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Lavender essential oils as natural food protectants: myth or a viable substitute?

Dheeraj Kumar,[a] Mahesh K. Samota,[b] Somnath Roy,[c] Ana Sanches Silva[d] and Abhay K. Pandey*[a]

The widespread application of synthetic pesticides for food preservation and crop protection is a significant concern for both environmental sustainability and public health. Past and recent studies conducted worldwide revealed that botanical pesticides based on essential oils (EOs) have been developed against pests and pathogens deteriorating food commodities under both storage and field conditions. While EO-based botanical pesticides are less widely available, they offer considerable potential for managing pathogens and insects that affect food crops. The genus *Lavandula* also known as *Lavender* is one of the most important genera of the family Lamiaceae, comprising over 39 accepted species and many varieties distributed across the Iberian Peninsula, the Mediterranean coastline, parts of Southern & Eastern Africa, the Middle East, and South Asia. *Lavandula* species can potentially be used in the food and pharmaceutical industries as medicinal herbs. The genus is known for its abundance of EOs, which exhibit high variability in chemical constituents between species owing to various extrinsic (geographical origin) and intrinsic (genetic variation) factors. Despite broad scientific interest in the bioprospection of *Lavandula* species, there is a general lack of information regarding the use of *Lavandula* EOs (LEOs) in protection of food commodities/crops from harmful organisms. The objectives of this paper were to systematically review the scientific literature on the efficacy of LEOs against pathogens and pests deteriorating food commodities/crops under both storage and field conditions. Besides, studies on chemical analysis of LEOs originating from different countries and recommendations for their use as an alternative to synthetic pesticides in food protection are described. We also discussed the challenges in the use of LEOs and safety assessments so that they can be used as safe botanical pesticides in food systems.

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Sustainability spotlight

The genus *Lavandula* also known as *Lavender*, is one of the most important genera of the family Lamiaceae, comprising over 39 species and many varieties distributed across the Iberian Peninsula, the Mediterranean coastline, parts of Southern & Eastern Africa, the Middle East, and South Asia. *Lavandula* species can potentially be used in the food and pharmaceutical industries as medicinal herbs. The present article summarizes that EOs and terpenoids derived from *L. angustifolia* and *L. latifolia* as well as other *Lavandula* species discussed in this review have broad antimicrobial and insecticidal properties against pathogens and pests deteriorating food commodities/hampering field food crops. There have been developments in the evaluation of LEO-based encapsulated products, such as thin films, biodegradable polymers, and nano-emulsion coatings against bacterial and fungal pathogens responsible for food spoilage, and investigators have found potential results. Therefore, botanical preservatives/pesticides derived from EOs of *Lavandula* species might be useful in combating microbial pathogens and insect pests in stored food commodities and field crops. A shift towards greener technologies directs an optimistic future towards safer deployment of LEOs in food preservation/crop protection.

1. Introduction

Lavandula also known as *Lavender*, a genus of over 39 species and 79 intraspecific taxa and hybrids[1] of higher plants in the mint family, Lamiaceae, has been recognized for its diverse therapeutic and aromatic properties since ancient times. The name *Lavender* is derived from the Latin "*lavare*" which means "to wash".[2] One of the most prevalent species, *i.e.*, *Lavandula angustifolia* Mill. (commonly known as English lavender), is native to the Mediterranean region. It thrives in countries such as Morocco, Algeria, Tunisia, Spain, Greece, France, Italy, India, and Turkey while *Lavandula latifolia* Medik. (commonly known as spike lavender) shares a similar Mediterranean basin origin. Like its counterpart, *Lavandula* species have been widely studied for their traditional and pharmacological uses.[3] *Lavandula* is commonly used today in perfumes, candles, baths,

[a]*Department of Mycology & Microbiology, Tea Research Association, North Bengal Regional R & D Center, Nagrakata, 735225, West Bengal, India. E-mail: abhaykumarpandey.ku@gmail.com*

[b]*Horticulture Crop Processing Division, ICAR – Central Institute of Post-Harvest Engineering & Technology, Abohar 152116, Punjab, India*

[c]*Tea Research Association, Tocklai Tea Research Institute, Jorhat 785008, Assam, India*

[d]*University of Coimbra, Faculty of Pharmacy, Polo III, Azinhaga de St[a] Comba, 3000-548 Coimbra, Portugal*

soap, talc powers, scanted sachets, aromatherapy, and massage.[4] In medieval and Renaissance Europe, *Lavandula* was commonly used in the preparation of 'nosegays' or small bouquets carried to ward off the plague, indicating its perceived antiseptic properties.[5] Various folk traditions have used *Lavandula* for a variety of medical purposes such as *Lavandula* used in the traditional Chinese medicine, to treat infertility,[6] infections, anxiety, and fever.[6] It has also been used in Arabic medicine to treat stomach aches and kidney problems.[7] It was considered an antispasmodic, antiemetic, antiflatulent, and antidepressant.[8] The extract of the genus was used to enhance bile flow, cure varicose ulcers, and to reduce carpal tunnel syndrome.[9]

Lavandula angustifolia and *L. latifolia* are highly valued for their essential oils (EOs), which are extensively used in aromatherapy and treating ailments like anxiety, depression, and sleep disorders. Several reviews have been published on *Lavandula* essential oils (LEOs).[10,11] For instance, *Lavandula* aromatherapy has garnered attention for its potential cognitive enhancing effects, as reviewed by Aprotosoaie *et al.*[10] In this review, they highlighted the chemical composition of LEOs, focusing on their main constituents such as linalool and linalyl acetate and discussed the variability in the chemical profiles due to different factors like geographical locations and harvesting times. Additionally, this review also emphasized the biological activities of LEOs, including their antimicrobial and antioxidant properties with reference to human pathogens, rather than against pathogens deteriorating food commodities.[9]

Another comprehensive review published by Malloggi *et al.*[11] explored the cognitive effects of LEO inhalation, focusing on arousal, attention, and memory and concluded that LEOs, particularly their main components linalool and linalyl acetate have the potential to decrease arousal and enhance sustained attention. Their review highlighted the importance of EO's quality and administration methods, noting that different diffusion devices and EO compositions can influence outcomes. Besides, in 2021, Heral *et al.*[1] described the taxonomy and morphology of *Lavandula* species along with a phytochemical analysis of their EOs. In particular, these reviews summarized the therapeutic and nutritional benefits as well as the phytochemical properties of LEOs rather than their application in food/crop protection. Therefore, a detailed review concerning the application of LEOs in food/crop protection is required to open opportunities for further research, especially in the areas of pest and pathogen control in food crops where the identification of potential biopesticides is still a limiting step. The objective of this paper was to provide a comprehensive review of the efficacy of LEOs, against insect pests and pathogens hampering/spoiling food commodities under both storage and field conditions. Besides, the chemical analysis of LEOs originating from different countries, challenges in using LEOs in food systems and safety assessments along with the scope of future research are also discussed.

The literature discussed in this review was explored and collected in 2023 and 2024. We surveyed the published research papers on the chemical composition and bio-efficacy of LEOs available through several online search engines, including Research Gate, Google Scholar, Sci Finder, Connected Papers, Web of Science, and Scopus using "*Lavandula* and essential oils" as the search keywords. Other keywords used for the survey of papers associated with LEOs were chemical composition, Gas Chromatography-Mass Spectrometry (GC-MS) analysis, medicinal, antibacterial, antifungal, insecticidal, nano-encapsulated LEOs, and antioxidant properties. The literature we have discussed here were mostly from Scopus and Web of Science indexed journals.

2. Phytochemical analysis of LEOs

Lavender EOs derived primarily from the genus *Lavandula*, are characterized by a complex composition of volatile compounds (Fig. 1), which confer their distinctive aromatic and therapeutic properties.[12] The chemical composition of LEOs can be analysed and quantified using techniques such as gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS).[13] This method allows for the accurate identification of individual components and their relative concentrations, providing insights into the quality and therapeutic potential of EOs.[14] The majority of studies used GC and GC-MS analysis to identify the chemical constituents present in LEOs.[14,15] In GC-MS analysis, the identification and quantification of compounds in EOs were performed based on their retention indices or retention times, and mass spectra. For instance, through GC-MS analysis, linalool, linalyl acetate, 1,8-cineole, camphor, and borneol were identified as the primary constituents of LEOs.[16] It is found that each component contributes to the EO's unique chemical profile and biological activities.

The chemical profile of EOs from *L. angustifolia*, *L. latifolia* and other *Lavandula* species, analysed by GC and GC-MS methods, originating from different countries, are summarized in Table 1 along with the extraction methods used to obtain the EOs. Investigators used various extraction methods for the isolation of EOs from *Lavandula* species. These include, hydro-distillation, headspace solvent microextraction, supercritical CO_2 extraction, headspace solid-phase microextraction, microwave-assisted hydro distillation, steam distillation, solvent extraction, ultrasound-assisted distillation, turbo hydrodistillation, hydrodistillation–headspace solvent microextraction, supercritical water distillation, microwave-assisted extraction, and microdistillation (Table 1). Most researchers, however, used hydrodistillation methods because they are cost-effective and require less resources.

