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Role of essential oils in food safety: Antimicrobial and antioxidant applications

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ABSTRACT

Essential oils (EOs) are more complex and comprise a number of volatile and natural bioactive compounds, which often used in food industries as the best alternatives. This review focuses on the impact of EOs and the roles of their major components in food manufacturing as natural preservatives with the related mechanisms of action. In addition, the major bioactive molecules of different types of EOs and their pharmacological activities such as antioxidant, antifungal and antimicrobial effects on crop protection were also discussed. The major compounds of EOs represent potential antioxidant, antimicrobial and antifungal activities through various mechanisms. Different types of EOs such as tea tree oil, lemon oil, clove oil, cinnamon oil and thyme oil from various traditional plants, have significantly showed better antimicrobial and antioxidant activities, and also effectively increased the shelf lives of the cereal products and increased the quality of food safety. The major groups of EOs such as terpenes and aromatic volatile compounds, play a key role in food safety without affecting the quality. Due to their various activities including antioxidant and antimicrobial activities, EOs could be used as alternative preservatives to increase the shelf lives of cereals and crops.

1. Introduction

Essential oils (EOs) are colorless liquids, mainly comprising the aromatic and volatile compounds naturally present in all parts of the plants including seeds, flowers, peel, stem, bark and whole plants [1]. They are widely used in various countries as medicine, perfumes, cosmetics and as food preservatives. Initially, they were used as medicine in the 19th century due to their aroma and flavor. Till date, 3000 EOs have been identified and about 300 types of EOs are being used in perfumery due to high aroma [2]. EOs are secondary metabolites, and are important for plant defense mechanism, hence, they have various medicinal properties including antimicrobial activity [3]. In 1881, De la Croix, first reported that the secondary metabolites, especially, the EO vapours showed antimicrobial effects [4]. Since then, EOs and their phyto-constituents have been reported to exhibit a wide range of biological activities including antibacterial [5], insecticidal [6], antiviral [7], and antifungal [8] activities. Oils extracted from various vegetable seeds are rich in proteins and vitamins, and most of the vegetable seeds including sunflower and perilla seeds have heterocyclic substances such as pyrazine, which play a key role in flavor and quality of the products [9]. Generally, the medicinal plants used in Siddha and Ayurveda are the major sources of various volatile compounds, which are responsible for various biological activities, for example, the major volatile compounds such as alkenes, alcohol, and esters are characterized as major constituents of EOs showing significant pharmacological effects [10].

Due to aroma, flavors and natural antimicrobial contents, EOs are primarily used in food industry for food preservation. For example, EOs which are extracted from citrus such as monoterpenes, sesquiterpenes, and oxygenated derivatives show strong inhibitory activities against pathogenic bacteria; hence, suggesting their use as flavoring and antioxidant agents. Physical, chemical, and few microbiological factors are essential for food preservation. For many years, manufacturers and consumers have been using synthetic preservatives in food industries but the usage of synthetic preservatives and their consumption can lead to some allergic effects, intoxications, cancer, and other degenerative diseases [11]. For this reason, there is a need to look for other alternatives. In recent years, the food industries have been using extracts of aromatic plants and EOs due to their abilities to control the growth of pathogenic microorganisms [12,13]. EOs extracted from cinnamon, oregano and thyme show significant antimicrobial activities against various microorganisms including *Listeria monocytogenes, Escherichia coli, Bacillus thermosphacta*, and *Pseudomonas fluorescens* [14]. However, detailed information about the applications of EOs and their properties, i.e., the mechanisms of action and

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impacts of EOs on food products and their biological activities including antimicrobial activity are still lacking. Hence, the present study focused on the current knowledge about the role of EOs in food preservation and their antimicrobial modes of action and antioxidant activities.

