risk of bias.

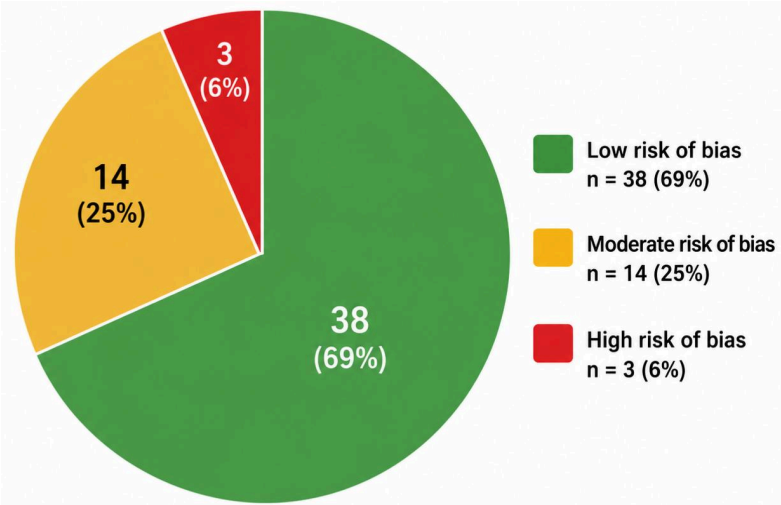


Figure 2. Distribution of risk of bias among the studies included in the review. Source: Author, 2026.

The methodological quality assessment indicated that most included studies presented a low risk of bias ($n = 38$), while 14 studies were classified as having a moderate risk of bias and only 3 studies were considered high risk. These findings suggest that the overall body of evidence is methodologically robust, although some limitations related to study design, reporting quality, and

experimental standardization were identified.

The criteria adopted for methodological quality assessment and risk of bias evaluation are presented in Table 1. These criteria were adapted from the Joanna Briggs Institute (JBI) critical appraisal framework and were applied to all studies included in the qualitative synthesis.

Table 1. Criteria used for methodological quality assessment and risk-of-bias classification of included studies.

Criterion	Description
Study design	Adequacy and appropriateness of the experimental design used to investigate the biological activity or technological

	application of essential oils
Phytochemical characterization	Identification and reporting of the major chemical constituents responsible for the observed biological effects
Methodological description	Sufficient methodological detail to allow study reproducibility, including extraction procedures, experimental conditions, and analytical methods
Outcome reporting	Completeness, clarity, and transparency of the reported results and outcome measures
Consistency of conclusions	Agreement between the presented data and the conclusions drawn by the authors

Source: Author (2026).

The methodological quality and risk of bias of the included studies were assessed using five predefined criteria: study design, phytochemical characterization, methodological description, outcome reporting, and consistency of conclusions (Table 1). Each criterion was scored as 0 (criterion not met) or 1 (criterion met), resulting in a maximum score of five points. Studies scoring 4–5 points were classified as low risk of bias, those scoring 2–3 points as moderate risk of bias, and those scoring 0–1 point as high risk of bias. The overall distribution of risk-of-bias classifications is presented in Figure 2.

2.6 Data Synthesis

Due to the substantial heterogeneity observed among the included studies, particularly regarding plant species, extraction techniques, experimental models, and outcome measures, a quantitative meta-analysis was not feasible. Therefore, the evidence was synthesized qualitatively and organized into thematic categories encompassing phytochemical composition, antioxidant activity, antimicrobial activity, anti-inflammatory activity, antitumor activity, and emerging technological applications, including nanoencapsulation strategies and nanotechnology-based delivery systems.

2.7 Limitations of the Review

Despite the systematic approach adopted in this study, several limitations should be acknowledged. First, the search was restricted to studies indexed in Scopus, Web of Science, and Google Scholar, which may have resulted in the exclusion of relevant publications available in other databases. Additionally, only articles published in English, Portuguese, and Spanish were considered, potentially introducing language bias.

Publication bias may also have influenced the available evidence because studies reporting positive

biological activities are generally more likely to be published than studies reporting negative or inconclusive findings. Furthermore, grey literature, including theses, dissertations, conference proceedings, and technical reports, was not included in the search strategy, which may have limited the identification of potentially relevant unpublished data.

Another important limitation is the predominance of *in vitro* and preclinical studies among the included publications. Although these studies provide valuable insights into the biological properties and mechanisms of action of essential oils, their findings cannot be directly extrapolated to clinical settings.

Although most studies were classified as low risk of bias, methodological heterogeneity remained substantial, particularly regarding extraction procedures, phytochemical characterization, biological assays, and outcome reporting. Therefore, caution is warranted when comparing results across studies.

Substantial heterogeneity was also observed regarding plant species, geographical origin, extraction techniques, phytochemical composition, analytical methodologies, biological models, and outcome measurements. This variability complicated direct comparisons among studies and limited the generalizability of the reported findings.

Finally, differences in methodological quality and reporting standards may have introduced additional sources of bias, reinforcing the need for standardized experimental protocols, comprehensive toxicological evaluations, and well-designed clinical investigations. Therefore, the conclusions presented in this review should be interpreted considering these limitations and the need for further high-quality and standardized research.

3. Results

3.1 General Overview of the Literature

A total of 55 studies published between 1995 and 2026 met the eligibility criteria and were included in this

systematic review. The selected publications covered a wide range of research approaches, including phytochemical characterization, biological activity assessment, mechanistic investigations, toxicological evaluations, and the development of innovative nanoencapsulation strategies (Sharifi-Rad et al., 2017;

Jugreet et al., 2020; de Sousa et al., 2023; Mohammed et al., 2024; Ben Miri, 2025). The main characteristics of the studies, including plant species, major constituents, biological activities, experimental approaches, and principal findings, are summarized in Table 2.

Table 2. Characteristics of studies included in the systematic review.

Author	Plant species investigated	Essential oil studied	Main chemical constituents	Biological activity evaluated	Experimental model	Main Findings
Al-Khayri et al. (2023)	<i>Coriandrum sativum</i> L.	Coriander seed essential oil	Linalool, γ -terpinene, α -pinene, camphor	Antioxidant, antimicrobial, anti-inflammatory	Review	<i>Coriandrum sativum</i> essential oil exhibited significant antimicrobial, antioxidant, anti-inflammatory, and pharmacological activities, largely attributed to its high linalool content
Amiri (2010)	<i>Teucrium orientale</i> subsp. <i>Taylorii</i>	Aerial-part essential oil	Oxygenated monoterpenes, sesquiterpenes	Antioxidant	In vitro	The essential oil showed strong antioxidant activity, suggesting potential application as a natural antioxidant source
Bayala et al. (2014)	<i>Boswellia serrata</i> , <i>Curcuma longa</i> , <i>Nigella sativa</i> , <i>Cymbopogon citratus</i>	Frankincense, turmeric-associated volatiles, black cumin and lemongrass oils	α -Pinene, limonene, citral, thymoquinone-related volatiles	Antitumor activity	Review	Essential oils and their constituents demonstrated promising anticancer effects through apoptosis induction and inhibition of tumor proliferation
Ben Miri (2025)	<i>Lavandula angustifolia</i> , <i>Thymus vulgaris</i> ,	Lavender, thyme, oregano and rosemary oils	Linalool, thymol, carvacrol, 1,8-cineole	Antioxidant, antimicrobial	Review	Essential oils possess broad biological activities, with

	<i>Origanum vulgare</i> , <i>Rosmarinus officinalis</i>					efficacy strongly influenced by their chemical composition
Blowman et al. (2018)	<i>Boswellia serrata</i> , <i>Citrus limon</i> , <i>Origanum vulgare</i>	Frankincense, citrus and oregano oils	α -Pinene, limonene, carvacrol	Antitumor	Review	Several essential oils exhibited selective cytotoxicity against cancer cells while presenting lower toxicity to normal cells
Burt (2004)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Syzygium aromaticum</i> , <i>Cinnamomum verum</i>	Oregano, thyme, clove and cinnamon oils	Carvacrol, thymol, eugenol, cinnamaldehyde	Antibacterial	Review	Essential oils rich in phenolic compounds displayed strong antibacterial activity and potential applications in food preservation
Carvalho-Silva et al. (2024)	<i>Melaleuca alternifolia</i> , <i>Thymus vulgaris</i> , <i>Origanum vulgare</i>	Tea tree, thyme and oregano oils	Terpinen-4-ol, thymol, carvacrol	Antimicrobial, antibiofilm	In vitro	Essential oils effectively inhibited biofilm formation and reduced microbial viability
Konfo et al. (2023)	<i>Rosmarinus officinalis</i> , <i>Thymus vulgaris</i> , <i>Origanum vulgare</i>	Rosemary, thyme and oregano oils	1,8-cineole, thymol, carvacrol	Antioxidant, food preservation	Review	Essential oils can serve as natural antioxidants and improve food stability during storage
Dias (2015)	<i>Cymbopogon citratus</i> , <i>Lippia alba</i> , <i>Ocimum basilicum</i>	Lemongrass, bushy matgrass and basil oils	Citral, carvone, linalool	Antitumor activity in cancer cells	In vitro	Several essential oils showed cytotoxic effects against tumor cell lines, indicating potential anticancer applications
de Matos et al. (2019)	<i>Lippia sidoides</i> , <i>Origanum vulgare</i> ,	Thyme-pepper, oregano and tea tree oils	Thymol, carvacrol, terpinen-4-ol	Nanoencapsulation and pharmacological applications	Review	Nanoencapsulation improved essential oil stability,

	<i>Melaleuca alternifolia</i>					bioavailability, and therapeutic performance
de Sousa et al. (2023)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i> , <i>Rosmarinus officinalis</i> , <i>Thymus vulgaris</i>	Lavender, peppermint, rosemary and thyme oils	Linalool, menthol, 1,8-cineole, thymol	Pharmacological activities	Review	Essential oils exhibit multiple pharmacological properties, including antimicrobial, antioxidant, anti-inflammatory, and anticancer activities
de Sousa et al. (2024)	<i>Origanum vulgare</i> , <i>Cymbopogon citratus</i> , <i>Ocimum basilicum</i>	Oregano, lemongrass and basil oils	Carvacrol, citral, linalool	Antioxidant, antimicrobial, anti-inflammatory	Review	Advances in essential oil research support their use as therapeutic agents and functional bioactive products
Dorman et al. (1995)	<i>Thymus vulgaris</i> , <i>Salvia officinalis</i> , <i>Rosmarinus officinalis</i>	Thyme, sage and rosemary oils	Thymol, carnosol-related diterpenes, 1,8-cineole	Antioxidant	In vitro	Antioxidant activity was associated with the presence of phenolic and oxygenated compounds in essential oils
El-Sakhawy et al. (2026)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Melaleuca alternifolia</i>	Oregano, thyme and tea tree oils	Carvacrol, thymol, terpinen-4-ol	Antibacterial mechanisms	Review	Essential oils disrupt bacterial membranes and interfere with multiple microbial metabolic pathways
Elshafie et al. (2023)	<i>Mentha spp.</i> , <i>Lavandula spp.</i> , <i>Rosmarinus officinalis</i>	Mint, lavender and rosemary oils	Menthol, linalool, 1,8-cineole	Biological activities	Review	Plant essential oils exhibit broad-spectrum biological activities against pathogens and oxidative stress
Elshafie et al. (2026)	<i>Origanum vulgare</i> , <i>Lavandula angustifolia</i>	Oregano and lavender oils	Carvacrol, linalool	Activity against pathogens	In vitro	Essential oils showed promising activity against plant and human

						pathogens through multiple mechanisms
Gonfa et al. (2023)	<i>Cymbopogon citratus</i> , <i>Mentha piperita</i>	Lemongrass and peppermint nanoemulsions	Citral, menthol	Nanoemulsion technology	Review	Nanoemulsions enhanced the stability and effectiveness of essential oils in pharmaceutical and food applications
Gonzalez-Coloma (2023)	<i>Azadirachta indica</i> , <i>Eucalyptus globulus</i> , <i>Cymbopogon citratus</i>	Neem-associated volatiles, eucalyptus and lemongrass oils	Citral, eucalyptol, limonene	Biopesticide activity	In vivo	Essential oils represent eco-friendly alternatives to synthetic pesticides
Gupta et al. (2023)	<i>Ocimum basilicum</i> , <i>Cymbopogon flexuosus</i> , <i>Mentha arvensis</i>	Basil, lemongrass and mint oils	Linalool, citral, menthol	Biopesticide activity	Review	Essential oils demonstrated strong biopesticidal activity and potential for sustainable agricultural applications
Annaz et al. (2025)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Mentha piperita</i>	Thyme, oregano and peppermint oils	Thymol, carvacrol, menthol	Insecticidal activity against <i>Tribolium castaneum</i>	In vivo	Essential oils induced significant mortality and physiological alterations in <i>Tribolium castaneum</i>
Huang et al. (2025)	<i>Rosmarinus officinalis</i> , <i>Origanum vulgare</i> , <i>Thymus vulgaris</i>	Rosemary, oregano and thyme oils	1,8-cineole, carvacrol, thymol	Antioxidant	Review	Essential oils effectively neutralized free radicals and reduced oxidative stress
Hyldgaard et al. (2012)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Melaleuca alternifolia</i>	Oregano, thyme and tea tree oils	Carvacrol, thymol, terpinen-4-ol	Food preservation and antimicrobial activity	Review	Essential oils are promising natural preservatives due to their antimicrobial properties
Jacob et al. (2025)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i> , <i>Cymbopogon</i>	Nano-delivery systems containing essential oils	Linalool, menthol, citral	Enhanced delivery and bioavailability	Review	Nano-delivery systems significantly improved essential oil