Table 1 also shows that the chemical composition of LEOs can vary depending on the region and cultivation conditions. Using the GC-MS method, Jianu *et al.*[54] analysed the EO of *L. angustifolia* grown in western Romania, and reported significant variations in the major chemical components. These differences can influence the biological activities of the EO, highlighting the importance of regional studies in understanding their efficacy. In addition, high-quality *L. angustifolia* EO was typically characterized by high levels of linalool and linalyl acetate through GC-MS analysis, whereas *L. latifolia* EO was distinguished by its higher camphor content.[46] The table also provides evidence that linalool and linalyl acetate are the

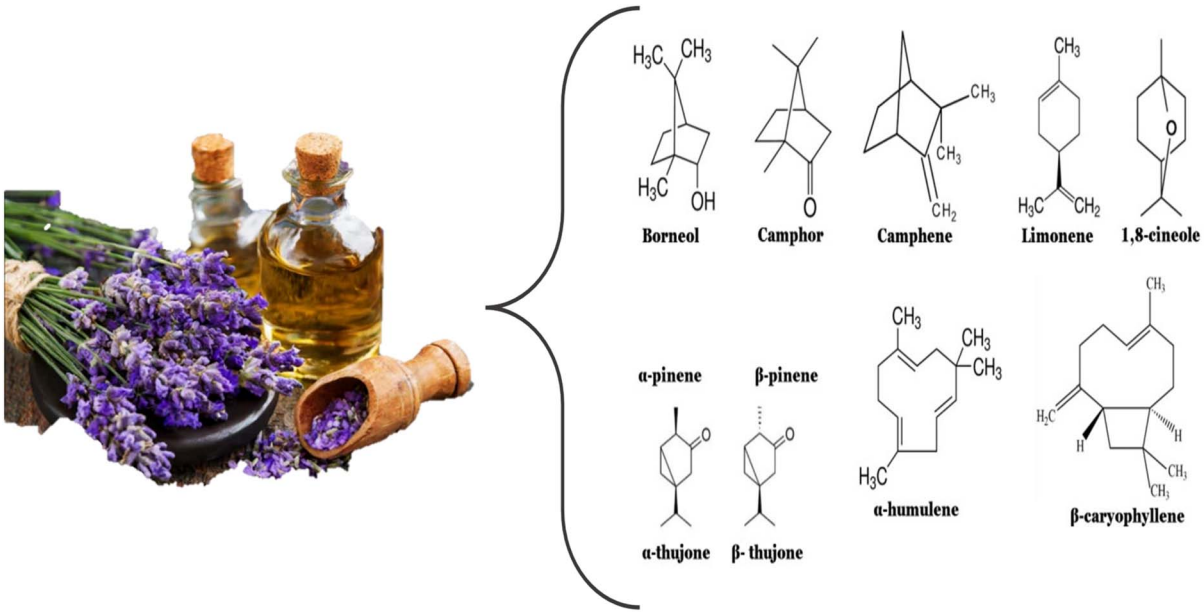

Fig. 1 Basic structure of major volatile compounds reported in *Lavandula* essential oils.

predominant compounds found in *L. angustifolia* EOs in the majority of the studies. In addition to the primary constituents, LEOs contain various secondary metabolites that contribute to their overall efficacy. These include terpenes such as lavandulol, geraniol, and α-terpineol, as well as sesquiterpenes like β-caryophyllene.[16,36]

In particular, *L. angustifolia* and *L. latifolia* are native to the Mediterranean region, with *L. angustifolia* being widely cultivated worldwide, including in China, Morocco, Italy and Algeria, while *L. latifolia* is commonly cultivated in Spain, France, and Italy (Table 1). Among these species, *L. angustifolia* from Romania has the highest concentration of linalool (73.0%) extracted *via* microwave-assisted hydro distillation.[55] In contrast, *L. latifolia*, from Spain, shows a higher concentration of γ-terpinene (26.8%) and camphor (13.8%) extracted by hydro distillation.[56] Besides, unique chemical constituents have also been identified in regional variants, such as *L. angustifolia* from Northeastern Algeria, which contains rare compounds like 2-furanmethanol (7.49%) and linalool oxide (11.98%), and in *L. latifolia*, known for its significant γ-terpinene content.[49] Although, all these studies used GC-MS analysis for the chemical characterization of LEOs, these variations highlight the diverse chemical profiles of *Lavandula* species depending on their geological origin and extraction methods.[39]

3. Use of LEOs as antibacterial agents against foodborne pathogens

Bacterial phytopathogens are a significant cause of yield losses in legumes, cereals, vegetables, fruits, and other food commodities/foodstuffs, affecting crops/commodities during pre-harvest, transit, and storage. These pathogens can lead to annual yield reductions in food crops or foodstuffs ranging from 20% to 40%, posing a serious threat to global food security and agricultural sustainability.[57] Their impact is particularly severe due to their ability to proliferate throughout the supply chain, from the field to the market, exacerbating economic losses and food waste.[58] The major bacterial species involved in food spoilage or crop loss include *Clavibacter michiganensis*, *Pseudomonas syringae*, *P. solanacearum*, *P. putida*, *Erwinia carotovora*, *E. amylovora*, *E. herbicola*, *Xanthomonas citri*, *X. axanopodis* pv. *malvacearum*, *X. campestris*, *Escherichia coli*, *Salmonella typhimurium*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Bacillus cereus*, and *Pseudomonas aeruginosa*, among others.[57,59,60] Such bacterial pathogens cause substantial yield losses and quality degradation in many food crops of national and international significance.[59] In the United States alone, foodborne illnesses caused by 14 major pathogens are estimated to cost $14 billion annually and result in a loss of 61 000 quality-adjusted life years (QALYs).[61] Developing countries face amplified impacts due to inadequate food safety infrastructure, resulting in higher morbidity and mortality, particularly among children under five.[62] For instance, in India, foodborne illnesses annually affect over 100 million people, contributing to significant economic losses from healthcare expenses and lost productivity.[63] In Canada, the annual societal cost of bacterial foodborne illnesses ranges from $9.3 to $12.9 billion, driven by healthcare expenses and lost productivity.[64] Such outbreaks also impact businesses through lawsuits, market losses, and consumer distrust, underlining the urgent need for improved food safety measures. Many EOs and plant extracts have been extensively evaluated by researchers from time to time for their antibacterial activity against these phytopathogenic and food spoilage bacteria under *in vitro* and *in vivo* conditions;[65–68] although LEOs are known for their significant antibacterial properties, particularly against foodborne pathogens,[69] there is limited information available about antibacterial properties of

Table 1 Major chemical compounds present in *Lavandula* spp. essential oils originating from different countries and their extraction methods

Year	*Lavandula* spp.	Part used	Extraction methods[a]	Major chemical compounds (%)	Origin	References
2005	*L. angustifolia*	Aerial parts	HD-HSME	Linalool (32.8%), linalyl acetate (17.6%), and lavandulyl acetate (15.9%)	Iran	17
2008	*L. angustifolia*	Aerial parts	HD	Linalool (44.54%), geraniol (11.02%), and lavandulyl acetate (10.78%)	China	18
2009	*L. angustifolia*	Flowers	HD	Linalool (30.6%), linalyl acetate (14.2%), and geraniol (5.3%)	Poland	19
2012	*L. angustifolia*	Aerial parts	HD	1,8-Cineole (29.0–38.0%), linalool (6.8–19.2%), and camphor (9.6–14.6%)	Iran	20
2012	*L. dentata*	Aerial parts	HD	Linalool (47.30%), linalyl acetate (28.65%), and camphor (2.32%)	Tunisia	21
2012	*L. latifolia*	Dried flowers	HD, SCE	Linalool (53%), linalyl acetate, camphor, and borneol	Australia	22
2013	*L. angustifolia*, *L. x intermedia*	Inflorescences	SD	Caryophyllene (24.1%), beta-phellandrene (16%), and eucalyptol (15.6%)	Romania	23
2013	*L. angustifolia*	Aerial parts	HS-SPME, MA–HS–SPME	1,8-Cineole (41.37–54.84%), camphor (15.83–23.25%), and borneol (12.32–5.0%)	Iran	24
2015	*L. angustifolia*, *L. latifolia*	Aerial parts	HD	Linalool (35–51%), eucalyptol (26–32%), camphor (10–18%), α-pinene (1–2%), α-terpineol (1–2%), and α-bisabolene (1–2%)	Spain	16
2015	*L. latifolia*	Flowering stems	SD	Linalool, 1,8-cineole, camphor, borneol, α- and β-pinene	Europe	25
2015	*L. latifolia*	Aerial parts	SCE	Linalyl acetate (44.1–59.8%), and β-caryophyllene (6.3–7.3%)	India	26
2016	*L. angustifolia*	Aerial parts	HD, SCE	Linalyl acetate (44.1–59.8%), and β-caryophyllene (6.3–7.3%)	India	27
2016	*L. angustifolia*	Flowers	HD, SFE, SPME	Linalool (35.65%) and linalyl acetate (33.63%)	Jordan	28
2016	*L. angustifolia*	Flowers	HD	Linalool (24.63%), camphor (13.58%), and linalyl acetate (8.89%)	Iraq	29
2016	*L. latifolia*	Leaves, flower buds, flowers	SD	Linalool (23.9%), linalyl acetate (22.3%), γ-terpinene (3.3%), and terpinen-4-ol (5.0%)	Poland	30
2016	*L. latifolia*	Flowers	HD, SD, THD, UAD, SWD, MAE	Linalool, linalyl acetate, camphor, borneol, and 1.8-cineole	France	31
2017	*L. angustifolia*	Aerial parts	HD, MD	Linalool (22.1%), lavandulyl acetate (15.3%), and linalyl acetate (14.7%)	Turkey	32
2017	*L. angustifolia*	Flowers	HD, SFE, SPME	Linalool (51.8%), lavandulol, terpinen-4-ol, and α-terpineol	Bosnia and Herzegovina	33
2018	*L. angustifolia*	Aerial parts	HD, MAE	Linalool (34.70%), camphor (12.77%), and eucalyptol (11.50%)	Romania	32
2018	*L. angustifolia*	Flowers	HD	Linalool (34.70%), camphor (12.77%), and eucalyptol (11.50%	Syria	34
2018	*L. stoechas*	Flowers	HD	Fenchone (52.7%), camphor (25.94%), and 1,8-cineole (4.84%)	Algeria	35
2018	*L. angustifolia*	Fresh flowers, aerial parts and stems	HD	Linalool (26.5–34.7%), linalyl acetate (19.7–23.4%), terpinen-4-ol (2–4.9%), α-terpineol (2.8–5.1%), β-ocimene (2.9–10.7%), geranyl acetate (1.7–2.8%), and oct-1-en-3-yl acetate (0.9–3.6%)	Poland	36
2018	*L. latifolia*	Fresh flowers, aerial parts and stems	HD	Linalool (26.5–34.7%), linalyl acetate (19.7–23.4%), terpinen-4-ol (2–4.9%), α-terpineol (2.8–5.1%), β-ocimene (2.9–10.7%), and geranyl acetate (1.7–2.8%)	Croatia	37

Table 1 (*Contd.*)