2. History of EOs

The term EOs is being used since 16th century as derived from the drug Quinta Essentia and named by Paracelsus von Hohenheim of Switzerland [15]. Due to their flammability, they are named as EOs or essences. Several researchers have attempted to give definition of EOs. According to the French Agency for Normalization: Association Francaise de Normalisation (AFNOR), EO is the product obtained from a vegetable raw material, either by steam distillation or by mechanical processes from the epicarp of citrus, or "dry" distillation. Later, it will be separated from aqueous phase by physical methods [16]. This definition includes the raw materials used for the extraction of EOs and their extraction methods such as using nonaqueous solvents or cold absorption. EOs are highly soluble in volatile compounds such as alcohol, ether, and fixed oils but insoluble in water. EOs extracted from cinnamon, sassafras, vetiver, and other natural sources are liquid in nature and colorless at room temperature due to the presence of aromatic compounds [17]. Hence, they are widely used in aromatherapy and cosmetics industry. The presence of volatile compounds such as ketones, aldehydes, and aromatic compounds in the EOs play key roles in aromatherapy as inhalation of those compounds, which are effectively reducing mental and physical stresses. EOs are also highly used for various therapeutic purposes including massage aromatherapy, psycho aromatherapy and olfactory aromatherapy. EOs also serve as chemical signals and are involved in plants to control and regulate their own environments such as to protect themselves from pests and attract beneficial insects such as pollinating insects, and use for communication between plants by release of chemical signals in the presence of herbivores. In the earlier periods, i.e., during the late 12th century, EOs were produced by conventional hydro distillation. Prior to this, Romans and Greeks used the primitive form of distillation to produce turpentine and camphor [18]. This method was not used in separation of other oils, however, it was practiced still 9th century and this method was used to produce distilled waters during this method, turpentine and camphor were formed as byproducts. Arabic scientists improved the distillation method though it was not clear to produce EOs. Therefore, historians have currently adopted in oil technology therapeutic use in Europe in the middle age from the 13th century work of Villanova who provided the earliest record that can be reliable authenticated [19]. In the late 20th century, EO based aromatherapy has become very popular due to its importance, popularity, and widespread use. EOs are the major ingredients in aromatherapy. There are several methods by which EOs are administered in trace amounts such as inhalation, massage or simple application on the skin surface. Inhalation and external application of the EOs are used in a wide range of therapeutic use including mental and physical balance, which is the very basis of aromatherapy. It significantly relieves the stress, rejuvenates and regenerates the individual for the next day's work. It mainly works on the olfactory nerve from nose to brain and have proven well for microbial infections, Alzheimer, cardiovascular and cancer diseases, and labor pain in pregnancy [20–23]. Recently, there is an increased trend to use aromatherapy for cancer and sleeping disorders. The other organic compounds present in the EOs act in supportive manner to increase the feeling of well-beingness [24].

3. Major constituents of EOs

EOs are very complex in nature as they are composed of a mixture of more than 50 components at quite different concentrations. Several numbers of differentiated compounds chemically produce EOs; especially, the number and characteristics of those compounds are highly variable. Mainly, EOs are located in the cytoplasms of certain plant cells, specifically secreted in trichomes or secretory hairs, epidermal cells, internal secretory cells, and secretory pockets. EOs are a mixture of over 300 different compounds; primarily consisting of volatile compounds with low molecular weights about below 1000 Da (usually 300 Da) [18]. Basically, few compounds are present as major ones at about 20%–70% compared to other compounds, which are present in trace amounts. For example, *Origanum compactum* has carvacrol (30%) and thymols (27%) as the major chemical components, linalool is the major component in *Coriandrum sativum* and other EOs such as α, and β, *a*- and *b*-thuyone (57%) and camphor (24%) are present at high concentrations in *Artemisia herba alba*. These major components are responsible for the various biological activities of EOs. Generally, these major components are classified as two groups of distinct biosynthetic origins such as terpenes/terpenoids and aromatic/aliphatic components [25–28]. At room temperature, the atmospheric pressure is sufficiently high, hence, EOs are mostly found in the partial vapor state. The volatile compounds are majorly categorized into various chemical classes such aldehydes, ketones, alcohols, amines, amides, phenols and mainly, terpenes. Among these, alcohols, aldehydes, and ketones offer a wide variety of aromatic effects to fruits and other parts of certain plants. For example, fruits have F-nerolidol, floral (Linalool) and herbals (γ-selinene) as major compounds. Volatile compounds such as hydrocarbons, 2-methyl, 4-heptanone and trimethylsilyl methanol extracted from bitter apple, are the major components responsible for pharmacological activities [29]. The low molecular weight compounds such as terpenes and terpenoids are present in most of the EOs and are responsible for various activities, including food preservation. EOs extracted from Rosemary have several monoterpenes including 1, 8-cineole, camphor as the major constituents, which act as antimicrobial bio preservatives in food production [30].