<i>n citratus</i>						bioavailability and controlled release
Jugreet et al. (2020)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i> , <i>Rosmarinus officinalis</i>	Lavender, peppermint and rosemary oils	Linalool, menthol, 1,8-cineole	Bioactivities of essential oils	Review	The biological effects of essential oils are closely related to their terpene composition and synergistic interactions
Kozics et al. (2025)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Salvia officinalis</i>	Oregano, thyme and sage oils	Carvacrol, thymol, camphor	Antioxidant, antimicrobial	Review	Essential oils possess diverse biological activities with potential applications in medicine and biotechnology
Lammari et al. (2020)	<i>Origanum vulgare</i> , <i>Cymbopogon citratus</i>	Encapsulated oregano and lemongrass oils	Carvacrol, citral	Encapsulation technologies	Review	Encapsulation technologies protect essential oils and improve their physicochemical stability
Moawad et al. (2025)	<i>Mentha piperita</i> , <i>Lavandula angustifolia</i>	Nanoformulated peppermint and lavender oils	Menthol, linalool	Drug delivery and antimicrobial activity	In vitro	Nanoformulations enhanced the therapeutic efficacy and stability of essential oils
Mohamed & Alotaibi (2023)	<i>Lavandula angustifolia</i> , <i>Rosmarinus officinalis</i>	Lavender and rosemary oils	Linalool, 1,8-cineole	Pharmacological activities	Review	Essential oils are valuable natural products with diverse pharmacological applications
Mohammed et al. (2024)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Cinnamomum verum</i>	Thyme, oregano and cinnamon oils	Thymol, carvacrol, cinnamaldehyde	Pharmacological activities	Review	Essential oils exhibit important pharmacological properties, supporting their use in health-related applications
Montalvão et al. (2023)	<i>Lippia alba</i> , <i>Croton</i> spp., <i>Ocimum</i> spp.	Various Brazilian essential oils	Citral, linalool, eugenol	Antitumor activity	In vitro	Several essential oils showed relevant antitumor activity against cancer cell lines

Nair et al. (2022)	<i>Melaleuca alternifolia</i> , <i>Origanum vulgare</i>	Tea tree and oregano oils loaded in nanoparticles	Terpinen-4-ol, carvacrol	Antimicrobial nanotechnology	Review	Nanoparticle incorporation improved antimicrobial activity and delivery efficiency of essential oils
Nazzaro et al. (2013)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Melaleuca alternifolia</i>	Oregano, thyme and tea tree oils	Carvacrol, thymol, terpinen-4-ol	Antimicrobial mechanisms	Review	Essential oils act against bacteria mainly through membrane disruption and metabolic interference
Nurzyńska-Wierdak (2025)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Lavandula angustifolia</i>	Thyme, oregano and lavender oils	Thymol, carvacrol, linalool	Antibiofilm activity	Review	Essential oils effectively inhibited biofilm formation and persistence.
Omidian et al. (2025)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i>	Nano-enhanced lavender and peppermint oils	Linalool, menthol	Drug delivery systems	Review	Nano-enhanced essential oils exhibited improved biological performance and stability
Pandey et al. (2017)	<i>Origanum vulgare</i> , <i>Rosmarinus officinalis</i> , <i>Cymbopogon citratus</i> , <i>Mentha piperita</i>	Oregano, rosemary, lemongrass and peppermint oils	Carvacrol, 1,8-cineole, citral, menthol	Antimicrobial activity	Review	Essential oils showed broad-spectrum antimicrobial activity against pathogenic microorganisms
Pezantes-Orellana et al. (2024)	<i>Lavandula angustifolia</i> , <i>Rosmarinus officinalis</i> , <i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Melaleuca alternifolia</i>	Lavender, rosemary, oregano, thyme and tea tree essential oils	Linalool, 1,8-cineole, carvacrol, thymol, terpinen-4-ol	Antimicrobial, antioxidant, anti-inflammatory and therapeutic applications	Systematic review	Current evidence supports the therapeutic potential of essential oils, although further clinical studies are required
Puvača et al. (2021)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Syzygium aromaticum</i>	Thyme, oregano and clove oils	Thymol, carvacrol, eugenol	Antimicrobial activity	Review	Essential oils demonstrated effective antimicrobial activity against a wide range of

						microorganisms
Raut & Karuppayil (2014)	<i>Ocimum basilicum</i> , <i>Lavandula angustifolia</i> , <i>Cymbopogon citratus</i>	Basil, lavender and lemongrass oils	Linalool, linalyl acetate, citral	Medicinal properties	Review	Essential oils possess important medicinal properties including antimicrobial, antioxidant, and anti-inflammatory effects
Raveau et al. (2020)	<i>Eucalyptus globulus</i> , <i>Mentha spp.</i> , <i>Cymbopogon spp.</i>	Eucalyptus, mint and lemongrass oils	Eucalyptol, menthol, citral	Biocontrol activity	Review	Essential oils have considerable potential as natural biocontrol agents in agriculture and food systems
Razzouk et al. (2022)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i>	Oregano and thyme oils	Carvacrol, thymol	Antimicrobial activity	Review	Antimicrobial efficacy of essential oils can be enhanced through advanced delivery systems
Saleh et al. (2010)	<i>Thymus vulgaris</i> , <i>Rosmarinus officinalis</i> , <i>Salvia officinalis</i>	Thyme, rosemary and sage oils	Thymol, 1,8-cineole, camphor	Antioxidant activity	In vitro	Essential oils exhibited substantial antioxidant activity and potential health benefits
Santos et al. (2024)	<i>Myrcia multiflora</i> , <i>Myrcia splendens</i> , <i>Myrcia sylvatica</i>	Myrcia leaf essential oils	α -Pinene, β -pinene, limonene, β -caryophyllene	Antioxidant, antimicrobial	In vitro	Myrcia essential oils demonstrated antioxidant and antimicrobial activities associated with terpene-rich compositions
Santos et al. (2022)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Rosmarinus officinalis</i> ,	Oregano, thyme, rosemary and cinnamon essential oils	Carvacrol, thymol, 1,8-cineole, cinnamaldehyde	Food preservation, antimicrobial activity and shelf-life extension	Review	Essential oils improved food preservation by reducing microbial growth and

	<i>Cinnamomum verum</i>					oxidative deterioration
Santos et al. (2017)	<i>Origanum vulgare</i> , <i>Thymus vulgaris</i> , <i>Syzygium aromaticum</i> , <i>Cinnamomum verum</i>	Oregano, thyme, clove and cinnamon essential oils	Carvacrol, thymol, eugenol, cinnamaldehyde	Antibacterial activity against foodborne pathogens	In vitro	Essential oils effectively inhibited foodborne pathogens and may serve as natural food preservatives
Santana de Oliveira et al. (2023)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i> , <i>Rosmarinus officinalis</i> , <i>Origanum vulgare</i>	Lavender, peppermint, rosemary and oregano oils	Linalool, menthol, 1,8-cineole, carvacrol	Overview of pharmacological and therapeutic applications	Editorial	The growing body of evidence supports expanding research and applications of essential oils in pharmacology
São Pedro et al. (2013)	<i>Melaleuca alternifolia</i> , <i>Origanum vulgare</i> , <i>Cymbopogon citratus</i>	Tea tree, oregano and lemongrass oils incorporated into nanostructured systems	Terpinen-4-ol, carvacrol, citral	Antimicrobial nanotechnology applications	Review	Nanotechnology can improve the antimicrobial efficacy and stability of essential oil formulations
Sharifi-Rad et al. (2017)	<i>Lavandula angustifolia</i> , <i>Rosmarinus officinalis</i> , <i>Origanum vulgare</i> , <i>Thymus vulgaris</i>	Lavender, rosemary, oregano and thyme oils	Linalool, 1,8-cineole, thymol, carvacrol	Antioxidant, antimicrobial, anti-inflammatory, antitumor	Review	Essential oils exhibit multiple biological activities driven by synergistic interactions among constituents
Sharopov & Wink (2015)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Syzygium aromaticum</i> , <i>Lavandula angustifolia</i>	Thyme, oregano, clove and lavender oil constituents	Thymol, carvacrol, eugenol, linalool	Radical scavenging and antioxidant activity	In vitro/computational	Phenolic essential oil constituents showed the highest radical-scavenging and antioxidant capacities
Sharma et al. (2022)	<i>Boswellia serrata</i> , <i>Citrus limon</i> , <i>Citrus sinensis</i> , <i>Nigella</i>	Frankincense, lemon, sweet orange and black cumin oils	α -Pinene, limonene, β -caryophyllene, thymoquinone-related volatiles	Antitumor activity	Review	Essential oils may act as complementary anticancer agents through modulation of multiple cellular

<i>sativa</i>						pathways
Silva et al. (2025)	<i>Lavandula angustifolia</i> , <i>Mentha piperita</i> , <i>Melaleuca alternifolia</i>	Essential oils loaded into lipid nanoparticles	Linalool, menthol, terpinen-4-ol	Improved stability, delivery and antimicrobial activity	In vitro	Lipid nanoparticles significantly improved the stability and bioactivity of essential oils
Spigarelli et al. (2026)	<i>Boswellia serrata</i> , <i>Origanum vulgare</i> , <i>Citrus limon</i> , <i>Lavandula angustifolia</i>	Frankincense, oregano, lemon and lavender oils	α -Pinene, carvacrol, limonene, linalool	Antitumor activity and molecular mechanisms	Review	Essential oils showed promising anticancer effects through apoptosis induction and tumor growth inhibition
Subudhi et al. (2025)	<i>Lavandula angustifolia</i> , <i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Eucalyptus globulus</i>	Lavender, thyme, oregano and eucalyptus oils	Linalool, thymol, carvacrol, eucalyptol	Anti-inflammatory activity	Review	Essential oils demonstrated relevant anti-inflammatory effects through modulation of inflammatory mediators
Tit & Bungau (2023)	<i>Rosmarinus officinalis</i> , <i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Salvia officinalis</i>	Rosemary, thyme, oregano and sage oils	1,8-cineole, thymol, carvacrol, camphor	Antioxidant activity	Review	Essential oils represent valuable natural antioxidants with potential therapeutic applications
Yasir et al. (2022)	<i>Thymus vulgaris</i> , <i>Origanum vulgare</i> , <i>Syzygium aromaticum</i>	Thyme, oregano and clove oils applied in milk systems	Thymol, carvacrol, eugenol	Antibacterial activity and food preservation	In vitro	Essential oils reduced bacterial contamination and improved microbiological quality of milk products
Zhao et al. (2023)	<i>Lavandula angustifolia</i> , <i>Rosmarinus officinalis</i> , <i>Eucalyptus globulus</i> , <i>Matricaria chamomilla</i>	Lavender, rosemary, eucalyptus and chamomile oils	Linalool, 1,8-cineole, eucalyptol, α -bisabolol	Anti-inflammatory mechanisms	Review	Anti-inflammatory effects of essential oils are mediated through regulation of cytokines and oxidative pathways

Source: Author (2026).

The quantitative analysis revealed that antimicrobial activity was the most frequently investigated application, being reported in 38 studies (69.1%), followed by antioxidant activity in 31 studies (56.4%), anti-inflammatory activity in 18 studies (32.7%), antitumoral activity in 16 studies (29.1%), and nanotechnology-related applications in 14 studies (25.5%). Several studies evaluated more than one biological activity, highlighting the multifunctional nature of essential oils and their bioactive constituents.

The reviewed literature demonstrated a marked increase in scientific production over the last decade, particularly from 2020 onwards. This trend reflects the growing interest in natural products capable of addressing major contemporary challenges, including antimicrobial resistance, oxidative stress, chronic inflammatory disorders, and the demand for sustainable alternatives to synthetic additives. Research activity was distributed across multiple disciplines, including pharmacology,

microbiology, food science, biotechnology, agriculture, and nanotechnology (Mohamed & Alotaibi, 2023; Elshafie & Camele, 2023; Kozics et al., 2025).

A notable finding was the diversification of research objectives over time. Earlier investigations primarily focused on phytochemical characterization and antimicrobial properties, whereas more recent studies increasingly explored antioxidant, anti-inflammatory, antitumoral, and technological applications. In particular, nanoencapsulation-based approaches have emerged as a rapidly expanding field, aiming to improve the stability, bioavailability, protection against degradation, and controlled release of essential oil constituents (Santana de Oliveira et al., 2023; de Sousa et al., 2024; Pezantes-Orellana et al., 2024).

As shown in Table 3, antimicrobial activity was the most frequently reported biological property, followed by antioxidant, anti-inflammatory, antitumor, and nanotechnology-based applications.

Table 3. Biological activities of essential oils and experimental evidence reported in the included studies.