Year	*Lavandula* spp.	Part used	Extraction methods[a]	Major chemical compounds (%)	Origin	References
2019	*Lavandula latifolia*	Aerial parts	SD	Carvacrol (78.2%), 2-methoxy-4-vinylphenol (2.5%), and spathulenol (2.2%)	Morocco	38
2020	*L. angustifolia*	Flowers	HD	Linalool (23.51–27.39%), and linalyl acetate (26.60–40.66%)	Romania	39
2020	*L. angustifolia*	Flowers	HD	Linalyl acetate (28.89%), linalool (24.30%), caryophyllene (7.89%), and borneol (2.60%)	China	40
2020	*Lavandula latifolia*	Aerial parts	HD	Linalyl acetate (26.1%), linalool (19.7%), and lavandulol acetate (12.6%)	China	41
2020	*Lavandula latifolia*	Inflorescences	SD	Linalyl acetate (46.76%), lavandulyl acetate (14.21%), lavandulol (1.54%), and linalool (16.82%)	China	42
2021	*L. angustifolia*	Inflorescences	HD	1,8-Cineol (eucalyptol) (2.0), β-caryophyllene (4.78%), (E)-β-farnesene (1.52%), and caryophyllene oxide (0.36%)		43
2021	*L. angustifolia*	Aerial parts	HD	Linalool (32.19–46.83%), linalyl acetate (17.70–35.18%), and terpinen-4-ol (3.63–7.70%)	Romania	44
2021	*L. latifolia*	Aerial parts	HD	Gamma-terpinene (26.8%), camphor (13.8%), and 1,8-cineole (10.2%)	Saudi Arabia	45
2022	*L. angustifolia*, *L. x intermedia*	Aerial parts	HD	Linalool (26.14–57.07%) and linalyl acetate (9.08–24.45%)	Ukraine	46
2022	*L. angustifolia*, *L. latifolia*	Aerial parts	HD	Linalool (39.5%), linalyl acetate (26.7%), and eucalyptol (43.08%)	Egypt, France, Australia	47
2022	*L. spica*	Leaves	SE	Linalool (39.5%), eucalyptol (43.08%), and linalyl acetate (26.7%)	Egypt	47
2022	*L. angustifolia*	Flowers	HD	Linalool (29.95%) and linalyl acetate (18.86%)	Morocco	48
2023	*L. angustifolia*	Flowers	HD	Linalool (31.27%) and camphor (16.21%)	Algeria	49
2023	*L. angustifolia*	Aerial parts	HD	Linalool (20.0–45.0%) and linalyl acetate (20.79–39.91%)	Bulgaria	50
2023	*L. latifolia*	Aerial parts (leaves, stems, flowers)	SD	Linalool (14.93%), camphor (14.11%), linalyl acetate (11.17%), and eucalyptol (10.99%)	Morocco	51
2024	*L. angustifolia*	Flowers	MAHD	α-Terpinolene (24.25%) and (−)-borneol (19.55%)	Turkey	52
2024	*L. angustifolia*	Stems	HD	Linalool (33.27%) and linalyl acetate (21.01%)	Tajikistan	53

[a] Hydro-distillation (HD), headspace solvent microextraction (HSME), supercritical CO_2 extraction (SCE), headspace solid-phase microextraction (HSPME), microwave-assisted hydro distillation (MAHD), steam distillation (SD), solvent extraction (SE), ultrasound-assisted distillation (UAD), turbo hydro-distillation (THD), and hydrodistillation-headspace solvent microextraction (HD-HSME), supercritical water distillation (SWD), microwave-assisted extraction (MAE), and microdistillation (MD).

LEOs against phytopathogenic and food spoilage bacteria. The antibacterial activity of LEOs reported by researchers is summarized in Table 2.

3.1. Antibacterial efficacy of free LEOs

Free LEOs have been extensively studied for their antibacterial activity. Researchers have demonstrated that LEOs exhibit broad-spectrum antibacterial properties, effectively inhibiting the growth of both Gram-positive and Gram-negative bacteria.[95] These properties have been confirmed through various studies showing significant antibacterial effects against a range of pathogens. For instance, LEOs exhibited potent antibacterial activity against fish pathogenic bacteria isolated from olive flounder.[73] The study demonstrated that LEOs were effective in inhibiting both Gram-negative (*Aeromonas sobria*, *Aeromonas*

Table 2 Potential of essential oils derived from *Lavandula* species against foodborne bacterial pathogens

Lavandula species	Bacterial pathogens	Sources	Effective doses	Country	References
L. angustifolia	*Listeria innocua*, *Pseudomonas fluorescens*, and *Escherichia coli*	Fish	Applied in biodegradable films	Spain	70
L. angustifolia	*Staphylococcus aureus* and *E. coli*	Ostrich meat	2% EO in coating	Iran	71
L. angustifolia	*Yersinia ruckeri*, *Aeromonas hydrophila*, and *Vibrio anguillarum*	Fish	MIC: 62.5–500 μl mL^{-1}	Turkey	72
L. angustifolia	*Bacillus subtilis*, *S. aureus*, *E. coli*, and *P. aeruginosa*	Food pathogens	MIC: 0.4–4.5 mg mL^{-1}	Poland	36
L. officinalis	*Aeromonas hydrophila*, *Lactococcus garvieae*, and *Vagococcus salmoninarum*	Fish	MIC: 500–62.5 μl mL^{-1}	Turkey	73
L. stoechas	*E. coli*, *L. monocytogenes*, and *Salmonella typhimurium*	Common foodborne pathogens	MIC: 5–80 μl mL^{-1}	Turkey	74
L. angustifolia	*Pseudomonas* spp. and Enterobacteriaceae	Chicken	0.2% EO in vacuum packaging	Slovakia	75
L. angustifolia	*E. coli* and *L. monocytogenes*	Chicken	0.4 ml L^{-1} in drinking water	Poland	76
L. stoechas	*Pseudomonas* spp. and Enterobacteriaceae	Poultry meat	100–200 ppm EO	Tunisia	77
L. angustifolia	*L. monocytogenes* and *S. typhimurium*	Common foodborne pathogens	MIC: 62.5 ml mL^{-1}	Turkey	74
L. angustifolia	*E. coli*	Pork sausages	(0.2%)	Seria	78
L. stoechas	*E. carotovora*	Causing potato soft rot	MIC: 5–10 μl mL^{-1}	Greece	79
L. angustifolia	Total mesophilic microorganisms	Cucumber	100–200 ml L^{-1} of EO vapor	Greece	80
L. hybrida	*E. coli*, *S. aureus*, and *B. cereus*	Pathogenic food-borne bacteria	MIC: 0.25–0.5 mg mL^{-1}	Spain	81
L. angustifolia	*S. aureus* and *E. coli*	Food-borne bacteria	MIC: 0.16–20 mg mL^{-1}	Poland	82
L. angustifolia	*S. aureus* and *E. coli*	Cake	600 ppm EO	Egypt	83
L. stoechas	*E. coli*	Milk	59.4%	Tunisia	84
L. stoechas	*S. aureus*	Milk	6.8%	Tunisia	85
L. angustifolia	*Lactobacillus acidophilus*, and *Bifidobacterium bifidum*	Fermented milk and Yogurt	1–3% EO	Iran	86
L. angustifolia	*Pseudomonas savastanoi*	General food pathogens	3000 mg mL^{-1} and 4000 mg mL^{-1}	Algeria	49
L. angustifolia	*E. coli*, *S. aureus*, *S. abony*, *P. aeruginosa*, and *B. subtilis*	Chocolate	MIC: 62.5–125 ml mL^{-1}	Italy	87
L. angustifolia	*S. aureus* and *P. aeruginosa*	General food pathogens	MIC: 0.25 ml mL^{-1}	South Africa	88
L. angustifolia	*S. aureus*, *E. coli*, and *L. monocytogenes*	Cherry tomatoes	50–300 ml/10 mL in nano-emulsions	China	89
L. officinalis	*Aerobic Mesophilic Bacteria*, and *Psychotropic bacteria*	Lamb meat	3% (W/W)	Turkey	90
L. angustifolia	*Pseudomonas tolaasii*	Button mushroom	0.1–0.4%	Netherlands	91
L. angustifolia	*S. aureus*, *E. coli*, *B. subtilis*, and *Staphylococcus epidermidis*, *P. aeruginosa*, and *S. enterica* sub sp. *enterica*	—	MIC: 17–97 μg mL^{-1}	Bosnia	33
L. officinalis	*E. coli* and *S. aureus*	General food pathogens	MIC: 1000–1200 ppm	Argentina	92
L. x intermedia, *L. angustifolia*	*S. enterica*	Food pathogens	MIC≥ 10.0 μl mL^{-1}	Italy	93
L. angustifolia	*E. coli* and *S. aureus*	Beef	MIC 0.25 μl mL^{-1}	Algeria	94

caviae, *Aeromonas hydrophila*, *Vibrio anguillarum*, *Pseudomonas aeruginosa*, *Yersinia ruckeri*, *Edwardsiella tarda*, *Lactococcus garvieae*, and *Vagococcus salmoninarum*) and Gram-positive (*Staphylococcus warneri*) bacteria, highlighting their potential as natural antibacterial agents in aquaculture. A similar study by Walasek-Janusz *et al.*[82] highlighted the antimicrobial activity of *L. angustifolia* crude oil against bacteria and yeast and concluded that LEOs showed antibacterial properties with MICs ranging from 2.5–10 mg mL^{-1} against tested microorganisms. In addition to their antimicrobial properties, free LEOs also

exhibit strong antioxidant activities,[82] further enhancing their utility in food preservation. The presence of phenolic compounds such as rosmarinic acid and caffeic acid in free LEOs contributes to their ability to scavenge free radicals and reduce oxidative stress.

In another study, *L. angustifolia* EO was shown to inhibit the growth of *E. coli*, *S. aureus* and *P. aeruginosa*, with average MICs of 3.33, 1.33 and 42.67 μl mL^{-1} respectively.[96] Similarly, *L. latifolia* EO rich in camphor and 1,8-cineole exhibits significant antibacterial activity against *Staphylococcus aureus* and *Listeria monocytogenes* at 2.5 and 5 mg mL^{-1}, respectively.[97] The antibacterial efficacy of LEOs is primarily attributed to their major constituents, such as linalool, linalyl acetate, camphor, and 1,8-cineole, which possess strong antimicrobial properties.[98] Few studies investigated the mode of action of LEO against bacterial cells. For instance, in the study by Benbrahim *et al.*,[99] *L. dentata* EO caused disruption of cell organelles of *K. pneumoniae* (Fig. 2). According to Benbrahim *et al.*,[99] the antibacterial efficacy of LEOs is largely due to their ability to disrupt microbial cell membranes, which leads to leakage of cellular contents and eventual cell death.