4. Terpenes

Terpenes are one of the major groups of chemical components, which are both structurally and functionally different. The basic structures of terpenes are 5-carbon based units, known as isoprenes. The synthesis of terpenes in medicinal plants consists of three important steps: in the first, isopentenyl diphosphate (IPP) precursor is synthesized; in the second, number of IPPs to form the prenyl-diphosphate precursor of the different types of terpenes and in the third step, synthetases of different types of the terpene precursor, allylic prenyl-diphosphate, undergo slight modification to form the terpene skeleton; in the final step, it undergoes redox reactions for secondary enzymatic modifications of the skeleton, which attributes to the functional properties of the different terpenes. Monoterpenes (C_{10}) and sesquiterpenes (C_{15}) are the major types of terpenes and apart from that, the other types are hemiterpenes (C_5), diterpenes (C_{20}), triterpenes (C_{30}) and tetraterpenes (C_{40}). Terpenoid is another type, which contains oxygen. Monoterpenes are formed by combining the two basic two-isoprene units (C_{10}) and they act as major compounds (90%) of EOs and are significantly associated with the formation of a great variety of structures. Fig. 1 represents the chemical structures of important and major monoterpenes.

5. Hydrocarbons

Hydrocarbons are the next major constituents of EOs and are composed of only two basic structures namely, carbon and hydrogen atoms. They are highly soluble in lipids and very poorly soluble in water. The simple hydrocarbons such as alkanes, alkenes, and benzenoids are also known as non-terpenoid hydrocarbons [31]. Based on the presence of open chain of carbon atoms, hydrocarbons are classified into aliphatic, alkanes, and aromatic hydrocarbons. Aliphatic hydrocarbons are linear chains, which do not have an aromatic ring. Aliphatic molecules are C_8, C_9, and C_{10} aldehydes, which contribute to the acrid-smelling and are found in citrus oil in trace amounts. C_6 compounds are found in some floral oils, which are responsible for leafy-green smelling, and the octanal aldehydes ($C_8H_{16}O$) are found in orange oil. Usually, aliphatic compounds are present in EOs in very small quantities and are responsible for odour due to the presence of oxygenated functional groups. In alkanes, all the atoms are linked together by a single bond between the two carbon atoms in their structures while alkynes have more than one carbon-carbon triple bond. In addition, most of

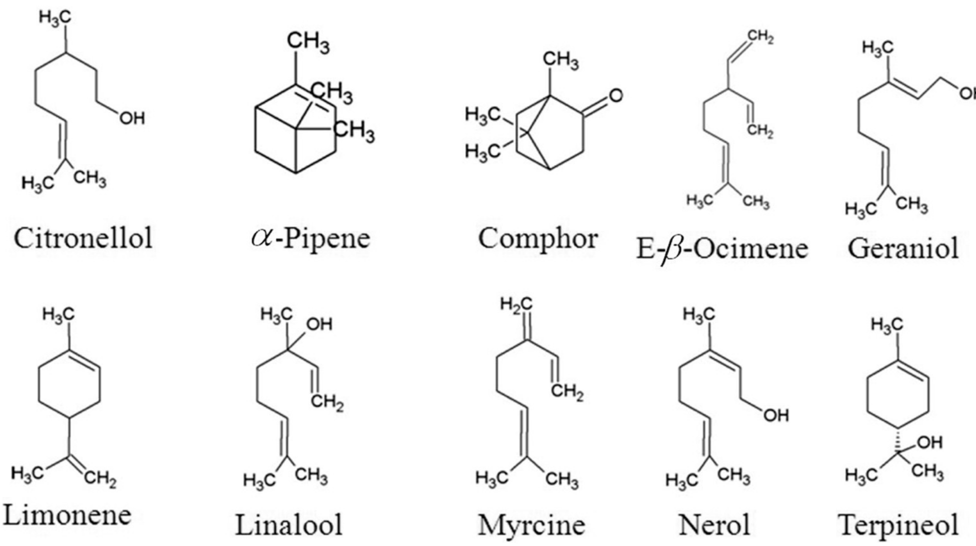


Fig. 1. The chemical structures of major monoterpenes of EOs.

the EOs have one or more ring structures and are called as mono-, bi-, tri-, tetracyclic, and so on. The third class of hydrocarbons are aromatic compounds such as benzyl, phenylethyl, and phenylpropyl; usually, they have a benzene ring (C_6H_6) as well as polycyclic structures such as naphthalene and benzopyrene, which are the first benzene derivatives isolated from plants and are responsible for pleasant smelling [32].