Biological Activity	Number of Studies	Main Constituents	Experimental Models	Main Outcomes
Antimicrobial	38	Thymol, Carvacrol, Eugenol	Bacteria, fungi, biofilms	Growth inhibition
Antioxidant	31	Thymol, Eugenol, Linalool	DPPH, ABTS, FRAP	ROS scavenging
Anti-inflammatory	18	B-Caryophyllene, Linalool	Cell cultures, animal models	Cytokine reduction
Antitumor	16	Limonene, α -Pinene, β -Caryophyllene	Cancer cell lines	Apoptosis and cell-cycle arrest
Nanotechnology-based applications	14	Multiple compounds	Nanoemulsions, nanocapsules	Enhanced stability and bioavailability

Source: Author (2026).

Overall, the reviewed evidence highlights a progressive transition from descriptive phytochemical studies toward application-oriented investigations, reinforcing the therapeutic, industrial, agricultural, and technological

potential of essential oils. Figure 3 provides a quantitative overview of the included studies, including the main biological activities investigated (Figure 3A), temporal publication trends (Figure 3B), and the most frequently reported bioactive constituents (Figure 3C).

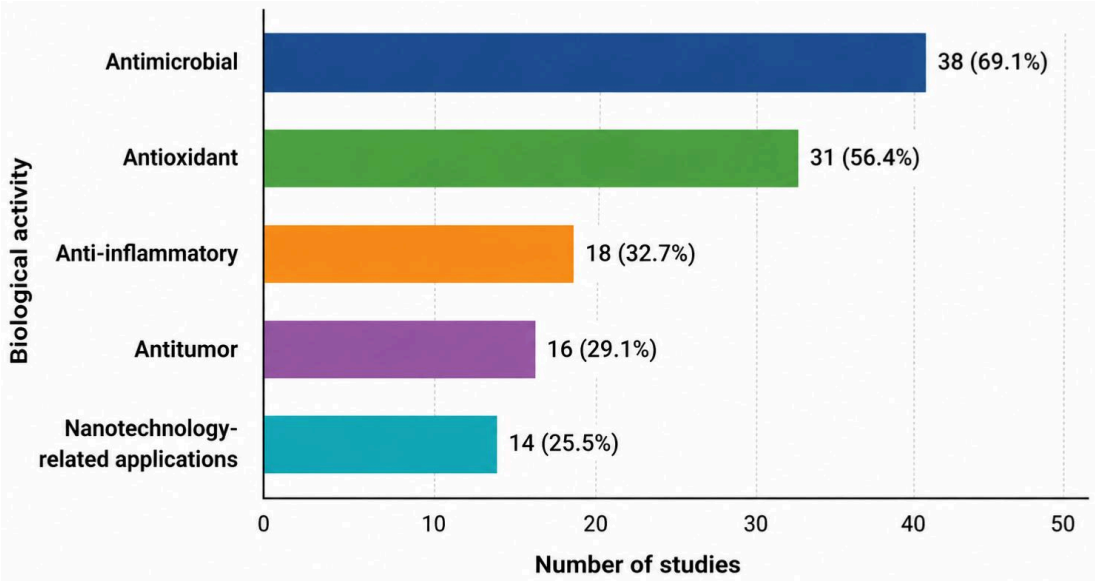


Figure 3A. Biological activities investigated in the included studies. Source: Author (2026).

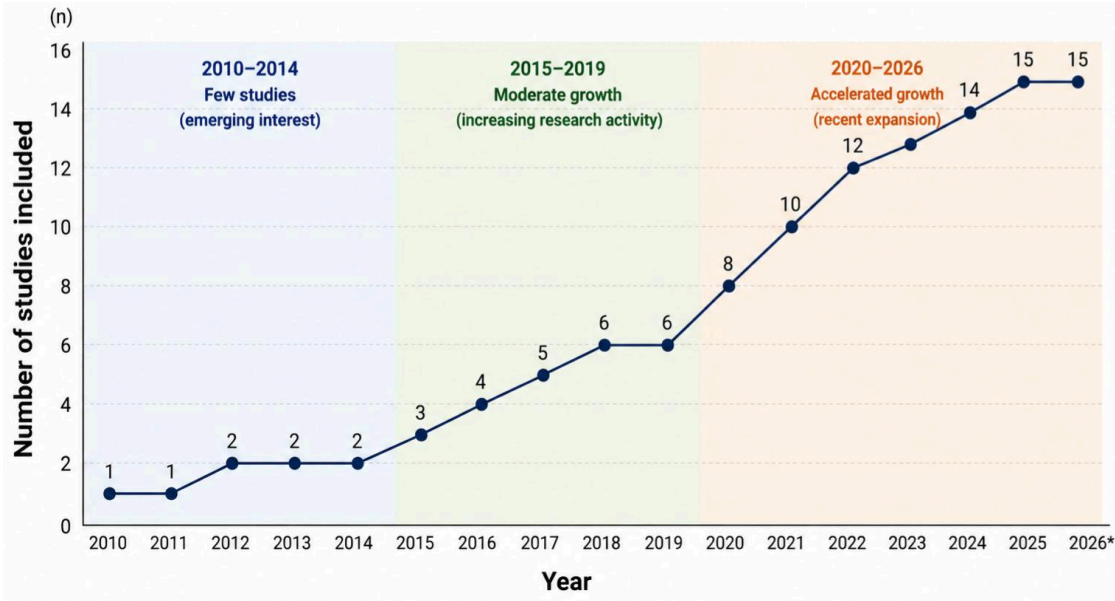


Figure 3B. Temporal distribution of publications included in the review (2010–2026). Source: Author (2026).

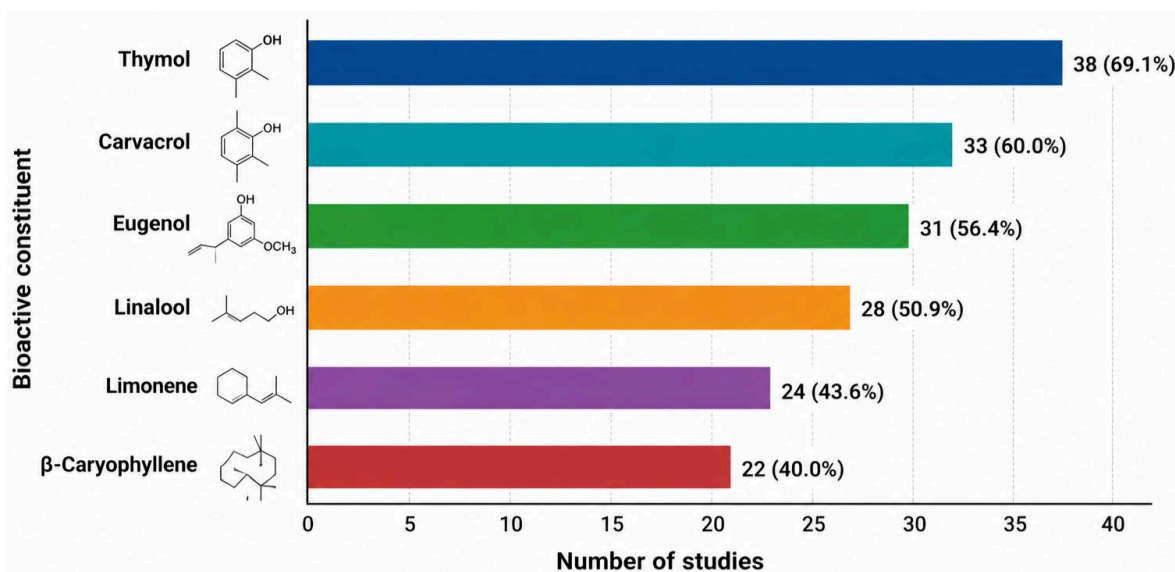


Figure 3C. Most frequently reported bioactive constituents in essential oils. Source: Author (2026).

3.2 Chemical Composition and Bioactive Constituents

The studies included in this review revealed substantial phytochemical diversity among essential oils obtained from different plant species and geographical regions. Despite this variability, several constituents were consistently identified as major components, including thymol, carvacrol, eugenol, linalool, limonene, α -pinene, β -pinene, terpinen-4-ol, citronellal, and β -caryophyllene (Al-Khayri et al., 2023; de Sousa et al., 2023; Santos et al., 2024). These compounds were among the most frequently reported bioactive constituents across the reviewed literature and were commonly associated with antimicrobial, antioxidant, anti-inflammatory, and antitumoral activities (Figure 3C).

The phytochemical composition of essential oils was strongly influenced by botanical species, geographical origin, climatic conditions, soil characteristics, developmental stage, cultivation practices, and extraction methods. Consequently, considerable compositional variation was observed among studies, including investigations involving the same plant species (Jugreet et al., 2020; Elshafie & Camele, 2023). This variability represents a major challenge for the standardization, reproducibility, and large-scale commercialization of essential oil-based products.

Monoterpenes and sesquiterpenes were consistently reported as the predominant classes of constituents,

reinforcing their central role in the biological activities attributed to essential oils (Sharifi-Rad et al., 2017; Ben Miri, 2025). Among these compounds, thymol and carvacrol were frequently associated with antimicrobial effects through membrane disruption mechanisms, whereas eugenol, linalool, and limonene were commonly linked to antioxidant and anti-inflammatory activities. β -Caryophyllene was repeatedly highlighted for its anti-inflammatory and potential antitumoral properties (de Sousa et al., 2023; Mohammed et al., 2024).

Importantly, the reviewed studies indicated that the biological activities of essential oils cannot generally be attributed to a single constituent. Instead, antimicrobial, antioxidant, anti-inflammatory, and antitumoral effects frequently arise from synergistic or additive interactions among multiple compounds present within the phytochemical matrix. Such interactions may enhance efficacy, broaden the spectrum of activity, and contribute to the multifunctional nature of essential oils (de Sousa et al., 2023; Mohammed et al., 2024).

Overall, the findings demonstrate that chemical composition is a key determinant of biological activity, while also highlighting the need for greater standardization of extraction procedures and phytochemical characterization protocols. The major phytochemical constituents identified in the reviewed studies and their associated biological activities are summarized in Table 4.

Table 4. Main biological activities of essential oils, major bioactive constituents, and reported biological effects. Summary of the principal biological activities reported in the literature, highlighting the major constituents associated with each activity and their respective biological effects.

Bioactive Constituent	Chemical Class	Main Biological Activities	Proposed Mechanisms
Thymol	Monoterpene phenol	Antioxidant, Antimicrobial, Anti-inflammatory	Membrane disruption; ROS scavenging
Carvacrol	Monoterpene phenol	Antimicrobial, Antioxidant	Membrane permeability alteration
Eugenol	Phenylpropanoid	Antioxidant, Antimicrobial	Free-radical neutralization
Linalool	Monoterpene alcohol	Antioxidant, Anti-inflammatory	Cytokine modulation
Limonene	Monoterpene	Antioxidant, Antitumor	Apoptosis induction
α -Pinene	Monoterpene	Anti-inflammatory, Antitumor	Signaling pathway modulation
β -Pinene	Monoterpene	Antioxidant, Antimicrobial	Oxidative stress reduction
β -Caryophyllene	Sesquiterpene	Anti-inflammatory, Antitumor	CB2 receptor interaction
Terpinen-4-ol	Monoterpene alcohol	Antimicrobial	Membrane disruption
Citronellal	Monoterpene aldehyde	Antimicrobial	Cellular metabolism interference

Source: Author (2026).

3.3 Antioxidant Activity

Antioxidant activity was one of the most frequently investigated biological properties among the studies included in this review, being reported in 31 of the 55 selected studies (56.4%). The antioxidant potential of essential oils was predominantly evaluated using in vitro assays, including DPPH, ABTS, FRAP, and lipid peroxidation inhibition methods, which consistently demonstrated their capacity to scavenge reactive oxygen species and reduce oxidative damage (Dorman et al., 1995; Amiri, 2010; Saleh et al., 2010).

The reviewed evidence indicates that antioxidant activity is closely associated with phenolic compounds and oxygenated terpenes. Essential oils rich in thymol, carvacrol, eugenol, and linalool generally exhibited the highest radical-scavenging capacities. Oils from *Coriandrum sativum* and other aromatic species showed significant antioxidant activity, particularly when characterized by high concentrations of oxygenated monoterpenes (Al-Khayri et al., 2023; Sharopov & Wink, 2015; Tit & Bungau, 2023).

Considerable variability in antioxidant performance was observed among studies, reflecting differences in plant species, geographical origin, environmental conditions, harvesting period, extraction methods, and phytochemical composition. As a result, oils obtained from the same species occasionally exhibited distinct

antioxidant capacities, highlighting the importance of phytochemical characterization and methodological standardization (de Sousa et al., 2023; Konfo et al., 2023; Huang et al., 2025).

Most studies were based on in vitro assays, limiting direct extrapolation to physiological conditions. Therefore, further in vivo and clinical investigations are required to confirm the antioxidant efficacy and bioavailability of essential oil constituents.

In addition to laboratory assays, antioxidant properties have been explored in food preservation systems. Essential oils were reported to delay lipid oxidation, reduce oxidative deterioration, and preserve sensory and physicochemical characteristics during storage, supporting their use as natural alternatives to synthetic antioxidants in food products, edible coatings, and active packaging systems (Konfo et al., 2023; Santos et al., 2022).

Overall, the findings demonstrate a strong relationship between phytochemical composition and antioxidant activity, with evidence suggesting that synergistic interactions among multiple constituents contribute substantially to the observed biological effects.