In a study, Speranza *et al.*[100] reported that LEOs showed strong antibacterial activity against *L. monocytogenes* and *Salmonella enterica*, two common pathogens in food products, with MICs as low as 0.3 μl mL^{-1}. Another study carried out by Salavati Hamedani *et al.*[98] demonstrated that LEOs effectively inhibit the growth of common foodborne pathogens such as *E. coli*, *S. aureus*, *L. monocytogenes*, *B. cereus*, and *S. typhi*. The oils caused significant leakage of intracellular components, leading to bacterial cell death even in the absence of linalool and linalyl acetate, compounds often thought to be key to *Lavandula* EOs' antibacterial properties. This ability to target multiple pathogens makes LEOs highly versatile as natural preservatives. In addition, Carrasco *et al.*[16] found that the high linalool content in *L. angustifolia* EOs (37–54%) contributes to its broad-spectrum antibacterial activity by disrupting the integrity of microbial membranes, thus inhibiting the growth of bacterial pathogens involved in food spoilage.

Similarly, Benaiche *et al.*[101] found that LEOs exhibited strong antibacterial effects against *P. aeruginosa* and *S. aureus*, pathogens known to contribute to foodborne illnesses. In this study, the EOs were especially effective in inhibiting *P. aeruginosa* growth, a notorious bacterium responsible for spoiling perishable foods. The study revealed that the MIC of *L. angustifolia* EO was as low as 0.3 μl mL^{-1}, demonstrating significant potential as a food preservative. These findings underscore the potential of LEOs as natural antibacterial agents against foodborne pathogens, offering a safer alternative to synthetic antibiotics. In particular, Gram-positive bacteria are more susceptible towards EOs than Gram-negative bacteria. The cell membrane of Gram-negative bacteria contains hydrophilic lipopolysaccharides that acts as a barrier to macromolecules and hydrophobic compounds, thus providing enhanced tolerance to hydrophobic antimicrobial compounds such as those found in EOs.[102] Therefore, it is difficult to predict the susceptibility of microorganisms to EOs due to broad genetic variations among species.

Although LEOs are well-known for their antimicrobial properties, some studies have shown that their efficacy can sometimes be lower than that of other EOs. For instance, in a study, Sienkiewicz *et al.*[103] evaluated the antibacterial activities of LEOs and *Thyme vulgaris* EOs against 120 bacterial strains, and reported LEOs had lower efficacy than *T. vulgaris* EO screened against *P. aeruginosa*. Thyme oil exhibited significantly stronger antibacterial effects against *Staphylococcus*, *Enterococcus*, *Escherichia*, and *Pseudomonas* genera, making it a more potent option for food preservation and safety applications. In another similar study, Rota *et al.*[104] specifically found *L. angustifolia* and *L. latifolia* EOs to be less effective than thyme (*T. vulgaris* L), and savory (*Satureja montana* L.) EOs in combating

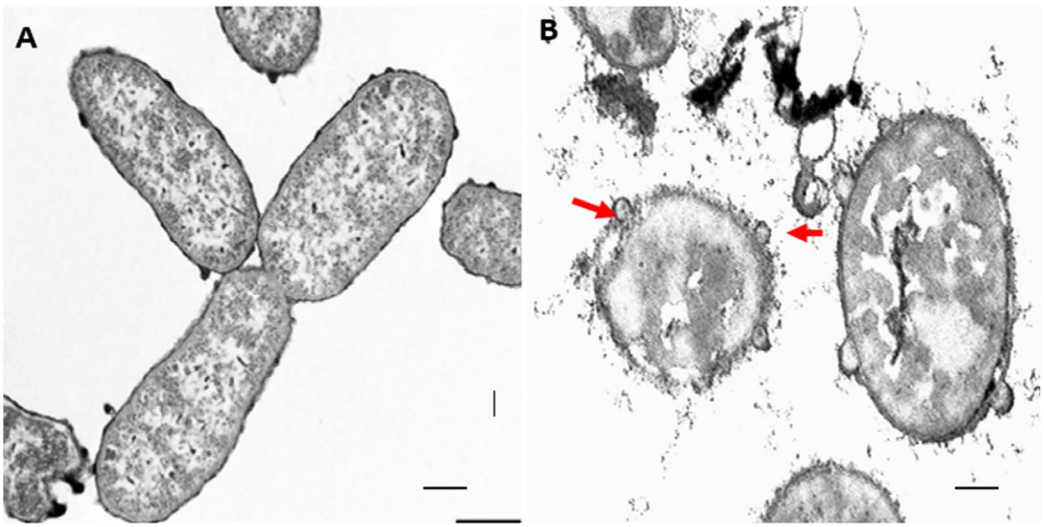

Fig. 2 Images showing the impact of *L. dentata* EO on the cell membrane and cell organelles of *Klebsiella pneumoniae*, A-bacterial cells of the control and B-bacterial cells treated with *L. dentata* EO showing disruption of cell membrane cell organelles (indicated with red arrow). Adopted with permission from Benbrahim *et al.*[99].

foodborne pathogens such as *Salmonella enteritidis*, *S. typhimurium*, *Yersinia enterocolitica*, *E. coli*, *L. monocytogenes*, *Shigella flexneri*, and *S. aureus*. They evaluated several EOs such as EOs from *T. vulgaris* from Spain and France, *Salvia sclarea*, *S. officinalis*, *S. lavandulifolia*, *L. latifolia*, *L. angustifolia*, three hybrids of *L. latifolia* × *L. angustifolia* (Lavandin 'Super', Lavandin 'Abrialis', and Lavandin 'Grosso'), *Rosmarinus officinalis*, *Hyssopus officinalis*, and *S. montana*. In each experiment, thyme EO showed more antibacterial activity than LEOs against all the test pathogens at lower concentrations. The variation in efficacy of LEOs and thyme EO may be due to variations in their chemical constituents as well as their origin. Furthermore, in cases where LEOs possess poor efficacy, their synergistic application with other EOs can be recommended as antibacterial agents against foodborne pathogens.

3.2. Antibacterial efficacy of encapsulated LEOs

In recent years, encapsulation techniques have revolutionized the application of EOs as antimicrobial agents in food systems or crop protection by overcoming their inherent limitations, such as volatility, low solubility, and sensitivity to environmental factors.[105] Nanoencapsulation, spray-drying, cyclodextrin encapsulation, and double-layer encapsulation techniques offer controlled release, improved stability, and targeted effects against harmful microorganisms in food systems.[106] The different techniques used for the encapsulation of EOs are summarized in Fig. 3 and have been discussed in our previous reviews.[107,108] Among these techniques, nanoencapsulation stands out for enhancing bioavailability and antimicrobial efficacy, as demonstrated by polymeric nanocapsules loaded with carvacrol and thymol, which exhibited superior bactericidal activity and stability over 20 days.[109] Spray-drying methods, employing protective matrices such as maltodextrin, have shown to stabilize thyme EO, significantly extending its antimicrobial properties in meat products.[110] Cyclodextrin inclusion complexes provide another approach, with hydroxypropyl β-cyclodextrin encapsulation ensuring controlled EO release and sustained antimicrobial effects.[111] Double-layer encapsulation, combining proteins and polysaccharides, has been successful in protecting pink pepper EO and enhancing its bioactivity in dairy matrices.[112] High-frequency ultrasound emulsification produces stable microemulsions, effectively delivering antimicrobial action against pathogens like *Listeria monocytogenes* and *E. coli*.[113] These encapsulation strategies not only preserve the functional properties of EOs but also enhance their controlled release and applicability as natural food preservatives. LEOs have also been encapsulated using these techniques to determine their effectiveness against harmful organisms that degrade food commodities/crops.

In many studies, encapsulated LEOs in various emulsion/particle systems have shown greater efficacy against foodborne bacteria than the LEOs used in crude form. For instance, encapsulated *L. latifolia* EOs exhibited enhanced antibacterial activity against *L. monocytogenes* compared to the crude oil.[97] The study found that the encapsulated form was more effective in disrupting bacterial cell membranes and inhibiting cell growth, highlighting the potential of encapsulation to improve the bioavailability and efficacy of LEOs. In addition, Yuan *et al.*[114] in their investigation found that encapsulated *L. angustifolia* EOs in alginate beads with 1.316 g hydroxypropyl-β-cyclodextrin which provided a controlled release of linalool and linalyl acetate, resulting in a sustained antibacterial effect against *B. cereus* and *S. typhimurium.*

A study by Türkoğlu *et al.*[115] explored the antibacterial efficacy of encapsulated *L. angustifolia* EO with bead sizes of 2.2 μm and 5.2 μm and found that it was more potent than the crude EO against *E. coli* and *S. aureus.* The encapsulation in these forms was not only effective in inhibiting bacterial growth but also demonstrated potential for use as an antibacterial agent due to its sustained release properties. Another study carried out by Balasubramanian and Kodam[116] encapsulated *L. angustifolia* EO in electrolyte-assisted polyacrylonitrile nanofibers. The encapsulated EO, with 88.44 nm bead size and concentrations ranging from 12.5 to 200 μg mL^{-1}, exhibited potential growth inhibition (14–15 mm zone of inhibition) against *S. aureus* and *Klebsiella pneumoniae*. This method of encapsulation significantly enhanced the antibacterial properties of LEOs. Additionally, Silva *et al.*[117] demonstrated the encapsulation of *L. latifolia* EO in gelatin nanoparticles with an average bead size of 100 nm and a concentration of 500 μg mL^{-1}. The study showed significant antibacterial activity against *S. aureus*, highlighting the potential of this encapsulation method in enhancing the antimicrobial properties of EOs. Encapsulated LEOs also offer controlled release properties, allowing for a sustained and gradual release of active compounds over time. This controlled release mechanism ensures a prolonged antibacterial effect, which is particularly beneficial in food preservation. The controlled release system not only enhance the antibacterial efficacy but also minimize the sensory impact on food products, making it a promising approach for natural food preservation. Additionally, the literature on the efficacy of encapsulated LEOs against phytopathogenic bacteria hampering food crops is limited and needs further exploration in future research.