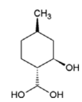
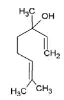
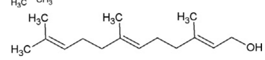
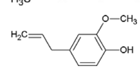
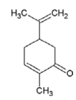
6. Types of EOs

EOs are extremely complex in nature having mixtures of more than 50 individual aroma compounds. EOs include tea tree oil, lemon oil, clove oil, cinnamon oil, thyme oil, mustard oil, oregano oil, lavender oil, eucalyptus oil, and peppermint oil, etc. They play a vital role in the inhibition of pathogenic microbial growth and food preservation. For example, the terpenes and the oxygenated terpenes in lemon essential oil, showed significant antifungal potential against *Candida* spp. such as *C. albicans*, *C. tropicalis*, and *C. glabrata* [33]. Cinnamon oil is a volatile compound extracted from the bark, leaf, and root of *Cinnamomum zeylanicum*. It contains three important components such as *trans*-cinnamaldehyde, eugenol, and linalool (obtained from the bark extract), which represent 82.5% of the total composition. Cinnamaldehyde is the most active compound of cinnamon EOs, which showed inhibitory effects on the growth of various pathogens including both gram negative and positive bacteria and possesses potential growth inhibitory effects on fungi [34,35]. Several studies revealed that the cinnamon EOs also had antioxidant, antiparasitic and free radical scavenging properties [36]. Moreover, the tea tree oil (TTO) from *Melaleuca alternifolia* (*Myrtaceae*) majorly contained terpinen-4-ol, γ-terpinene, *p*-cymene, *α*-terpinene, 1,8-cineole, *α*-terpineol, and *α*-pinene [37]. It showed a strong inhibitory activity on fungal strains [38]. Clove oil is mostly extracted from clove buds and it contains the phenylpropanoids viz. eugenol, eugenyl acetate, carvacrol, thymol, cinnamaldehyde, *β*-caryophyllene, and 2-heptanone, as major compounds. Among those, eugenol is widely used as an antimicrobial agent, could reduce the synthesis of ergosterol, a specific cell wall component and could inhibit the germ tube formation in *C. albicans.* It showed strong radical scavenging activity when tested against tert-butylated hydroxytoluene and revealed inhibitory effects on multi resistant *Staphylococcus* spp. [39]. Lavender oil is majorly extracted from the family Lamiaceae, especially, *Lavandula angustifolia* by steam distillation and it was found to contain linalool, linalyl acetate (3,7-dimethyl-1,6-octadien-3yl acetate), linalool (3,7-dimethylocta-1,6-dien-3-ol), lavandulol, 1, 8-cineole, lavandulyl acetate, *B*-ocimene, terpinen-4-ol, l-fenchone, viridiflorol and camphor as major components [40,41]. However, the concentration levels of these compounds were varying from species to species. Linalool is one of the active compounds in lavender oil [42]. Lavender oil showed antibacterial activity against antibiotic resistant bacteria, yeasts, dermatophytes, *Cryptococcus neoformans, Aspergillus* strains and *C.* species [43,44]. Eucalyptus oil comprises of 1,8-cineole as the major compound and have other compounds such as cryptone, *α*-pinene, *p*-cymene, *α*-terpineol, *trans*-pinocarveol, phellandral, cuminal, globulol, limonene, aromadendrene, spathulenol, and terpinene-4-ol [45]. EOs extracted from eucalyptus are mainly used as flavoring agents and showed significant activities in controlling the growth of pathogenic and food spoilage microorganisms [46,47]. Table 1 demonstrated that the major components of EOs and their biological activity. The bioactive compounds of EOs, especially, antimicrobial and antifungal compounds may target various cell structures or chemical pathways such as cell wall degradation, membrane damage and disruption of proton motive force etc. However, there is limited data on the mechanism of antibacterial and antifungal activities of eucalyptus oil. It was noticed that the antimicrobial activity was highly related to the synergic effects between the major and minor compounds present in eucalyptus oil rather than a single compound [45]. Among the eight different species of eucalyptus, EOs extracted from *Eucalyptus odorata* showed strong cytotoxic effects and inhibitory activities against *S. pneumonia, S. aureus*, *H. influenza* and *S. pyogenes* [45]. Peppermint oil showed momentous growth inhibitory activity on *Staphylococci.* Several studies reported that it exhibited antifungal activity against both standard and clinical pathogenic fungal strains of *Candida* species at IC_{50} concentrations ranging from 0.5 to 8 μg/mL, and showed good antifungal effects on azole-resistant and azole-susceptible strains [48].