3.4 Geographic Distribution of Studies

The geographical analysis of the included studies revealed a broad global interest in the biological and technological applications of essential oils. Research

efforts were unevenly distributed across regions, with a greater concentration of publications originating from Asia and South America, followed by Europe and North America (Figure 4). Countries such as China, Brazil, India, and the United States were among the most represented contributors, highlighting their prominent role in natural product, phytochemical, and pharmaceutical research.

The observed geographical distribution may be associated with regional biodiversity, the traditional use of medicinal and aromatic plants, and investments in pharmaceutical, agricultural, and food-related research. Countries located in tropical and subtropical regions possess a rich diversity of aromatic species, which likely contributes to the greater scientific interest in exploring

essential oils as sources of bioactive compounds with antimicrobial, antioxidant, anti-inflammatory, antitumoral, and technological applications.

The predominance of studies from Asia and South America also reflects increasing efforts to valorize native plant resources and develop sustainable alternatives for healthcare, agriculture, and food preservation. In contrast, the lower representation of studies from Africa and Oceania suggests the existence of important research gaps, despite the considerable biodiversity found in these regions. Expanding research activities in underrepresented areas may contribute to the discovery of novel essential oil chemotypes and bioactive compounds with potential industrial and therapeutic applications.

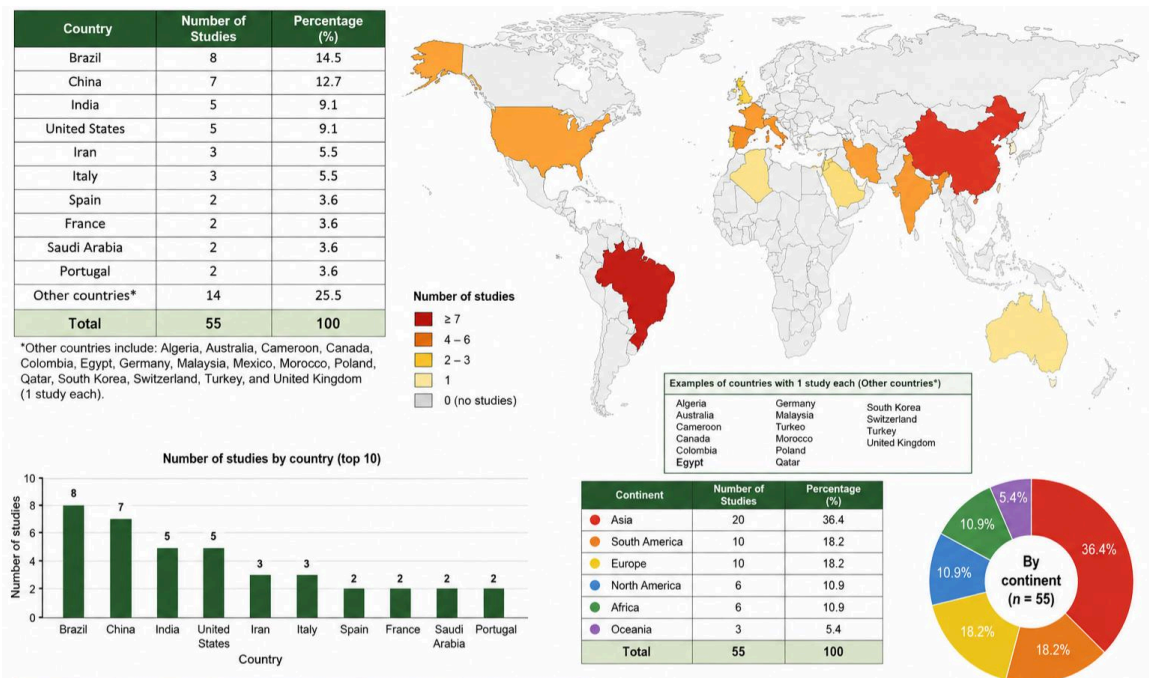


Figure 4. Geographic distribution of research efforts among the studies included in this systematic review. Source: Author (2026).

3.5 Antimicrobial Activity

Antimicrobial activity was the most extensively investigated biological property among the studies included in this review, being reported in 38 of the 55 selected studies (69.1%). Essential oils demonstrated inhibitory effects against a broad spectrum of microorganisms, including Gram-positive and Gram-negative bacteria, yeasts, filamentous fungi, and microbial biofilms. These effects are primarily attributed to terpenes and phenolic compounds that disrupt membrane integrity, alter permeability, and interfere with essential cellular processes (Burt, 2004; Nazzaro et al., 2013; Pandey et al., 2017).

Among the microorganisms evaluated, *Staphylococcus aureus* and *Escherichia coli* were the most frequently investigated bacterial species, while *Candida albicans* was the principal fungal model. Other relevant pathogens included *Pseudomonas aeruginosa*, *Salmonella* spp., and *Listeria monocytogenes* (Hyldgaard et al., 2012; Puvača et al., 2021; Razzouk et al., 2022; Yasir et al., 2022). Essential oils rich in thymol, carvacrol, eugenol, and terpinen-4-ol consistently exhibited strong antimicrobial activity.

Although most studies reported positive results, antimicrobial efficacy varied according to phytochemical composition, microbial susceptibility, and experimental conditions. Gram-positive bacteria generally appeared

more susceptible than Gram-negative species, likely due to structural differences in the cell envelope that limit the penetration of hydrophobic compounds.

Recent studies have also demonstrated the ability of essential oils to inhibit biofilm formation and disrupt mature biofilms, particularly those produced by *S. aureus*, *P. aeruginosa*, and *C. albicans* (Carvalho-Silva et al., 2024; Nurzyńska-Wierdak, 2025; Elshafie et al., 2026). These findings expand their potential applications in infection prevention and microbial control.

Beyond medical applications, essential oils have shown promise in food preservation by inhibiting spoilage microorganisms and foodborne pathogens, supporting their incorporation into natural preservatives, edible coatings, and active packaging systems (Santos et al., 2017; Santos et al., 2022).

Despite the promising evidence, most studies remain limited to in vitro models, highlighting the need for further in vivo and clinical investigations, as well as greater standardization of phytochemical characterization and antimicrobial testing methodologies.

3.6 Anti-Inflammatory Activity

Anti-inflammatory activity was reported in 18 of the 55 studies included in this review (32.7%). The reviewed evidence demonstrated that several essential oils and their constituents can modulate inflammatory responses through the inhibition of pro-inflammatory mediators and signaling pathways associated with immune activation and tissue injury (Zhao et al., 2023; Subudhi et al., 2025).

Reductions in tumor necrosis factor-alpha (TNF- α), interleukin-1 beta (IL-1 β), interleukin-6 (IL-6), nitric oxide (NO), and prostaglandins were consistently reported following treatment with essential oils or isolated constituents (de Sousa et al., 2024; Mohammed et al., 2024). Monoterpenes and sesquiterpenes, particularly linalool, β -caryophyllene, thymol, carvacrol, and α -pinene, were the compounds most frequently associated with these effects. Several studies suggested that anti-inflammatory activity results from synergistic interactions among multiple constituents rather than the action of individual compounds alone.

Although substantial variability was observed regarding experimental models and methodologies, the available evidence consistently supports the anti-inflammatory potential of essential oils. Furthermore,

antioxidant and anti-inflammatory activities appear closely interconnected, as the reduction of oxidative stress may contribute to the attenuation of inflammatory processes and cellular damage (Kozics et al., 2025).

Most investigations remain limited to in vitro and preclinical models, highlighting the need for further clinical studies to confirm efficacy, safety, and therapeutic applicability.

3.7 Antitumor Activity

Antitumor activity was reported in 16 of the 55 studies included in this review (29.1%), representing one of the most promising applications of essential oils. Experimental studies demonstrated cytotoxic effects against a wide range of tumor cell lines, including breast, lung, colorectal, prostate, liver, cervical, and hematological cancers (Bayala et al., 2014; Dias, 2015; Blowman et al., 2018).

The reported effects were associated with multiple mechanisms, including reduced cell viability, inhibition of proliferation, induction of apoptosis, cell-cycle arrest, and modulation of pathways involved in tumor growth, angiogenesis, invasion, and survival (Sharma et al., 2022; Montalvão et al., 2023). Among the constituents most frequently linked to antitumor activity were limonene, α -pinene, β -caryophyllene, thymol, and carvacrol, which were reported to influence oxidative stress, mitochondrial function, apoptosis, and cellular proliferation.

Despite these promising findings, most evidence remains restricted to in vitro studies, with limited validation in animal models. Variability in tumor types, experimental protocols, and tested concentrations further complicates direct comparisons among studies. Therefore, additional investigations addressing toxicological profiles, pharmacokinetics, bioavailability, formulation strategies, and long-term safety are required before clinical applications can be established (Spigarelli et al., 2026).

Overall, the available evidence supports the potential of essential oils as sources of bioactive compounds for oncology research and future drug development.

A summary of the principal biological activities, target organisms, experimental models, and associated phytochemical constituents reported in the reviewed studies is presented in (Table 5).

Table 5. Major bioactive constituents identified in essential oils and their associated biological activities. Overview of the most frequently reported constituents in essential oils and the biological activities attributed to each constituent according to the reviewed studies.

Biological Activity	Main Target Organisms/Models	Major Constituents	Main Biological Effects
Antioxidant	DPPH, ABTS, FRAP assays	Thymol, Eugenol, Linalool	ROS scavenging and lipid peroxidation inhibition
Antimicrobial	<i>S. aureus</i> , <i>E. coli</i> , <i>C. albicans</i>	Thymol, Carvacrol, Terpinen-4-ol	Growth inhibition and biofilm disruption
Anti-inflammatory	Macrophages, animal models	B-Caryophyllene, Linalool	Reduction of TNF- α , IL-1 β , IL-6
Antitumor	Breast, lung, colon, prostate cancer cell lines	Limonene, α -Pinene, β -Caryophyllene	Apoptosis and proliferation inhibition
Nanotechnology applications	Nanoemulsions, nanocapsules, liposomes	Multiple constituents	Improved stability and bioavailability

Source: Author (2026)

The quantitative distribution of the major biological activities reported in the reviewed studies is presented in Figure 3A, highlighting the predominance of antimicrobial (69.1%) and antioxidant (56.4%) investigations, followed by anti-inflammatory (32.7%) and antitumor (29.1%) studies.

3.8 Technological Applications and Nanotechnology-Based Systems

Technological applications involving nanoencapsulation strategies were reported in 14 of the 55 studies included in this review (25.5%), representing one of the fastest-growing research areas associated with essential oils. Although essential oils exhibit diverse biological activities and considerable industrial potential, their practical use is often limited by high volatility, low aqueous solubility, susceptibility to oxidation, and chemical instability.

To address these limitations, numerous studies have investigated nanotechnology-based delivery systems designed to improve the physicochemical properties, stability, and biological performance of essential oils (São Pedro et al., 2013; de Matos et al., 2019; Nair et al., 2022).

Among the nanoencapsulation platforms evaluated, nanoemulsions, nanocapsules, lipid nanoparticles, polymeric nanoparticles, and other nanocarrier systems were the most frequently investigated. These technologies protect essential oil constituents from environmental degradation, enable controlled release, improve the dispersion of hydrophobic compounds in aqueous media, and may enhance interactions with biological targets. As a result, they have expanded the potential applications of essential oils in pharmaceutical, cosmetic, food, and agricultural sectors (Lammari et al., 2020; Gonfa et al., 2023; Jacob et al., 2025; Omidian et al., 2025).

Most reviewed studies reported improvements in stability, bioavailability, and biological efficacy following nanoencapsulation. Enhanced antimicrobial, antioxidant, and anti-inflammatory activities were frequently observed when compared with conventional formulations. These findings suggest that improved protection and delivery of phytochemical constituents can significantly enhance biological performance and help overcome major limitations associated with essential oil utilization (Moawad et al., 2025; Silva et al., 2025).

Despite these advances, important challenges remain. Considerable heterogeneity was observed in nanoencapsulation composition, particle size, encapsulation efficiency, release profiles, storage stability, and biological evaluation methods. This variability complicates direct comparisons among studies and underscores the need for greater methodological standardization. In addition, relatively few investigations have evaluated long-term safety, toxicological profiles, environmental impacts, large-scale manufacturing feasibility, or regulatory requirements. These factors remain critical barriers to commercial and clinical implementation.

Applications have expanded across multiple sectors. In the food industry, nanoencapsulation-based systems have been investigated as natural preservatives and components of active packaging technologies capable of extending shelf life and improving food safety. In pharmaceutical and cosmetic products, nanocarriers have demonstrated potential to improve stability, facilitate controlled release, and enhance the delivery of bioactive constituents. Agricultural studies have also explored nanoencapsulation as a platform for developing biopesticides and sustainable crop protection products, further highlighting the versatility of these technologies.

Taken together, the available evidence indicates that nanotechnology can substantially improve the practical

applicability of essential oils. Future research should prioritize methodological standardization, safety assessment, scalability, and regulatory compliance to facilitate the successful translation of these technologies from laboratory research to industrial and clinical

applications.

The principal nanotechnology-based systems investigated for essential oil delivery, stabilization, and controlled release are summarized in Table 6.

Table 6. Nanotechnology-based delivery systems developed for essential oils and their main applications. Summary of nanoencapsulation strategies employed to improve the stability, bioavailability, controlled release, and biological performance of essential oils in pharmaceutical, food, cosmetic, and agricultural applications.