4. Use of LEOs as antifungal agents against food pathogens

Food commodities are also affected by several groups of fungi during preharvest and postharvest stages. The major fungal communities responsible for the biodeterioration of food commodities and field crops are described in our previous review.[102] During infection, these pathogenic fungi also produce mycotoxins and render food unhealthy for consumption.[118,119] In tropical climates fungal infection of food and foodstuffs is a major problem due to high humidity. Fungal infections deteriorate both quality and quantity of produce and losses have been estimated up to 60% worldwide.[59] By affecting quality, fungal pathogens reduce the nutrient content of food commodities, *e.g.* proteins in pulses.[120] During infection process, fungi also produce various types of mycotoxins depending upon the commodities, which can lead to famines in developing countries.[121] In this regard, food contamination by

Table 3 Potential of essential oils derived from *Lavandula* species against fungal pathogens deteriorating food commodities/crops

Lavandula species	Target fungal species	Source	Effective doses	Origin	References
L. officinalis	*Penicillium expansum* and *Botrytis cinerea*	Apples	1% EO	Italy	131
L. angustifolia	*P. expansum* and *P. crustosum*	Meat ball	500 μl L^{-1}	Slovakia	132
L. angustifolia	*Aspergillus niger* and *Penicillium* spp.	Bread dough	2.5%	Bulgaria	133
L. angustifolia	*P. expansum*, *P. crustosum*, and *Aspergillus flavus*	Bread	125–500 μl L^{-1}	Slovakia	134
L. angustifolia	*A. niger* and *P. expansum*	Food pathogens	0.4 to 4.5 μg mL^{-1}	Poland	36
L. angustifolia	*Monilinia fructicola*	Flat peaches	800 μl L^{-1}	China	135
L. angustifolia	*M. fructicola*	Apricots	1%	Pakistan	136
L. angustifolia	*P. chrysogenum*, *Fusarium moniliforme*, *A. niger*, and *A. flavus*	Chocolate	MIC: 62.5–125 lL mL^{-1}	Italy	87
L. stoechas	*B. cinerea*	Tomato	1.6 μg mL^{-1} air	Turkey	137
L. stoechas	*P. infestans*	Late blight in tomato	12.8–51.2 μg mL^{-1}	Turkey	138
L. angustifolia	*A.nidulans*, *Leptosphaeria maculans* and *Sclerotinia sclerotiorum*	Agricultural fungi	MIC: 0.5–2.0 μl mL^{-1}	Australia	127
L. angustifolia	*Verticillium fungicola*	Causing dry bubble in mushrooms	0.5–1 mg cm^{-3}	Poland	139
L. angustifolia	*Pseudomonas tolaasii*	Button mushroom	70% aqueous solution	Iran	140
L. stoechas subsp.*Stoechas*	*P. infestans*	Late blight disease in tomato	0.4–2.0 μg mL^{-1} air	Turkey	141
Lavender	*M. perniciosa*	Button mushroom	2000 μl L^{-1}	Iran	142
L. stoechas	*Cladobotryum* sp.	Causing cobweb disease in mushrooms	1.6 μg mL^{-1} air concentration	Serbia	143
L. angustifolia	*Phoma exigua* var.*foveata*	Causing potato gangrene	0.1–0.4%	Russia	144
L. angustifolia	*B. cinerea*, *S. sclerotiorum*, *F. oxysporum*, *Phytophthora parasitica*, *Pythium aphanidermatum*, *Alternaria brassicae*, *Cladobotryum mycophilum*, and *Trichoderma aggressivum* f.sp. *europaeum*	Vegetables and button mushroom	5–32 μl mL^{-1}	Spain	145
L. angustifolia	*Colletotrichum nymphaeae*	Strawberry anthracnose	EC_{50}: 12.97 ppm (mycelial inhibition)	Iran	146
L. viridis	*Cryptococcus neoformans*	Agricultural fungi	MIC 0.32–0.64 μl mL^{-1}	Portugal	147,148
L. angustifolia	*A. niger* and *A. tubingensis*	Grapes	0.313 μL cm^{-3}	Slovakia	149
L. × *hybrid*	*Botrytis cinerea*	Grey mold in grapes	Vapors at 50 kPa reduced 65%	Italy	150
L. angustifolia	*Epicoccum nigrum*	Sugarcane, potatoes, and marine plant	MIC: 10.0 to 100.0 μl mL^{-1}	Serbia	151
L. stoechas	*Fusarium oxysporum* f.sp. *radicis-cucumerinum*	Cucumber	MIC: 0.125–1 μl mL^{-1}	Turkey	152
L. angustifolia	*P. brevicompactum*, *P. citrinum*, *P. crustosum*, *P. expansum* and *P. griseofulvum*	Stored fruits and vegetables	2.5, 1.5, 3.5, 3.0, and 3.25 μl mL^{-1}	Slovakia	153
L. angustifolia	*A. niger* and *A. flavus*	Cereal grains, legumes, and tree nuts	0.52 to 1.00 mg mL^{-1}	South Korea	154
L. officinalis	*Monilinia laxa* and *B. cinerea*	Stone fruits	1% EO	Italy	155
L. angustifolia	*Rhizopus stolonifer*, *B. cinerea*, and *Aspergillus niger*	Pathogenic fungi	EC_{50} (311.24 ppm)	Iran	156
L. angustifolia	*Fusarium roseum*	Pathogenic fungi	MIC: 3000 μg mL^{-1}	Algeria	49
L. angustifolia	*Eurotium amstelodami*, *E. herbariorum*, *E. repens*, *E. rubrum*, *A. flavus*, *A. niger*, and *Penicillium corylophilum*	Bakery products	MIC: 500 μl L^{-1}	Slovakia	157
L. angustifolia	*C. cladosporioides*	Lesions on berries	625 μl L^{-1} air	Slovakia	158

Table 3 (*Contd.*)

Lavandula species	Target fungal species	Source	Effective doses	Origin	References
L. angusti folia	*Verticillium fungicola* and *Trichoderma harzianum*	Button mushroom	0.1–0.4%	Netherlands	91
L. angustifolia	*B. cinerea*	Strawberry	0.125–0.25 g per plate or sachet	Thailand	159
L. angustifolia	*B. cinerea*	Grey mold in grapes	0.125–0.25 g in alginate beads	Thailand	160
L. angustifolia	*Colletotrichum gloeosporioides*	Avocado anthracnose	0.05–0.2% EO	USA	161

Alternaria, *Penicillium*, *Aspergillus*, *Rhizopus*, and *Fusarium* spp. is of great significance because of the related health hazards and other environmental problems.[122] Hence, prevention of fungal growth by EOs during storage and transit as well as at the field level could be a cost-effective approach to reduce economic losses of food commodities. Worldwide, the antifungal potential of LEOs and other EOs is increasingly considered as important.[123–126] From time to time many investigations have focused on studying the antifungal activity of LEOs both in their crude and encapsulation forms against fungal pathogens infecting various food commodities/crops. Some of the potential findings are discussed below.

4.1. Fungitoxic activity of free LEOs

The LEOs also exhibit notable antifungal activities, making them effective against various fungal pathogens that contaminate food products and infect field crops.[58,107,108] The previously published research papers on LEOs revealed that they have potential fungitoxic activity against a wide range of fungal pathogens causing food contamination and mycotoxin development. Studies have demonstrated that LEOs can inhibit the growth and proliferation of fungi such as *Aspergillus niger*, *Penicillium expansum*, and *Fusarium oxysporum* infecting food commodities during storage.[127] Another study found that the crude oil of *L. stoechas* exhibited strong antifungal activity against *Candida albicans* and *Aspergillus niger*.[128] In one study, 60 μL of EO derived from *L. stoechas* L. ssp. *stoechas* was effective against *Rhizoctonia solani* and *Fusarium oxysporum*, while less effective against *A. flavus*.[129] While in another study, *L. stoechas* subsp. *luisieri* EO showed strong fungitoxicity against all pathogens infecting strawberries fruits including *A. carbonarius*, *Rhizopus stolonifer*, *Penicillium brevicompactum*, *Aureobasidium pullulans*, and *Saccothecium rubi*, with MIC and MFC values ranging from 0.07–0.29 μl mL^{-1} and 0.58–9.33 μl mL^{-1}, respectively.[130]

Some important references on the antifungal activity of LEOs against fungal pathogens infecting food and food products/commodities are summarized in Table 3. As summarized in this table, the majority of studies showed that the potential antifungal activity of LEOs may be attributed due to presence of linalool, linalyl acetate, camphor, and 1,8-cineole.[130] The study also revealed that the higher concentrations of 1,8-cineole and camphor present in the crude oil disrupt fungal cell wall synthesis and inhibit spore germination, thereby reducing fungal proliferation. For instance, Xiong *et al.*[135] reported that LEO effectively inhibited the growth of *Monilinia fructicola* by damaging their cell walls and membranes. Later, Soylu *et al.*[108] also revealed that exposure of *Botrytis cinerea* infecting tomatoes to *L. stoechas* EO at 25.6 μg mL^{-1} caused considerable morphological degeneration of the fungal hyphae such as vacuolations, cytoplasmic coagulation, hyphal shriveling and protoplast leakage and loss of conidiation (Fig. 4). In addition, recent reports showed that LEOs also interfere with protein synthesis and energy metabolism in fungal pathogens, *e.g.*, Fu *et al.*[162] found that treatment of *Ustilaginoidea virens*, an infectious agent responsible for rice false smut disease, with LEO resulted in the downregulation of genes related to cell wall synthesis, cell membrane synthesis, protein synthesis, and the energy metabolism pathway.

Aside from their antifungal mode of action, LEOs have also shown inhibition of mycotoxin production in food commodities. For example, *L. angustifolia* EO was found to be effective in reducing mycotoxin production by *A. flavus*.[163] In their another study,[164] LEO was found to be less effective than thyme, clove, oregano, cinnamon and lemongrass in inhibiting mycotoxin production in bread samples by four strains of *Aspergillus* (*A. flavus*, *A. parasiticus*, *A. ochraceus* and *A. westerdijkiae*). Similar results were reported by Hlebová *et al.*[165] who found that *L. angustifolia* EO had a less toxic effect than cinnamon bark, lemongrass, and litsea EOs which were able to significantly inhibit the growth, sporulation, and mycotoxin production by toxigenic *A. ochraceus* and *A. parasiticus*. In the same line, LEO was less effective than star anise EO at 0.5 μl g^{-1} against *A. flavus* and *A. parasiticus* causing aflatoxin production in sorghum and peanut.[166] Conversely, LEO completely inhibited the mycotoxin production and proliferation of *Penicillium digitatum* in lemon fruits at 350 μL per air and was found more effective than mint and basil EOs.[167] The study attributed this effect to the high levels of linalool and linalyl acetate in the crude oil, which inhibited the enzyme activities involved in mycotoxin biosynthesis. The variation in efficacy might be due to variation in the chemical constituents of EOs or the origin of fungal strains. Furthermore, where LEOs show poor effectiveness, their synergistic application in food systems to prevent mycotoxin contamination/production should be adopted. These findings highlight the potential of LEOs as natural antifungal agents in