Nanotechnology System	Main Characteristics	Main Advantages	Reported Applications
Nanoemulsions	Oil droplets dispersed in an aqueous phase with nanometric size	Improved solubility, stability, and dispersion of hydrophobic compounds	Food preservation, cosmetics, pharmaceuticals
Nanocapsules	Core-shell structures encapsulating essential oil constituents	Controlled release and protection against degradation	Drug delivery and therapeutic formulations
Lipid Nanoparticles	Solid or liquid lipid matrices containing bioactive compounds	Enhanced bioavailability and prolonged stability	Pharmaceutical and biomedical applications
Polymeric Nanoparticles	Biopolymer-based carrier systems	Protection from oxidation and environmental degradation	Agriculture, medicine, and food technology
Liposomes	Phospholipid vesicles capable of entrapping hydrophobic compounds	Improved cellular uptake and targeted delivery	Pharmaceutical and cosmetic formulations

Source: Author (2026).

Figure 5 illustrates the relationship between the major bioactive constituents commonly identified in essential

oils, their associated biological activities, and the role of nanoencapsulation technologies in enhancing stability, bioavailability, and practical applicability across different industrial sectors.

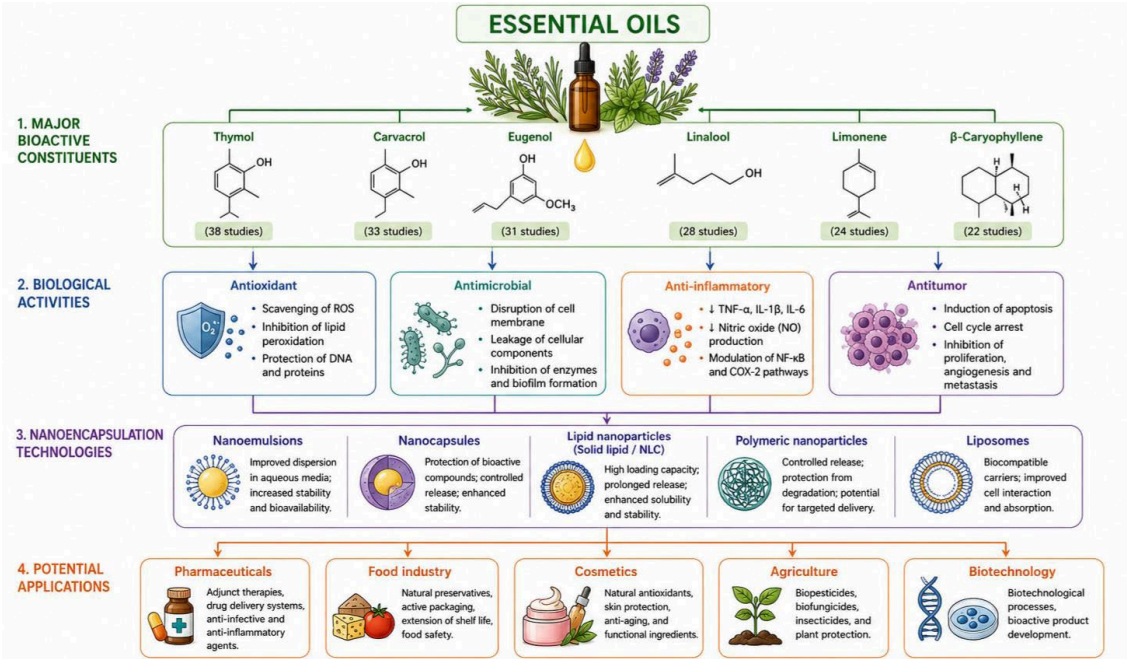


Figure 5. Conceptual framework illustrating the relationships among major bioactive constituents of essential oils, their biological activities, nanoencapsulation technologies, and potential applications in pharmaceutical, food, cosmetic, and

agricultural sectors. Source: Author (2026).

3.9 Emerging Trends and Future Perspectives

The reviewed literature reveals a clear diversification of research involving essential oils, reflecting their growing relevance across multiple scientific disciplines. Although antimicrobial and antioxidant activities remain the most extensively investigated areas, recent studies have shown increasing interest in anti-inflammatory and antitumor applications. Particular attention has been given to elucidating molecular mechanisms of action, identifying bioactive constituents, and exploring potential therapeutic targets.

Advances in nanoencapsulation technologies have also emerged as a major research focus. These approaches aim to improve the stability, bioavailability, and efficacy of essential oil-based products, thereby enhancing their practical applicability across different sectors (de Sousa et al., 2024; Pezantes-Orellana et al., 2024).

Another important trend is the expansion of agricultural applications. Essential oils have been widely investigated as biopesticides, bioinsecticides, and environmentally friendly alternatives for crop protection. Studies involving economically important pests, including *Tribolium castaneum*, have demonstrated promising insecticidal, repellent, and growth-inhibitory effects, supporting the incorporation of essential oils into integrated pest management programs.

Their antifungal and antibacterial properties have further stimulated interest in controlling plant pathogens and reducing dependence on synthetic agrochemicals (Gonzalez-Coloma, 2023; Gupta et al., 2023; Annaz et al., 2025; Raveau et al., 2020).

Recent publications also highlight growing interest in the use of essential oils for food preservation, active packaging systems, cosmetic products, and pharmaceutical formulations. These applications are largely driven by consumer demand for natural products, sustainable technologies, and alternatives to synthetic additives. Consequently, essential oils are increasingly recognized not only as aromatic plant products but also as multifunctional bioactive resources with significant technological and commercial value.

Despite these advances, several challenges continue to limit broader implementation. The lack of standardized extraction procedures, variability in phytochemical composition, limited toxicological information, scarcity of clinical investigations, and regulatory constraints remain major barriers to large-scale adoption. These issues were repeatedly identified across the reviewed literature and should be considered priority areas for future research.

Taken together, the available evidence demonstrates the versatility of essential oils and supports their continued investigation across pharmaceutical, agricultural, food, cosmetic, and biotechnological sectors. Future studies should prioritize phytochemical standardization, quality control protocols, toxicological assessment, pharmacokinetic evaluation, clinical validation, and the development of innovative nanoencapsulation strategies. Such efforts will be essential to facilitate the translation of experimental findings into commercial products and evidence-based therapeutic applications.

As illustrated in Figure 5, essential oils contain diverse phytochemical constituents associated with multiple biological activities and technological applications, highlighting their multifunctional nature and broad development potential.

4. Discussion

4.1 Chemical Diversity as the Basis of Biological Activity

The broad spectrum of biological activities attributed to essential oils is largely a consequence of their phytochemical diversity. These complex mixtures contain monoterpenes, sesquiterpenes, phenylpropanoids, and other volatile metabolites whose composition is influenced by genetic, environmental, geographical, and methodological factors (Sharifi-Rad et al., 2017; Jugreet et al., 2020; Al-Khayri et al., 2023; Elshafie & Camele, 2023).

The studies included in this review consistently indicate that phytochemical composition is a major determinant of biological activity. However, biological performance cannot be explained solely by the presence of dominant constituents. Evidence from different species suggests that minor compounds and synergistic interactions within the phytochemical matrix substantially contribute to antioxidant, antimicrobial, anti-inflammatory, and antitumor effects (Al-Khayri et al., 2023; Mohamed & Alotaibi, 2023; Mohammed et al., 2024).

Compounds such as thymol, carvacrol, eugenol, linalool, limonene, and β -caryophyllene were repeatedly associated with multiple biological activities, highlighting the multifunctional nature of essential oils. At the same time, variations in chemical composition frequently resulted in different biological responses, even among oils derived from the same species, emphasizing the influence of phytochemical variability on biological performance.

Despite significant advances, important challenges remain. Methodological differences in extraction,

phytochemical characterization, constituent quantification, and biological assays continue to limit reproducibility and direct comparisons among studies. Therefore, future research should prioritize standardized characterization protocols and mechanistic investigations to better understand phytochemical interactions and support the development of scientifically validated applications.

Overall, chemical diversity represents both the basis of the biological potential of essential oils and one of the main obstacles to their standardization and large-scale application.

4.2 Antioxidant Activity and Protection Against Oxidative Stress

The studies included in this review consistently support the antioxidant potential of essential oils and their relevance as natural sources of bioactive compounds capable of mitigating oxidative stress. Given the role of oxidative damage in the development of chronic diseases, antioxidant activity remains one of the most extensively investigated properties of essential oils (Dorman et al., 1995; Saleh et al., 2010).

Antioxidant effects are closely associated with phytochemical composition, particularly the presence of compounds such as thymol, carvacrol, eugenol, linalool, and limonene. However, the reviewed evidence indicates that antioxidant performance depends not only on major constituents but also on synergistic interactions among compounds and factors such as plant origin, environmental conditions, harvesting period, and extraction methods (Sharopov & Wink, 2015; Al-Khayri et al., 2023; Konfo et al., 2023).

Considerable variability among studies was observed, partly reflecting differences in phytochemical composition and partly resulting from methodological heterogeneity. Antioxidant activity has been evaluated using multiple assays, including DPPH, ABTS, FRAP, ORAC, and lipid peroxidation methods, which assess distinct mechanisms and complicate direct comparisons across investigations.

Another important limitation is the predominance of *in vitro* studies. Although these assays provide valuable mechanistic information, they do not fully reflect physiological conditions, and factors such as bioavailability, metabolism, and tissue distribution may substantially influence biological responses *in vivo*.

Beyond direct antioxidant effects, evidence suggests that the reduction of oxidative stress may contribute to anti-inflammatory and cytoprotective activities, reinforcing the multifunctional nature of essential oils. In addition, several studies have highlighted their potential

application in food preservation by delaying lipid oxidation and extending product shelf life (Konfo et al., 2023; Huang et al., 2025).

Recent advances in nanoencapsulation technologies may further enhance these applications by improving stability, protecting bioactive constituents, and enabling controlled release. Nevertheless, additional *in vivo* and clinical investigations are required to establish the practical effectiveness of essential oils as antioxidant agents in healthcare and industrial settings.

4.3 Antimicrobial Activity and its Relevance in the Context of Resistance

Antimicrobial activity is among the most extensively investigated and commercially relevant properties of essential oils. Numerous studies have demonstrated inhibitory effects against bacteria, fungi, yeasts, and biofilm-forming microorganisms, highlighting their broad-spectrum potential (Burt, 2004; Hyldgaard et al., 2012; Pandey et al., 2017). Their antimicrobial effects are largely attributed to a multitarget mode of action involving membrane disruption, increased permeability, interference with enzymatic activity, and impairment of cellular metabolism (Nazzaro et al., 2013; Razzouk et al., 2022; El-Sakhawy et al., 2026).

This multifactorial activity has attracted considerable interest in the context of antimicrobial resistance, as essential oils may affect several cellular processes simultaneously and potentially enhance the effectiveness of conventional antimicrobial strategies. Evidence also suggests synergistic interactions between essential oils and conventional antimicrobial agents, although most findings remain limited to *in vitro* studies (Puvača et al., 2021; Yasir et al., 2022).

The reviewed studies revealed substantial variability in antimicrobial efficacy, reflecting differences in phytochemical composition, microbial susceptibility, extraction procedures, and experimental methodologies. Gram-positive bacteria generally appeared more susceptible than Gram-negative species, although effective inhibition of selected Gram-negative pathogens has also been reported under specific conditions (Hyldgaard et al., 2012; Yasir et al., 2022). These findings highlight the importance of phytochemical characterization and methodological standardization when comparing results across studies.

Particular attention has been directed toward the antibiofilm properties of essential oils. Several studies reported inhibition of biofilm formation and disruption of mature biofilms in clinically relevant microorganisms such as *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Candida albicans* (Carvalho-Silva et al., 2024;

Nurzyńska-Wierdak, 2025; Elshafie et al., 2026). Given the role of biofilms in persistent infections and antimicrobial tolerance, these findings support the potential application of essential oils as complementary tools for infection control.

Despite promising results, practical implementation remains limited by factors such as chemical instability, compositional variability, potential cytotoxicity, and the predominance of laboratory-based investigations. Recent advances in nanoencapsulation and controlled-release systems may help overcome some of these challenges by improving stability, bioavailability, and antimicrobial performance.

Overall, current evidence supports the antimicrobial potential of essential oils and their possible contribution to alternative strategies for infection control and food preservation. However, further research employing standardized methodologies, pharmacological characterization, and well-designed clinical studies is required to establish their real-world effectiveness.

4.4 Anti-Inflammatory Potential and Therapeutic Applications

The findings of this review support the growing recognition of essential oils as promising sources of anti-inflammatory agents. Several studies demonstrated the ability of essential oils to modulate key inflammatory mediators, including TNF- α , IL-1 β , IL-6, nitric oxide, and prostaglandins, suggesting activity across multiple stages of the inflammatory response (de Sousa et al., 2024; Mohammed et al., 2024; Zhao et al., 2023).

The available evidence indicates that anti-inflammatory effects are associated with diverse phytochemical profiles, particularly those rich in monoterpenes and sesquiterpenes such as linalool and β -caryophyllene. Rather than being attributed to individual compounds alone, these effects frequently appear to result from synergistic interactions among multiple constituents within the phytochemical matrix (Subudhi et al., 2025).

Considerable variability in efficacy has been reported among studies, reflecting differences in plant origin, extraction methods, phytochemical composition, dosage regimens, and experimental models. This heterogeneity highlights the importance of phytochemical characterization and methodological standardization for improving the comparability and reproducibility of findings.