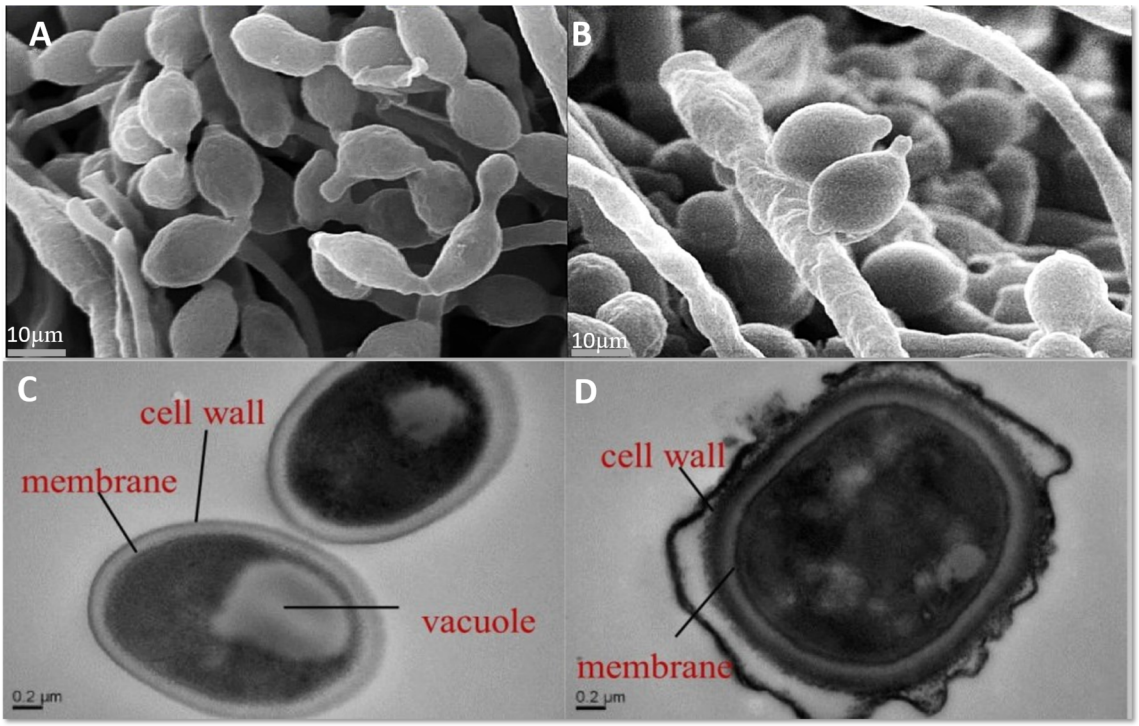

Fig. 3 Images showing scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images of *Monilinia fructicola*, a fruit rot pathogen exposed to LEO (800 μL L^{-1}). A and C are control sets, B and D are treated colonies showing abnormal cell structure in SEM and damage of cell membrane and cellular organelles in TEM analysis, respectively (Adopted with permission from Xiong *et al.*[135]).

food preservation, offering an alternative to synthetic fungicides that are often associated with health and environmental concerns.

4.2. Fungitoxic activity of encapsulated LEOs

As previously described, encapsulation enhances the antifungal activity of EOs by providing a controlled release mechanism and protecting the active compounds from degradation. Encapsulated LEOs offer several advantages over their crude form, particularly in terms of improving their antifungal efficacy and application in food preservation. Researchers encapsulated LEOs including *L. angustifolia* and *L. latifolia* EOs in various forms to enhance their antifungal properties against pathogens infecting food commodities/crops. One decade ago, Soylu *et al.*[108] focused their study on *L. angustifolia* encapsulated oil with MIC values ranging from 0.32–0.64 μl mL^{-1}, which exhibited significant antifungal activity against *B. cinerea*, infecting tomato. Previously, Inouye *et al.*[168] also highlighted the encapsulated oil's inhibitory effects on *A. fumigatus* showcasing its broad-spectrum antifungal potential. The oils were composed of 3 groups. The first group included citron (*Citrus medica* L), LEO and tea tree oils (*Camellia sinensis* (L.) Kuntze). The 2nd group consisted of perilla (*Perilla frutescens* (L.) Britt.) and lemongrass oils (*Cymbopogon citratus* DC. Stapf.) and the third group consisted of cinnamon bark (*Cinnamomum verum* J.S. Presl) and thyme oil (*Thymus vulgaris* L).

In 2020, Hammoudi *et al.*[169] developed alginate–montmorillonite nanocomposite films incorporating LEOs. These films exhibited potent antifungal activity against common pathogenic fungi such as *B. cinerea* and *Alternaria alternata* infecting fruits and vegetables. The encapsulated LEOs provided sustained release and improved antifungal efficacy.[169] Another study by Fagundes *et al.*[170] tested the antifungal activity of food additives, including LEOs, in hydroxypropyl methylcellulose (HPMC)-lipid edible coatings. The coatings were effective in reducing fungal growth on cherry tomatoes, highlighting the potential of encapsulated LEOs in food preservation, because the antifungal properties of LEOs are preserved over a longer period, making them more effective in food preservation. The nanoemulsions provided a protective barrier around the oil droplets, preventing the loss of volatile compounds and maintaining their efficacy. The controlled release system not only enhanced the antifungal efficacy but also minimized the sensory impact on food products, making it a promising approach for natural food preservation.

5. Potential of LEOs in preservation of food commodities

A significant number of studies have been conducted on the potential applications of LEOs in food preservation, either in their free form or encapsulated, due to their potent antimicrobial and antioxidant properties. The active components of these oils, particularly linalool, linalyl acetate, and camphor, have been shown to combat foodborne pathogens and prevent oxidative degradation of food products. As consumers move toward more natural preservatives, these LEOs have emerged as effective alternatives to synthetic preservatives. LEOs exhibit

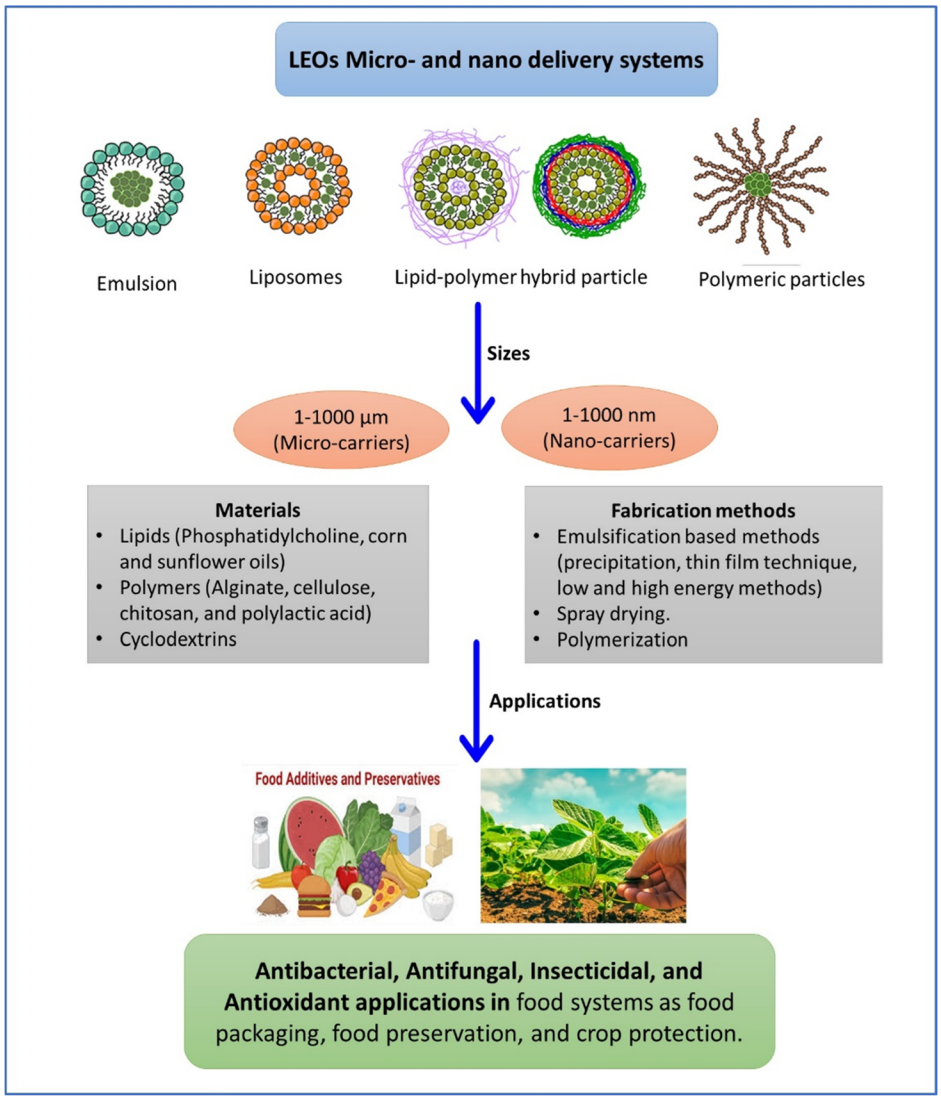

Fig. 4 Outline of the most common LEO delivery systems, materials used, fabrication techniques, and applications in food/crop protection.

both antibacterial and antifungal effects, helping to protect food products and perishables from microbial contamination while extending their shelf life.

In 2018, Blažeković *et al.*[37] demonstrated the potential of *L. angustifolia* EO against *Candida albicans* and food spoilage bacteria and reported that the EO showed a broad-spectrum of antibacterial (MICs 0.25–2.5 mg mL^{-1}) and antifungal (MICs 0.1–2 mg mL^{-1}) activities. The EO was able to inhibit spore germination and fungal growth, highlighting its potential use in controlling fungal spoilage in food products. Similarly, another study by Al-Ansari *et al.*[45] explored the antifungal activity of *L. latifolia* EO against *Trichophyton mentagrophytes*, a major fruit-spoliating fungus in custard apple. The results revealed that *L. latifolia* EO, which is rich in camphor and 1,8-cineole, exhibited a strong fungicidal effect, with an MIC value of 0.125 µg mL^{-1}. In another study, Sun *et al.*[89] used LEO nano-emulsions in the range of 50–300 µl/10 mL incorporated into gelatine films and found strong antibacterial effects against food spoilage bacteria such as *Staphylococcus aureus*, *Escherichia coli*, and *Listeria monocytogenes*. Applied to cherry tomatoes, the films effectively extended shelf life for over 7 days at 25 °C by reducing weight loss, delaying acid and phenolic component degradation, and suppressing microbial growth, indicating improved preservation compared to untreated controls.

The antifungal food preservative properties of *Lavandula* EO were further supported by Kahramanoğlu *et al.*,[171] who studied the effects of *L. angustifolia* EO on *B. cinerea*, the fungus responsible for gray mold in strawberries. In an *in vivo* vapor application, *L. angustifolia* EO significantly reduced the severity of fungal infections while maintaining the fruits' weight and sugar contents during storage. They also found that strawberries treated with *L. angustifolia* EO showed a 50% reduction in mold growth compared to untreated fruits, which contributed to a significant increase in their shelf life. Untreated strawberries typically developed mold within 4 to 5 days, while those treated with LEO remained mold-free for an additional 5 to 7 days, thereby extending the total shelf life to around 10–12 days. This finding suggests that LEOs are effective natural

alternatives to synthetic fungicides, especially in the preservation of high-moisture fruits.

The use of LEOs in food preservation is further enhanced by their incorporation into active packaging materials. A study conducted in 2023 (ref. 172) explored the application of LEO as a treatment for packaging paper, showing its effectiveness in extending the shelf life of packaged food items by preventing microbial spoilage. In this study, LEO-treated paper exhibited a 60–90% reduction in microbial growth within the first two hours, maintaining its effectiveness for up to 120 hours. The EO was particularly effective against *S. aureus*, *B. cereus*, *E. coli*, *P. aeruginosa*, *Salmonella abony*, *Saccharomyces cerevisiae*, *Aspergillus brasiliensis*, and *Fusarium moniliforme,* making it a promising solution for food preservation in biodegradable and eco-friendly packaging materials. In another study, Tancinova *et al.*[158] demonstrated that EOs from the Lamiaceae family, including *L. angustifolia*, significantly inhibited the growth of *Cladosporium cladosporioides*, a common pathogen responsible for post-harvest spoilage of berries. The study revealed that the application of *L. angustifolia* EO could extend the shelf life of fruits by inhibiting fungal growth by up to 100% during the 14-day cultivation period, compared to the control group, which showed complete fungal colonization and spoilage during this time. Such applications align with the growing consumer demand for natural preservatives and eco-friendly packaging solutions in the food industry.

Furthermore, Caprari *et al.*[173] investigated the effect of *L. angustifolia* EO on the shelf life of stored apples. The results indicated that the application of LEOs delayed the onset of fungal spoilage by 30% to 50% compared to the control group. While untreated apples developed fungal infections within 14 days of storage, the lavender-treated apples remained mold-free for an additional 7–10 days, significantly prolonging their shelf life. Thus, these LEOs can be used for the fabrication of botanical fungicides for the safe storage of food commodities. However, before making recommendations, their large-scale evaluation at the warehouse/at field level is required.

6. Use of LEOs as insecticidal agents in food commodities/crops

Food commodities/crops are deteriorated by several insects during storage and pre-harvest, as noted by Gupta *et al.*[174] Crops infested with insect pests have undergone significant changes since the dawn of the 21st century due to technological and ecological changes. While the numbers of many insect pests have declined, there has been an increase in the prevalence of other insect pests, including mealy bugs, particularly *Phenacoccus solenopsis* Tinsley, *Spodoptera litura* Fab., *Callosobruchus* species, diamond back moths, *Plutella xylostella* L., and *Tribolium* species, on various food crops or in stored grains. Globally, 40–80% crop losses have been estimated due to infestation by insect pests at both the field and storage levels.[175] Plant-based insecticides have become more popular in food crops due to the health hazards associated with synthetic insecticides used extensively for crop protection and post-harvest grain storage. There is no doubt that plant-based botanical insecticides are among the most promising, eco-friendly, and sustainable approaches for controlling insect pests on food crops. Since insect pests have developed resistance to commercial insecticides, EO-based botanicals developed from many aromatic plants have been evaluated as potential sources of repellents, ovicides, antifeedants, and insecticides to control insect pests.[176] In this section, we have summarized the efficacy of LEOs against insect pests under both storage and field conditions. The insecticidal activity of LEOs is well-supported by numerous studies compiled in Table 4.

A study by Al-Ansar *et al.*[45] evaluated the insecticidal activity of *L. latifolia* EO. The research revealed that gamma-terpinene, camphor, and 1,8-cineole were the predominant components, contributing to the oil's efficacy against *Euphoria leucographa* Gory and Percheron, a pest affecting custard apple fruit. The EO exhibited strong contact toxicity and fumigant activity, with an effective concentration (EC_{50}) value of 0.37%, highlighting its potential as a natural insecticide. *L. angustifolia* EO has also demonstrated efficacy against the pea aphid, *Acyrthosiphon pisum* Harris.[198] The investigators conducted fumigation tests that showed increased mortality rates of aphids with higher concentrations of the oil (Table 4). The major components, including linalool and linalyl acetate, played a crucial role in achieving an LC_{50} value of 11.2 μl L^{-1} of air. The study emphasized the importance of the complete mixture of constituents for maximum toxicity, suggesting the potential of *L. angustifolia* oil as a bioinsecticide.

Furthermore, the combined use of 1.14 and 1.7 μl L^{-1} air of *L. angustifolia* EO with 200 Gy gamma irradiation was explored for controlling the Mediterranean flour moth, *Ephestia kuehniella* Zeller. In this regard, Zallaghi and Ahmadi[199] found that the combination treatment significantly increased mortality rates and reduced growth rates compared to treatments with either the oil or gamma radiation alone. The results suggest a synergistic effect, enhancing the insecticidal efficacy of *L. angustifolia* EOs.[200] In addition to direct insecticidal effects, LEOs can enhance the efficacy of conventional insecticides when used together. In this regard, Faraone *et al.*[200] investigated the synergistic effects of *L. angustifolia* and *T. vulgaris* EOs with imidacloprid and spirotetramat against the green peach aphid, *Myzus persicae* Sulzer. The effective dose for the EOs in the study was approximately 0.3% v/v for both LEO and thyme EOs. The study revealed that *L. angustifolia* EO significantly enhanced the toxicity of imidacloprid, indicating the potential for using EOs to reduce the required doses of synthetic insecticides.

Lavandula angustifolia EO has also been found to be effective against the lesser mulberry pyralid, *Glyphodes pyloalis* Walker.[202] Yazdani *et al.*[201] reported that the major constituents of LEO, such as borneol and linalool, significantly reduced the total protein, carbohydrate, and lipid contents in the larvae of *G. pyloalis*, impacting their growth and development. The study highlighted the potential of *L. angustifolia* EO as a natural insect growth regulator. Moreover, the insecticidal activity of *L. angustifolia* EO against the rice weevil, *Sitophilus oryzae* L., has also been investigated by Al-Harbi *et al.*[196] who demonstrated that the EO caused 100% mortality at a concentration of 6 mg

Table 4 Potential of essential oils derived from *Lavender* species against insect pests

Lavandula species	Target insect pests	Sources	Effective doses	Country	References
L. angustifolia	*Sitophilus zeamais*	Maize, cereals	200 μl kg^{-1}	Cameroon	177
L. angustifolia	*Tribolium castaneum*, *Rhyzopertha dominica*, and *Trogoderma granarium*	Flour, grains, cereals	2–6%	Pakistan	178
L. angustifolia	*T. castaneum*, *Sitophilus oryzae*, *Stegobium paniceum*, and *Plodia interpunctella*	Cereals	100–300 μl g^{-1}	India	179
L. angustifolia	*T. castaneum*, *Sitophilus granarius*, and *Oryzaephilus surinamensis*	Stored cereals, dried fruits, and flour	42.51–374.16 μl L^{-1} air	Iran	180
L.angustifolia	*Sternechus pinguis* and *Rhyssomatus subtilis*	Soybean plants	0.40–1 μl cm^{-2}	Argentina	181
L. angustifolia	*Plutella xylostella* and *Cotesia glomerata*	Cruciferous vegetables, including cabbage and broccoli	1–6 g L^{-1}	South Korea	182
L.angustifolia	*Xanthogaleruca luteola*	Elm tree leaves	287.5 ppm	Iran	183
L. angustifolia	*Sitophilus granaries*	Wheat, barley, and rye	0.449 mg per adult (contact toxicity)	Italy	29
L. angustifolia	*S. oryzae*	Stored rice, wheat, barley	6 mg cm^{-2} (contact toxicity	Saudi Arabia	184
L. angustifolia	*Ceratitis capitata*	Citrus, stone fruits, and other soft fruits	0.1 μL per fly (topical application)	Italy	185
L. angustifolia	*C. capitata*	Citrus, stone fruits, and other soft fruits	0.1 μL per fly (topical application)	Italy	185
L. angustifolia	*Tribolium confusum*	Flour, stored grains, and cereal products	Various	Algeria	186
L. angustifolia	*Plodia interpunctella*	Dry food products, grains, and cereals	LD_{50} 22.8 μg cm^{-2} (contact toxicity)	Argentina	187
L. latifolia	*Drosophila suzukii*	Soft fruits such as strawberries, cherries, and blueberries	EC50 3.79 μL oil per L air (fumigation)	Canada	188
L. angustifolia	*Rhipicephalus annulatus*	Cattle	0.5–8% w/v (acaricidal)	Iran	189
L. angustifolia	*Euphoria leucographa*	Beetle larvae feed on crop roots	EC50 0.37% (fumigation	Saudi Arabia	45
L. angustifolia	*Ephestia kuehniella*	Stored flour and grains	225 μl per L air (fumigation)	Turkey	190
L. angustifolia	*Acanthoscelides obtectus*	Bean seeds	13.33–106.66 μl per L air (fumigation)	Algeria	191
L. angustifolia	*Callosobruchus chinensis*, and *C. maculatus*	Cowpeas, mung beans, and other legumes	0.5–1% (contact toxicity)	Egypt	192
L. stoechas	*Tetranychus cinnabarinus*	Tomatoes, cucumbers, beans, and other greenhouse crops	LC50: 2.92 μg mL^{-1}	Turkey	193
L. angustifolia	*S. granaries*	Wheat, barley, oats	LC_{50}: 1.5 mg L^{-1}, LC90: 4.1 mg L^{-1}	Italy	194
L. spica	*T. confusum*	Flour, stored grains	LC_{50}: 19.5 μL per L air	Algeria	195
L. angustifolia	*S. oryzae*		100% mortality at 6 mg cm^{-2}	Saudi Arabia	196
L. angustifolia	*S. granarius*	Wheat, barley, oats	LC_{50}: 1.5 mg L^{-1} without wheat, 10.9 mg L^{-1} with wheat	Italy	197

cm^{-2} within 24 hours of exposure. The study also noted a significant upregulation of detoxification and cytochrome P450 genes, indicating the impact of EOs on the metabolic pathways of the insect.