An important observation emerging from the reviewed literature is the close relationship between antioxidant and anti-inflammatory activities. By reducing oxidative stress, essential oils may indirectly attenuate inflammatory signaling pathways, reinforcing their multifunctional

therapeutic potential (Zhao et al., 2023; Kozics et al., 2025).

Despite encouraging results, most available evidence remains limited to in vitro and animal studies. Consequently, important questions regarding pharmacokinetics, bioavailability, tissue distribution, long-term safety, and clinical efficacy remain unresolved. Recent advances in nanoencapsulation technologies may help overcome some of these limitations by improving stability, bioavailability, and controlled delivery of bioactive constituents, although further validation is required.

Overall, essential oils represent promising candidates for the development of novel anti-inflammatory strategies. However, future research should prioritize standardized experimental protocols, mechanistic investigations, pharmacokinetic studies, and well-designed clinical trials to clarify their therapeutic applicability in human inflammatory disorders.

4.5 Antitumor Activity: Opportunities and Challenges

Antitumor activity represents one of the most promising applications of essential oils identified in this review. Experimental studies have demonstrated cytotoxic effects against a variety of cancer cell lines, including breast, colorectal, lung, liver, and prostate cancers, suggesting that essential oils can interfere with key processes involved in tumor development and progression (Bayala et al., 2014; Blowman et al., 2018; Dias, 2015).

The antitumor effects reported in the literature appear to result from multiple complementary mechanisms. Essential oils and their constituents have been associated with apoptosis induction, inhibition of cell proliferation, cell-cycle arrest, modulation of oxidative stress, and interference with signaling pathways involved in tumor growth and survival (Sharma et al., 2022; Montalvão et al., 2023). Such multifunctional activity may represent an advantage over approaches that target a single molecular pathway.

Despite these promising findings, considerable variability in efficacy has been reported among studies. Differences in phytochemical composition, extraction procedures, cancer cell lines, exposure times, and tested concentrations frequently influence experimental outcomes. In addition, evidence suggests that biological activity is not determined solely by major constituents such as limonene, α -pinene, β -caryophyllene, thymol, and carvacrol, but also by synergistic interactions involving minor compounds within the phytocomplex (Montalvão et al., 2023; Sharma et al., 2022).

A major challenge for the field is the limited translational value of the current evidence. Most studies

remain restricted to in vitro models, which do not fully reproduce the complexity of tumor microenvironments, immune responses, angiogenesis, and pharmacokinetic processes observed in vivo. Furthermore, information regarding toxicity, bioavailability, metabolism, and long-term safety remains scarce, restricting the assessment of therapeutic potential and clinical applicability.

Recent advances in nanotechnology may help overcome some of these limitations. Nanoencapsulation systems have demonstrated potential to improve chemical stability, protect volatile constituents from degradation, enhance bioavailability, and facilitate targeted delivery. Although preliminary results are encouraging, further preclinical and clinical investigations are required to

establish the safety and effectiveness of these approaches.

Overall, essential oils constitute a valuable source of bioactive compounds for oncology research. However, methodological heterogeneity, insufficient pharmacological characterization, and the scarcity of clinical studies continue to limit definitive conclusions regarding their therapeutic utility. Future investigations should prioritize standardized experimental protocols, mechanistic studies, pharmacokinetic evaluations, toxicological assessments, and well-designed clinical trials. A schematic overview of these mechanisms is presented in (Figure 6).

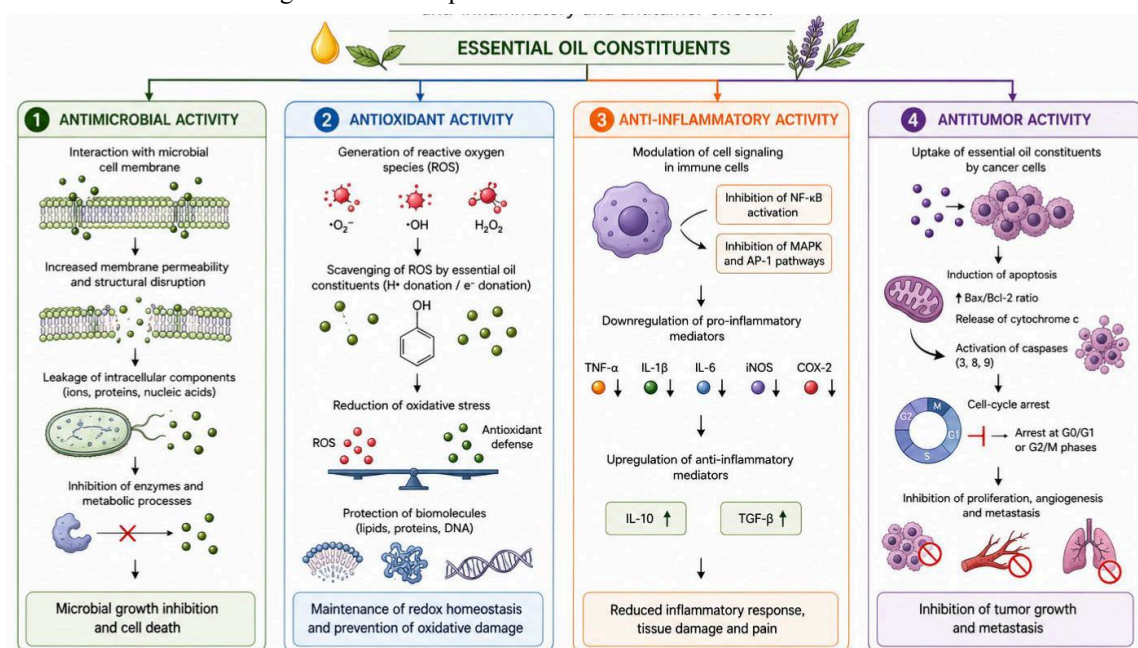


Figure 6. Principal mechanisms of action underlying the biological activities of essential oils. Source: Author (2026).

4.6 Nanotechnology as a Tool to Enhance Essential Oil Performance

Despite their considerable biological potential, the practical application of essential oils is often limited by physicochemical constraints, including high volatility, poor water solubility, susceptibility to oxidation, rapid degradation, and low bioavailability. These characteristics can reduce biological efficacy, shorten shelf life, and hinder the development of stable commercial products. As a result, nanotechnology has emerged as a promising strategy to overcome these limitations and expand the use of essential oils in pharmaceutical, food, cosmetic, and agricultural applications (São Pedro et al., 2013; de Matos et al., 2019).

The studies reviewed consistently demonstrate that

nanoencapsulation can improve the stability and functionality of essential oils. However, the benefits achieved vary according to the delivery system employed. São Pedro et al. (2013) highlighted the ability of nanoemulsions to improve dispersion and protect volatile constituents, whereas de Matos et al. (2019) emphasized the controlled-release properties of nanocapsules. Similarly, Lammari et al. (2020) reported enhanced physicochemical stability in lipid-based formulations, while Nair et al. (2022) demonstrated improvements in bioavailability and biological performance. These findings indicate that the effectiveness of nanoencapsulation depends largely on formulation design and intended application rather than on a universally superior carrier system.

Considerable variation has also been reported regarding biological performance. Gonfa et al. (2023) and

Moawad et al. (2025) observed substantial improvements in antimicrobial and antioxidant activities following encapsulation, attributing these effects to enhanced protection of bioactive constituents and improved interactions with target systems. In contrast, other studies reported only moderate gains, particularly when highly active essential oils were used prior to encapsulation. Such differences suggest that nanoencapsulation does not automatically guarantee enhanced efficacy and that outcomes are strongly influenced by encapsulation efficiency, particle size distribution, release kinetics, and the intrinsic properties of the oil being formulated.

Recent investigations have increasingly focused on the relationship between nanocarrier characteristics and biological activity. Jacob et al. (2025) and Omidian et al. (2025) demonstrated that optimized nanoformulations can improve bioavailability and cellular uptake, potentially enhancing antioxidant, anti-inflammatory, and antitumor effects. However, Silva et al. (2025) emphasized that improvements observed under laboratory conditions may not necessarily translate into industrial-scale applications because of manufacturing complexity, production costs, and formulation stability during storage. This highlights a persistent gap between experimental success and commercial feasibility.

Another challenge identified across the literature is the lack of methodological standardization. Studies differ substantially in nanoparticle composition, preparation techniques, encapsulation efficiency, particle size distribution, storage conditions, and biological evaluation methods. These inconsistencies make direct comparisons difficult and complicate the identification of optimal formulation strategies. Consequently, reported differences among delivery systems should be interpreted cautiously until more standardized evaluation frameworks become available.

Safety and regulatory considerations remain additional barriers to large-scale implementation. Although most investigations focus on improving efficacy, relatively few provide detailed toxicological assessments or evaluate the long-term effects of exposure to nanocarriers. This limitation is particularly important because regulatory agencies increasingly require robust safety data before approving nanotechnology-based products. The absence of harmonized toxicological protocols therefore continues to restrict both clinical translation and industrial adoption.

The technological framework presented in Figure 5 illustrates how nanoencapsulation can bridge the gap between biological activity and practical application. By integrating major bioactive constituents such as thymol, carvacrol, eugenol, linalool, limonene, and β -caryophyllene with advanced delivery systems,

nanotechnology offers opportunities to improve stability, efficacy, and product performance across multiple sectors.

Current evidence supports the view that nanotechnology is not merely a complementary strategy but a key enabling technology for the development of next-generation essential oil-based products. Nevertheless, important challenges related to scalability, cost-effectiveness, regulatory approval, and long-term safety remain unresolved. Future research should prioritize standardized characterization methods, comparative evaluations of delivery systems, industrial-scale production studies, and comprehensive toxicological assessments to facilitate the translation of promising laboratory findings into commercially viable and scientifically validated products.

4.7 Emerging Applications and Future Perspectives

Although pharmaceutical and biomedical applications remain the dominant focus of essential oil research, the literature analyzed in this review demonstrates a progressive expansion into agricultural, environmental, food, and industrial sectors. This diversification reflects the growing demand for sustainable technologies capable of reducing reliance on synthetic chemicals while addressing concerns related to environmental contamination, consumer safety, and ecosystem preservation.

However, the level of scientific maturity differs substantially among these application areas, and most available evidence still originates from laboratory-scale investigations.

Among the emerging applications, the use of essential oils as biopesticides and biocontrol agents has attracted considerable attention. Gonzalez-Coloma (2023) and Gupta et al. (2023) reported promising insecticidal and repellent activities against a broad range of agricultural pests, supporting the incorporation of essential oils into integrated pest management programs. Similarly, Annaz et al. (2025) demonstrated significant bioactivity against *Tribolium castaneum*, highlighting potential applications in grain protection and post-harvest management.

Despite these encouraging findings, results obtained under controlled laboratory conditions are not always reproduced in field environments. Environmental factors such as temperature fluctuations, ultraviolet radiation, rainfall, humidity, and volatilization can substantially reduce persistence and efficacy. Consequently, laboratory performance may overestimate practical agricultural outcomes.

A comparable pattern is observed in studies focused on plant disease management. Raveau et al. (2020)

emphasized the antifungal and antibacterial potential of essential oils against important phytopathogens, supporting their use as alternatives to conventional agrochemicals. Nevertheless, relatively few investigations have examined long-term field performance, formulation stability, or environmental persistence.

Concerns regarding impacts on non-target organisms also remain insufficiently explored. Although essential oils are often perceived as environmentally friendly alternatives, comprehensive assessments involving pollinators, beneficial insects, and soil microbial communities are still scarce. This limitation restricts definitive conclusions regarding their ecological safety.

Beyond agricultural applications, increasing attention has been directed toward food preservation systems, active packaging technologies, cosmetic formulations, and sustainable industrial processes. Several studies reported that essential oils can enhance microbiological safety and extend product shelf life, reinforcing their potential as natural alternatives to synthetic preservatives.

Industrial implementation, however, presents challenges that are less frequently discussed in experimental studies. Volatility, strong sensory characteristics, raw material standardization, manufacturing scalability, and production costs may significantly affect commercial feasibility. Therefore, technological effectiveness alone may not guarantee successful market adoption.

Recent reviews by Pezantes-Orellana et al. (2024) and Kozics et al. (2025) indicate a notable shift in research priorities. Earlier studies focused primarily on biological activity screening and phytochemical characterization, whereas contemporary investigations increasingly emphasize molecular mechanisms of action, nanoencapsulation strategies, and multifunctional product development. This evolution reflects the growing effort to translate promising laboratory findings into practical applications.

Despite this progress, the literature remains fragmented across disciplines and frequently employs different extraction procedures, analytical techniques, biological models, and reporting standards. Such heterogeneity continues to hinder reproducibility and direct comparison among studies.

The quantitative trends summarized in Figure 2 further support the growing scientific interest in essential oils. Antimicrobial activity remains the most extensively investigated application, whereas studies addressing anti-inflammatory, antitumor, and nanotechnology-based approaches have increased substantially in recent years. In parallel, compounds such as thymol, carvacrol, eugenol, linalool, limonene, and β -caryophyllene

continue to be among the most frequently reported bioactive constituents, reinforcing their central role in the multifunctional properties attributed to essential oils.