Besides, Germinara *et al.*[203] evaluated the contact and fumigant toxicity of *L. angustifolia* EO against the granary weevil, *Sitophilus granarius*. The study found that the major components of the EO, including linalool and 1,8-cineole, provided significant protection against the pest, suggesting its use as a natural preservative for stored grains. Furthermore, LEOs have shown potential in integrated pest management programs. Modarres Najafabadi[175] conducted a comparative

study on the acaricidal activities of EOs from various plants, including *L. angustifolia*, against *Tetranychus cinnabarinus* Boisduval on cut roses. The study found that *L. angustifolia* EO significantly reduced the fecundity and fertility of the mites, supporting its inclusion in IPM strategies. Thus, these potential LEOs should be screened on a larger scale and after obtaining fruitful results they can be used for the development of botanical insecticides.

7. Challenges and safety assessment studies

While LEOs have received significant attention in food/crop research due to their natural origin, it is not easy to fix the dose for optimal *in vitro* effects in food preservation or crop protection. One of the major challenges in the application of LEOs is that their volatile natural compounds may interact with the proteins or carbohydrates present in food products/commodities, causing destabilization of LEOs and the development of new unwanted compounds, thereby decreasing their potential antimicrobial and insecticidal effects. This needs a higher amount of LEOs to ensure the effective preservation of food commodities. Nevertheless, the use of higher amounts of LEOs in food systems has been observed to modify the taste, quality and aroma of food commodities, making them less acceptable for consumption. But, the long-lasting aroma and flavour of LEOs allow for good effects at low doses instantaneously limiting negative organoleptic changes. The EOs derived from *Lavandula* species are considered safe for consumption due to their non-toxic nature and hypo allergenicity. The inappropriate application of LEOs and their derivatives in the preservation of food commodities or in pest protection may cause hostile side effects on human beings including respiratory issues, skin related problems, headache, and acute oral toxicity.[204] With this perspective, anti-inflammatory and antinociceptive activities of LEO (*L. angustifolia*) has already been investigated by Silva *et al.*,[117] which demonstrated its ability to decrease both acute and chronic forms of nociception. However, this aspect is not evaluated for EOs derived from other *Lavandula* species. It is important to be aware of their potential side effects before using these natural sources internally or as food additives or preservatives.

Besides, the LEOs, if applied at higher doses, may cause harmful effects on the human organs such as the liver and stomach.[205] Thus, LEOs and their derivatives must be tested for safety, appropriate doses, and toxicity. In this regard, many toxicological studies have been conducted on LEOs and reviewed by Cardia *et al.*[206] For example, genotoxic and cytotoxic effects of LEOs are well studied.[202] In another study, Arantes *et al.*[207] studied the toxicological properties of *L. stoechas* subsp. *luisieri* EO in Alentejo (Portugal) and found that rats exhibited normal behaviour after administration of 200 mg per kg body weight, revealing low toxicity. Similar results were reported by Mekonnen *et al.*[208] in Ethiopia; they found in their experiments that administering 2000 mg kg^{-1} of *L. angustifolia* EO to rabbits caused no significant changes ($p > 0.05$) in body weight, gross abnormalities, biochemical parameters, food and water intake. Furthermore, they did not find abnormality in kidneys and livers after histopathologic analysis. Besides, application of 10% ointment formulation did not cause any skin irritation which showed that the EO was nontoxic.[208] Thus, LEOs can be promising candidates for use as food supplement applications.

The deployment of LEOs as food preservatives/crop protectants has many advantages due to their efficient activity against pathogens and insects hampering food crops both in storage and in the field with negligible harmful effects on beneficial organisms. To date, many LEOs including *L. angustifolia* EOs have demonstrated mosquitocidal activity against *Culex pipiens* larvae, a vector for *West Nile virus*,[209] with an LC_{50} of 140 μg mL^{-1}. At present, LEOs and some of their major constituents are used in aromatherapy as well as for the development of medicines for urogenital, respiratory, digestive, nervous, and vascular disorders.[210] Additionally, past and recent studies have shown the potential of LEOs against pathogens and insect pests deteriorating food commodities[197,211] and hampering field crops.[212,213] In Asian, African, and European countries, as well as in the United States, the potential of LEOs has been recognized, but they have not yet been commercialized. Unfortunately, no bio-preservatives or biopesticides derived from LEOs are currently available on the market. Practical applications are rarer than published results at the field level, which is why published results are more common. Aside from the low production cost–benefit ratio, the low persistence of effects, and strict European Union regulations, LEOs have not yet been commercialized as botanical pesticides on a larger scale and remain confined to laboratory experiments.[214] In addition, the direct application of LEOs as food preservatives against pathogens and insect pests deteriorating food commodities/hampering field crops has several limitations, including short shelf life, poor stability, and regulatory problems regarding their exposure to the environment.

Although, many LEOs have been investigated for their efficacy against food deteriorating pathogens and insect pests, the majority of investigations were conducted under laboratory conditions or on a smaller scale. During the application of LEOs in fields or storehouses, they may lose their efficacy. Therefore, to re-store their efficiency, stabilization methods including encapsulation technology can be considered. For instance, many research studies have shown that the efficacy and shelf life of LEOs are extended after their encapsulation.[215,216] Thus, using LEOs to produce potential nano-preservatives could help to prevent their degradation. Thus, botanical preservatives fabricated from LEOs must be scientifically certified regarding their residual phytotoxicity on crops, deployment protocols, overcoming regulatory and toxicological barriers, and mitigating problems related to the environment for their long-term application for food preservation/crop protection. It is also challenging for LEOs to gain widespread approval for their compounds and legitimize them as biopesticides due to complex authorization procedures. Furthermore, their approval and registration procedures are very expensive due to their inherent toxicity costs and the need for a suitable evaluation environment.

8. Research gaps and future outlook

The LEOs and their derivatives have been evaluated for their functional properties in food system/crop protection including antibacterial, antifungal, and insecticidal activities; however, the majority of studies were focused on lab conditions. However, investigations regarding the field application of LEOs against phytopathogens and insect pests, as well as their impact on beneficial organisms including bees have not been conducted and need to be addressed in future research. Although, more than 39 species of *Lavender* exist worldwide, majority of pesticidal, food preservative, and toxicological studies have focused on EOs derived from *L. angustifolia*, *L. latifolia*, and *L. stoechas*. However, little attention has been given to *L. lanata*, *L. viridis*, *L. dentata*, among others, which could be evaluated against pests and pathogens of foods and food crops in future.

A higher concentration of LEOs in food systems was observed to affect the taste, quality, and aroma of the food commodities, resulting in less consumer acceptance. The encapsulation technology can be one of the possible solutions to this problem. The encapsulation technology not only decreases the instability of LEOs (*e.g.*, their reaction towards substrate protein), but also safeguards the pesticidal properties through controlled release. On this aspect, few investigators studied the antimicrobial and insecticidal properties of encapsulated LEOs, *i.e.*, *L. angustifolia* and *L. latifolia* EOs; however the majority of other *Lavandula* species remain unexplored. To ensure food safety, safe dosage limits, and food preservation composition, this aspect needs to be concentrated in food research. Encapsulating LEOs improves their bio-efficacy, controlled release, shelf life and provides a relatively safer approach for the protection of food crops from pest/pathogen attacks. Preventive measures should be taken before commercialization to ensure that LEOs and their related derivatives are not harmful to beneficial organisms. Therefore, future studies are needed in order to achieve the (i) safe dosage limit, (ii) stability and bioactivity of LEOs and their related compounds, (iii) interaction of surface proteins on food commodities with LEOs' bioactive compounds, (iv) allergic reactions, (e) their optimal dosage limit to prevent deterioration/spoilage of taste, quality, and aroma of food commodities, and (f) improved encapsulation methods and controlled release to ensure increased shelf-life of food commodities and related products.

Lastly, the EOs of *Lavandula* species from various countries were characterized through GC-MS analysis and the results revealed that LEOs exhibit a broad range of variations in their constituents in different plant samples. However, there are knowledge gaps regarding the modes of action of a particular compound derived from EOs of *Lavandula* species against harmful organisms deteriorating food commodities/crops. However, based on prevailing toxicological and pharmaceutical investigations, LEOs have raised no concerns regarding their use in food preservation or crop protection and can be considered eco-friendly at the normally recommended doses reviewed here after their field trials. As a result of their multifaceted antimicrobial and insecticidal properties, LEOs may be used as botanical pesticides once the government of the concerned country determines the cost–benefit ratio and conducts other regulatory risk assessments. Last but not least, a robust and sustainable environment in the future requires a gradual and efficient approach for approving LEO-based botanical pesticides to mitigate pests and pathogens without interfering with marketable public interests.

9. Conclusion

The present article summarizes that EOs and terpenoids derived from *L. angustifolia*, *L. latifolia*, and *L. stoechas* have broad antimicrobial and insecticidal properties against pathogens and pests deteriorating food commodities/crops. In several investigations these EOs were found to be non cyto/geno toxic. There have been developments in the evaluation of LEO-based encapsulated products, such as thin films, biodegradable polymers, nano-emulsion coatings against bacterial and fungal pathogens responsible for food spoilage and investigators have found potential results. Based on the toxicological and pharmacological studies available, LEOs appear to be safer to the environment and consumers than synthetic pesticides. Therefore, LEO-based botanical pesticides might be useful in combating microbial pathogens and insect pests in stored food commodities and field crops. Unfortunately, LEOs that have been reported as efficient against pests and pathogens, are often the most phytotoxic. Therefore, sustainable protection of food commodities and crops from biodeterioration needs special attention. Like other alternatives, LEO based biopesticides are not a panacea for controlling harmful organisms hampering food commodities/field crops; however there will be prevailing market niches focused on worker and environmental safety, where LEO-based bio preservatives/biopesticides will find wide acceptance among farmers/retailers. Therefore, extensive research is required to address the challenges associated with LEOs, particularly regarding safe dosage limits and potential adverse effects. These challenges include unfavourable organoleptic properties, low stability, and a lack of standardization, all of which hinder their broader application as biopesticides. A shift towards greener technologies directs an optimistic future towards the safer deployment of LEOs in food preservation/crop protection.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Conflicts of interest

The authors declare no conflict of interests.

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