The conceptual framework presented in Figure 5 highlights how future advances will likely depend on the integration of phytochemistry, pharmacology, biotechnology, materials science, agronomy, and nanotechnology. Rather than focusing exclusively on the discovery of new bioactive compounds, future innovation will increasingly rely on technologies capable of improving stability, bioavailability, controlled release, and large-scale applicability.

This multidisciplinary perspective suggests that the next generation of essential oil-based products will emerge from the convergence of biological and technological research rather than from phytochemical discovery alone.

Taken together, the evidence reviewed reinforces the considerable potential of essential oils across healthcare, food preservation, sustainable agriculture, and environmental management. Nevertheless, realizing this potential will require multidisciplinary collaboration, long-term validation studies, comprehensive toxicological assessments, standardized methodologies, and regulatory harmonization. Addressing these challenges will be essential for bridging the gap between promising experimental findings and the safe, effective, and economically viable implementation of essential oil-based technologies.

4.8 Clinical Translation and Regulatory Challenges

Despite the growing body of evidence supporting the antioxidant, antimicrobial, anti-inflammatory, antitumor, and technological applications of essential oils, their successful translation into clinically approved products remains limited. A recurring observation throughout the literature is the substantial gap between the large number of *in vitro* and preclinical studies and the relatively small number of well-designed clinical investigations.

Although numerous studies have demonstrated promising biological activities under experimental conditions, only a limited number of essential oils and essential oil-based formulations have progressed to human clinical evaluation. Consequently, the scientific evidence supporting therapeutic efficacy in real-world clinical settings remains fragmented and insufficient for many applications.

One of the major barriers to clinical translation is the limited availability of high-quality clinical evidence. Existing human studies have investigated the use of essential oils in areas such as anxiety management, stress reduction, sleep disorders, pain control, oral health,

wound healing, and supportive care interventions.

While several studies have reported beneficial outcomes, considerable heterogeneity exists regarding study design, sample size, intervention duration, formulation type, dosage regimens, and outcome assessment methods. These methodological differences hinder comparisons among studies and limit the establishment of standardized therapeutic recommendations. Therefore, larger randomized controlled trials with rigorous methodological designs are required to confirm efficacy and establish evidence-based clinical protocols.

Safety assessment represents another critical challenge. Although many essential oils are generally recognized as safe when used appropriately, adverse reactions including skin irritation, allergic responses, mucosal toxicity, phototoxicity, and potential systemic effects have been documented. Furthermore, toxicological profiles vary substantially among different botanical species, chemical compositions, administration routes, and concentrations.

While certain widely used oils have undergone extensive toxicological evaluation, many less-studied species remain insufficiently characterized regarding chronic exposure, reproductive toxicity, developmental toxicity, genotoxicity, and long-term safety. Consequently, significant knowledge gaps persist, limiting confidence in their widespread therapeutic use and regulatory acceptance.

Pharmacokinetic limitations further complicate the clinical development of essential oil-based products. Many bioactive constituents, particularly monoterpenes and phenylpropanoids, exhibit poor aqueous solubility, rapid metabolism, high volatility, and limited bioavailability. These characteristics may reduce therapeutic effectiveness and contribute to discrepancies between *in vitro* activity and *in vivo* outcomes. In addition, information regarding absorption, distribution, metabolism, and excretion remains scarce for many essential oil constituents. The lack of comprehensive pharmacokinetic data restricts dose optimization, safety evaluation, and the development of standardized therapeutic formulations.

Recent advances in nanotechnology have emerged as promising approaches to overcome several of these limitations. Nanoemulsions, liposomes, solid lipid nanoparticles, nanostructured lipid carriers, and polymeric nanocapsules have demonstrated the ability to enhance stability, protect volatile compounds from degradation, improve controlled release, increase bioavailability, and potentially reduce toxicity.

Although these delivery systems have produced encouraging preclinical results, evidence regarding their

long-term safety, large-scale production feasibility, regulatory acceptance, and clinical effectiveness remains limited. Consequently, nanoencapsulation should currently be viewed as a promising enabling technology rather than a fully validated solution for clinical implementation.

Regulatory requirements represent an additional challenge for the development and commercialization of essential oil-based products. Regulatory agencies, including the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA), require robust evidence of quality, safety, efficacy, and manufacturing consistency before therapeutic claims can be approved. However, the intrinsic chemical variability of essential oils poses a significant obstacle to meeting these requirements. Factors such as plant genotype, geographical origin, environmental conditions, cultivation practices, harvesting time, and extraction methods can substantially influence phytochemical composition. As a result, achieving reproducible chemical profiles and consistent biological performance remains a major challenge for regulatory approval and product standardization.

Commercialization faces similar constraints. Beyond demonstrating biological efficacy, successful market implementation requires sustainable raw material sourcing, standardized production processes, quality assurance systems, regulatory compliance, product stability, and economic viability.

Batch-to-batch variability remains one of the most significant barriers to industrial-scale production, particularly for pharmaceutical applications where reproducibility and quality control are fundamental requirements. Furthermore, the increasing global demand for natural products highlights the need for sustainable cultivation practices and responsible management of plant resources to ensure long-term supply chain stability.

Taken together, current evidence indicates that essential oils represent promising sources of multifunctional bioactive compounds with considerable therapeutic and technological potential. However, substantial scientific, toxicological, pharmacokinetic, clinical, regulatory, and industrial challenges remain unresolved.

Future progress will depend not only on the continued identification of biological activities but also on the generation of robust clinical evidence, comprehensive safety assessments, standardized production protocols, regulatory harmonization, and the development of innovative delivery systems capable of supporting safe, effective, and commercially viable applications. Addressing these challenges will be essential for facilitating the successful integration of essential oils into

evidence-based healthcare and modern industrial practices.

4.9 Limitations of the Review

Several limitations should be considered when interpreting the findings of this review.

First, publication bias may have influenced the available evidence, as studies reporting positive biological activities are generally more likely to be published than those presenting negative, neutral, or inconclusive results. Consequently, the biological potential of essential oils may be overestimated in the published literature.

Second, the exclusion of grey literature, including theses, dissertations, conference proceedings, technical reports, and unpublished studies, may have reduced the comprehensiveness of the evidence base. Although restricting the search to peer-reviewed publications improves methodological rigor and reliability, potentially relevant findings may have been overlooked.

Another limitation concerns the review process itself. Study screening, eligibility assessment, and data extraction were conducted by a single reviewer. Although predefined eligibility criteria and standardized procedures were applied throughout the review process to minimize bias and enhance consistency, the absence of independent duplicate screening may have increased the risk of selection bias and subjective judgment during study identification, selection, and data extraction. Future reviews should incorporate independent reviewers and consensus procedures to further strengthen methodological rigor and reproducibility.

The predominance of *in vitro* and preclinical studies among the included publications also limits the interpretation of the findings. While these studies provide valuable insights into mechanisms of action and biological activities, they do not necessarily predict clinical efficacy, safety, pharmacokinetic behavior, or long-term outcomes in humans. This limitation was particularly evident in investigations addressing antioxidant, antimicrobial, anti-inflammatory, and antitumor activities.

Substantial methodological heterogeneity was observed across the included studies. Differences in plant species, geographical origin, cultivation conditions, extraction techniques, phytochemical characterization, experimental models, biological assays, and outcome measurements frequently hindered direct comparisons. For example, antioxidant activity was evaluated using different analytical methods, whereas antimicrobial studies employed distinct microbial strains and susceptibility testing protocols, often generating divergent

results.

In addition, the intrinsic chemical variability of essential oils remains a major challenge. Essential oils obtained from the same botanical species may exhibit markedly different phytochemical compositions depending on genetic factors, environmental conditions, harvesting periods, and extraction methods. Such variability directly influences biological activity, complicates standardization efforts, and limits reproducibility across studies.

Furthermore, a formal meta-analysis was not feasible because of the substantial heterogeneity observed among studies regarding phytochemical composition, experimental models, outcome measures, and methodological approaches. Consequently, the findings were synthesized narratively, which may limit quantitative comparisons and prevent the estimation of pooled effect sizes.

Despite these limitations, this review provides a comprehensive and up-to-date overview of the multifunctional biological and technological properties of essential oils. Future research should prioritize methodological standardization, detailed phytochemical characterization, pharmacokinetic investigations, long-term toxicological assessments, and well-designed clinical trials. Such efforts will strengthen the evidence base and facilitate the translation of experimental findings into safe, effective, and commercially viable applications.

5. Conclusion

This systematic review provides a comprehensive synthesis of the current evidence regarding the multifunctional properties of essential oils and their expanding applications across pharmaceutical, agricultural, food, cosmetic, and biotechnological sectors. The analysis of 55 studies published between 2010 and 2026 confirms that essential oils possess significant antioxidant, antimicrobial, anti-inflammatory, and antitumor potential, largely attributed to their complex phytochemical composition and the presence of bioactive constituents such as thymol, carvacrol, eugenol, linalool, limonene, and β -caryophyllene.

The findings demonstrate that essential oils act through multiple and often interconnected biological mechanisms, including modulation of oxidative stress, disruption of microbial structures, regulation of inflammatory pathways, and induction of tumor cell death. However, the evidence also reveals substantial variability among studies, reflecting differences in phytochemical composition, geographical origin, extraction procedures, experimental models, and analytical methodologies. Such heterogeneity remains

one of the principal obstacles to reproducibility, standardization, and direct comparison of results.

Recent advances in nanoencapsulation and controlled-release technologies have emerged as promising strategies to overcome important limitations associated with essential oils, including volatility, low aqueous solubility, chemical instability, and limited bioavailability. Nevertheless, despite encouraging experimental findings, the translation of these technologies into clinically approved and commercially viable products remains constrained by insufficient toxicological data, limited pharmacokinetic information, regulatory challenges, and the scarcity of well-designed clinical studies.

Beyond their biomedical relevance, essential oils also represent valuable resources for sustainable innovation. Their potential use in food preservation, active packaging systems, crop protection, environmental management, and cosmetic formulations highlights opportunities for industrial diversification and the development of environmentally friendly products. These perspectives are particularly relevant for biodiversity-rich countries, where the sustainable exploitation of plant resources may contribute to both economic development and conservation strategies.

Overall, the available evidence supports the considerable scientific and technological potential of essential oils; however, their successful translation into evidence-based applications will require greater methodological standardization, comprehensive toxicological and pharmacokinetic investigations, robust clinical validation, and regulatory harmonization. Future interdisciplinary research integrating phytochemistry, pharmacology, nanotechnology, biotechnology, and materials science will be essential to bridge the gap between promising laboratory findings and the safe, effective, and sustainable implementation of essential oil-based products.

6. References

- Al-Khayri, J. M., Banadka, A., Nandhini, M., Nagella, P., Al-Mssallem, M. Q., & Alessa, F. M. Essential oil from *Coriandrum sativum*: phytochemistry and biological activity. *Molecules*, 28(2), 696, 2023. <https://doi.org/10.3390/molecules28020696>
- Amiri, H. Antioxidant activity of the essential oil and methanolic extract of *Teucrium orientale* (L.) subsp. Taylorii. *Iranian Journal of Pharmaceutical Research*, 9(4), 417-423, 2010.
- Annaz, H., Cacciola, F., Kounnoun, A., Bouayad, N., & Rharrabe, K. Impact of essential oils on enzymes activity, reserve products, biomarkers, and gene expression of *Tribolium castaneum*. *Comparative Biochemistry and Physiology C: Toxicology & Pharmacology*, 293, 110167, 2025. <https://doi.org/10.1016/j.cbpc.2025.110167>
- Bayala, B., Bassolé, I. H., Scifo, R., Gnoula, C., Morel, L., Lobaccaro, J-M. A., & Simpoire, J. Anticancer activity of essential oils and their chemical components – a review. *American Journal of Cancer Research*, 4(6), 591-607, 2014.
- Ben Miri, Y. Essential oils: chemical composition and biological activities. *Natural Product Communications*, 20, 2025. <https://doi.org/10.1177/1934578X241311790>
- Blowman, K., Magalhães, M., Lemos, M. F. L., Cabral, C., & Pires, I. M. Anticancer properties of essential oils and natural products. *Evidence-Based Complementary and Alternative Medicine*, 2018. <https://doi.org/10.1155/2018/3149362>
- Burt, S. Essential oils: antibacterial properties and applications in foods. *International Journal of Food Microbiology*, 94(3), 223-253, 2004. <https://doi.org/10.1016/j.ijfoodmicro.2004.03.022>
- Carvalho-Silva, J. M., Teixeira, A. B. V., Valente, M. L. D. C., Shimano, M. V. W., & Dos Reis, A. C. Antimicrobial activity of essential oils against biofilms. *Biofouling*, 40(2), 114-129, 2024. <https://doi.org/10.1080/08927014.2024.2332709>
- Konfo, T. R. C., Djouhou, F. M. C., Koudoro, Y. A., Dahouenon-Ahoussi, E., Avlessi, F., Sohounhloue, C. K. D., & Simal-Gandara, J. Essential oils as natural antioxidants for food preservation. *Food Chemistry Advances*, 2, 100312, 2023. <https://doi.org/10.1016/j.focha.2023.100312>
- Dias, H. Cytotoxicity screening of essential oils in cancer cell lines. *Revista Brasileira de Farmacognosia*, 2015. <https://doi.org/10.1016/j.bjp.2015.02.009>
- de Matos, S. P., Teixeira, H. F., de Lima, Á. A. N., Veiga-Junior, V. F., & Koester, L. S. Essential oils and isolated terpenes in nanosystems. *Biomolecules*, 9(4), 138, 2019. <https://doi.org/10.3390/biom9040138>
- de Sousa, D. P., Damasceno, R. O. S., Amorati, R., et al. Essential oils: chemistry and pharmacological activities. *Biomolecules*, 13(7), 1144, 2023. <https://doi.org/10.3390/biom13071144>
- de Sousa, D. P., de Oliveira, F. A., Arcanjo, D. D. R., Fonsêca, D. V., Duarte, A. B. S., Barbosa, C. O., Ong, T. P., & Brocksom, T. J. Essential oils – part II. *Biomedicines*, 12(6), 1185, 2024. <https://doi.org/10.3390/biomedicines12061185>
- Dorman, H., Deans, S., Noble, R., & Surai, P. Evaluation *in vitro* of plant essential oils as natural antioxidants. *Journal of Essential Oil Research*, 7(6), 645-651,

1995.
<https://doi.org/10.1080/10412905.1995.9700520>
- El-Sakhawy, M. A., Donia, A. E. R. M., Juraybi, T. N., Ateya, A. A. E-S., Osman, W., & Abd-Elghani, A. A. Mechanisms of essential oils against bacteria. *International Journal of Microbiology*, 2026. <https://doi.org/10.1155/ijm/7468450>
- Elshafie, H. S., Camele, I. Plant essential oils (II). *Plants*, 12(20), 3616, 2023. <https://doi.org/10.3390/plants12203616>
- Elshafie, H. S., Crescenzi, A., & Camele, I. Biological effects of essential oils on pathogens. *Plants*, 15(4), 542, 2026. <https://doi.org/10.3390/plants15040542>
- Gonfa, Y. H., Joshi, A., Chaubey, K. K., & Bachheti, R. K. Nanoemulsions from essential oils: Preparation, characterization, and their applications. In: *Current Trends in Green Nano-emulsions*, Springer, 2023. https://doi.org/10.1007/978-981-99-5398-1_2
- Gonzalez-Coloma, A. Essential oils as biopesticide ingredients. *Agriculture*, 13, 1141, 2023. <https://doi.org/10.3390/agriculture13061141>
- Gupta, I., Singh, R., Muthusamy, S., Sharma, M., Grewal, K., Singh, H. P., & Batish, D. R. Essential oils as biopesticides. *Plants*, 12(16), 2916, 2023. <https://doi.org/10.3390/plants12162916>
- Huang, Y., Ebrahimi, H., Berselli, E., Foti, M. C., & Amorati, R. Essential oils as antioxidants. *Antioxidants*, 15(1), 37, 2025. <https://doi.org/10.3390/antiox15010037>
- Hyldgaard, M., Mygind, T., & Meyer, R. L. Essential oils in food preservation. *Frontiers in Microbiology*, 3, 12, 2012. <https://doi.org/10.3389/fmicb.2012.00012>
- Jacob, A., Nixon, R., Thirumurthy, D., Angel, S., & Haldar, D. Essential oil nano-delivery systems: recent developments and emerging applications. *Natural Product Communications*, 20(11), 2025. Doi:10.1177/1934578X251390689
- Jugreet, S., Suroowan, S., Rengasamy, K. R. R., & Mahomoodally, F. M., Chemistry and bioactivities of essential oils. *Trends in Food Science & Technology*, 101, 2020. <https://doi.org/10.1016/j.tifs.2020.04.025>
- Kozics, K., Mesárošová, M., Šramková, M., Bučková, M., Puškárová, A., & Pangallo, D. Evaluation bioactivity of essential oils: cytotoxic/genotoxic effects on colorectal cancer cell lines, antibacterial activity, and survival of lactic acid bacteria. *Molecules*, 30(4), 890, 2025. <https://doi.org/10.3390/molecules30040890>
- Lammari, N., Louaer, O., Meniai, A. H., & Elaissari, A. Encapsulation of essential oils via nanoprecipitation process: overview, progress, challenges and prospects. *Pharmaceutics*, 12(5), 431, 2020. <https://doi.org/10.3390/pharmaceutics12050431>
- Moawad, S., Badr, A. N., Farouk, A., Alzunaidy, N. A., Elshibani, F. A., Alayouni, R., & Mohammed, H. A. Bioactivity and nanoformulation of Eucalyptus camaldulensis essential oils: Implications for antioxidant and anti-inflammatory applications. *ACS Omega*, 10(25), 26729-26742, 2025. <https://doi.org/10.1021/acsomega.5c01246>
- Mohamed, A. A., & Alotaibi, B. M. Essential oils mini review. *Journal of Umm Al-Qura University*, 9, 40-49, 2023. <https://doi.org/10.1007/s43994-022-00018-1>
- Mohammed, H., et al. Essential oils pharmacological activity. *Process Biochemistry*, 144, 112-132, 2024. <https://doi.org/10.1016/j.procbio.2024.05.021>
- Montalvão, M. M., Felix, F. B., Santos, E. W. P., Ribeiro, A. S., Cavaleiro, C., Machado, S. M. F., Scher, R., & Corrêa, C. B. Cytotoxic activity of essential oil from leaves of *Myrcia splendens* against A549 lung cancer cells. *BMC Complementary Medicine and Therapies*, 23, 139, 2023. <https://doi.org/10.1186/s12906-023-03969-y>
- Nair, A., Mallya, R., Suvarna, V., Khan, T. A., Momin, M., & Omri, A. Nanoparticles – attractive carriers of antimicrobial essential oils. *Antibiotics*, 11(1), 108, 2022. <https://doi.org/10.3390/antibiotics11010108>
- Nazzaro, F., Fratianni, F., Martino, L., Coppola, R., & De Feo, V. Effect of essential oils on pathogenic bacteria. *Pharmaceutics*, 6(12), 1451-1474, 2013. <https://doi.org/10.3390/ph6121451>
- Nurzyńska-Wierdak, R. Antibiofilm potential of natural essential oils. *Applied Sciences*, 15(11), 5847, 2025. <https://doi.org/10.3390/app15115847>
- Omidian, H., Cubeddu, L. X., & Gill, E. J. Harnessing Nanotechnology to enhance essential oil applications. *Molecules*, 30(3), 520, 2025. <https://doi.org/10.3390/molecules30030520>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Lalu, M. M., McDonald, S., Stewart, L. A., Thomas, J., Tricco, A. C., Whiting, P., & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Revista Panamericana de Salud Publica*, 46, e112. <https://doi.org/10.26633/RPSP.2022.112>
- Pandey, A. K., Kumar, P., Singh, P., Tripathi, N. N., & Bajpai, V. K. Essential oils: Sources of antimicrobials and food preservatives. *Frontiers in Microbiology*, 7, 2161, 2017. <https://doi.org/10.3389/fmicb.2016.02161>
- Pezantes-Orellana, C., Bermúdez, F. G., De la Cruz, C. M., Montalvo, J. L., & Orellana-Manzano, A.

- Essential oils: a systematic review of revolutionizing health, nutrition, and omics for optimal well-being. *Frontiers in Medicine*, 11, 2024. <https://doi.org/10.3389/fmed.2024.1337785>
- Puvača, N., Milenković, J., Coghill, T. G., Bursić, V., Pelić, M., Pelić, D. L., & Miljković, T. Antimicrobial activity of selected essential oils against selected pathogenic bacteria: In vitro study. *Antibiotics*, 10(5), 546, 2021. <https://doi.org/10.3390/antibiotics10050546>
- Raut, J. S., & Karuppayil, S. M. A status review on the medicinal properties of essential oils. *Industrial Crops and Products*, 62, 250-264, 2014. <https://doi.org/10.1016/j.indcrop.2014.05.055>
- Raveau, R., Fontaine, J., & Lounès-Hadj Sahraoui, A. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: A review. *Foods*, 9(3), 365, 2020. <https://doi.org/10.3390/foods9030365>
- Razzouk, S., Mazri, M. A., Jeldi, L., Mnasri, B., Ouhmane, L., & Alfeddy, M. N. Chemical composition and antimicrobial activity of essential oils from three mediterranean plants against eighteen pathogenic bacteria and fungi. *Pharmaceutics*, 14(8), 1608, 2022. <https://doi.org/10.3390/pharmaceutics14081608>
- Saleh, M. A., Clark, S., Woodard, B., & Deolu-Sobogun, S. A. Antioxidant and free radical scavenging activities of essential oils. *Ethnicity & Disease*, 20, S1-78, 2010.
- Santos, E. J. B., Bezerra, F. W. F., Silva, L. R. R., Silva, M. P., Chaves-Neto, A. M. J., Vilhena, K. S. S., Andrade, E. H. A., & Oliveira, M. S. Exploring the potential of *Myrcia* genus essential oils: A review of biological activities and recent advances. *Molecules*, 29(12), 2720, 2024. <https://doi.org/10.3390/molecules29122720>
- Santos, M. I. S., Marques, C., Mota, J., Pedroso, L., & Lima, A. Applications of essential oils as antibacterial agents in minimally processed fruits and vegetables – A review. *Microorganisms*, 10(4), 760, 2022. <https://doi.org/10.3390/microorganisms10040760>
- Santos, M. I. S., Martins, S. R., Veríssimo, C. S. C., Nunes, M. J. C., Lima, A. I. G., Ferreira, R. M. S., Pedroso, L., Sousa, I., & Ferreira, M. A. S. S. Essential oils antibacterial agents against food-borne pathogens: Are they really as useful as they are claimed to be?. *Journal of Food Science and Technology*, 54(13), 4344-4352, 2017. <https://doi.org/10.1007/s13197-017-2905-0>
- Santana de Oliveira, M., Vostinaru, O., Rigano, D., & Andrade, E. H. A. Editorial: Bioactive compounds present in essential oils: Advances and pharmacological applications. *Frontiers in Pharmacology*, 14, 1130097, 2023. <https://doi.org/10.3389/fphar.2023.1130097>
- São Pedro, A., Santo, I. E., Detoni, C., Cabral-Albuquerque, E. The use of nanotechnology as an approach for essential oil-based formulations with antimicrobial activity. In: Microbial pathogens and strategies for combating them: science, technology and education, 2, 1364-1374 p., 2013.
- Sharifi-Rad, J., Sureda, A., Tenore, G. C., Daglia, M., Sharifi-Rad, M., Tundis, R., Loizzo, M. R., Sharifi-Rad, R., Ayatollahi, S. A., & Iriti, M. Biological activities of essential oils: From plant chemoeology to traditional healing systems. *Molecules*, 22(1), 70, 2017. <https://doi.org/10.3390/molecules22010070>
- Sharopov, F., & Wink, M. Radical scavenging and antioxidant activities of essential oil components – An experimental and computational investigation. *Natural Product Communications*, 10(1), 153-156, 2015. <https://doi.org/10.1177/1934578X1501000135>
- Sharma, M., Grewal, K., Jandrotia, R., Batish, D. R., Singh, H. P., & Kohli, R. K. Essential oils as anticancer agents: Potential role in malignancies, drug delivery mechanisms, and immune system enhancement. *Biomedicine & Pharmacotherapy*, 146, 112514, 2022. <https://doi.org/10.1016/j.biopha.2021.112514>
- Silva, E. F. D., dos Santos, F. A. L., Pires, H. M., Bastos, L. M., & Ribeiro, L. N. M. Lipid nanoparticles carrying essential oils for multiple applications as antimicrobials. *Pharmaceutics*, 17(2), 178, 2025. <https://doi.org/10.3390/pharmaceutics17020178>
- Spigarelli, R., Valerii, M. C., Bernacchi, A., Dussias, N. K., Mbiriki, L., & Spisni, E. Essential oils as a source of anticancer molecules: Critical assessment of current evidence and methodological limitations – A systematic review. *International Journal of Molecular Sciences*, 27(10), 4379, 2026. <https://doi.org/10.3390/ijms27104379>
- Subudhi, L., Thatoi, H., & Banerjee, A. Anti-inflammatory activity of essential oil from medicinal plants: An insight in to molecular mechanism, *in-silico* studies and signaling pathways. *Phytomedicine*, 138, 156364, 2025. <https://doi.org/10.1016/j.phymed.2025.156364>
- Tit, D. M., & Bungau, S. G. Antioxidant activity of essential oils. *Antioxidants*, 12(2), 383, 2023. <https://doi.org/10.3390/antiox12020383>
- Yasir, M., Nawaz, A., Okla, M. K., Wadood, A., Akhtar, N., Din, M., Hameed, Y., & Imran, M. Anti-bacterial

activity of essential oils against multidrug-resistant foodborne pathogens isolated from raw milk. *Brazilian Journal of Biology*, 84, e259449, 2022. <https://doi.org/10.1590/1519-6984.259449>

Zhao, Q., Zhu, L., Wang, S., & Jin, F. Molecular mechanism of the anti-inflammatory effects of plant essential oils: A systematic review. *Journal of Ethnopharmacology*, 301, 115829, 2023. <https://doi.org/10.1016/j.jep.2022.115829>

Author's Contributions

The author conceived and designed the study, collected and analyzed the data, interpreted the results, drafted the manuscript, and approved the final version for publication.

Ethics

The author declares that this manuscript complies with current ethical standards. The study did not involve experimentation on humans or animals. All data used were obtained and utilized in accordance with applicable standards and guidelines. The author assumes responsibility for clarifying and resolving any ethical issues that may arise following publication.