7. Antimicrobial activity of EOs

EOs and their constituents play a key role in exerting antimicrobial activity. Due to their hydrophobic nature, EOs significantly move across the lipids of the cell membranes of bacteria, disrupt the cell wall structures, and make them more permeable [49]. This membrane permeability change leads to the leakage of ions and other cellular materials [50], leading to cell death. EOs show both single and multiple target activities. For example, *trans*-cinnamaldehyde, one of the major compounds of EOs have the proficiency to control the growth of *E. coli* and *S. typhimirium* by depleting the intracellular ATP levels. It also gains access to the periplasm and deeper portions of the cell. Carvone is another important EOs constituent, which disrupts the outer membranes of the cells but does not affect the cellular ATP pools [51]. Antibacterial activities of EOs are highly associated with the presence of major compounds, namely, cinnamaldehyde, citral,

Table 1
The major components of EOs and their biological activity.

Compound	Chemical structure	Source	Activity
(-)-Menthol		Peppermint or mint oils	Antioxidant, antimicrobial, anti-inflammatory
Linalool		Lemon and cinnamon oil	Antimicrobial, antioxidant, insecticide
Farnesol		Rose oil, citronella oil	Antiseptic, antibacterial, anti-inflammatory
Eugenol		Clove oil	Antiseptic, antibacterial, antifungal, anaesthetic
Carvone		Caraway, spearmint oil	Aromatherapy and complementary medicine

carvacrol, eugenol, or thymol which belongs to the phenol shows significant activity, followed by terpenes and other compounds including ketones (β-myrcene, α-thujone, or geranyl acetate) shows weaker activity and hydrocarbons are mostly inactive [52]. Carvacrol, eugenol, and thymol, are the major active compounds, which effectively inhibit the growth of microorganisms by disrupting the cell membranes, leading to the alterations in electron flow, driving force of protons and active transport, and coagulation of cell contents. Fig. 2 represents the different actions of EOs on microorganisms [53].

EOs comprises several bioactive compounds including terpineol, thujanol, myrcenol, neral, thujone, camphor, and carvone, etc., which show significant activities. Among those, carvacrol has a high activity with less toxicity; hence, it is widely used in food products such as drinks and sweets as a preservative and flavoring agent. Generally, EOs are more active in gram-positive bacteria due to the presence of peptidoglycan layer, which lies outside the outer membrane. In gram-negative bacteria, the outer membrane is composed of a double layer of phospholipids, which is linked with the inner membrane by lipopolysaccharides (LPS). LPS consist of three basic components such as lipid A, a core polysaccharide and O-side chain, which are responsible for the resistance of the gram-negative bacteria to EOs. The presence of hydrophilic transmembrane channels in the outer membrane plays a key role in the transfer of small hydrophilic solutes through outer membranes. The interactions of EOs with the outer membrane restrict the diffusion of hydrophobic drugs through its lipopolysaccharide film [54]. Furthermore, the major compounds present in EOs and the properties of volatile compounds and their interactions may enhance the antibacterial activity. In some cases, the combination of one or two compounds shows greater activity than when used individually. However, synergistic effects are also observed when they are used in combination and several studies reported that the use of whole EOs would show greater activity than that of the major compounds used in combination [2]. For example, the combined activity of volatile compounds and benzoic acid derivatives against the microorganisms such as L. *monocytogenes* and *S. enteritidis* showed higher inhibitions than the sum of the inhibitory effects of the individual components [55].

EOs extracted from *S. aromaticum* (clove) and *Rosmarinus officinalis* showed increased antifungal effects against *C. albicans* when they were used in combination [56]. Lambert et al. [47] reported that the combination of carvacrol and thymol showed higher activities against *S. aureus* and *P. aeruginosa* while using half-fold dilutions. Another report suggested the synergistic effects of the combined use of cinnamaldehyde with thymol or carvacrol against *S. typhimirium* and the results showed two different hypotheses. One of the mechanisms suggested that the combination of cinnamaldehyde with thymol or carvacrol could have altered the membrane permeability to facilitate easily entry into the cell. Another one proposed that this combination could have increased the number, size, or duration of the existence of the pores in the cell membrane by binding with cell membrane proteins [57].

Terpenoids are one of the major compounds present in EOs and have oxygen atoms or methyl groups, which are localized or removed from specific enzymes by which they show greater activities. The well-known terpenes such as thymol, carvacrol linalool, and menthol show enhanced antimicrobial activities due to the presence of highly active functional groups, which delocalized electrons [52]. Monoterpene *p*-Cymene, the precursor of

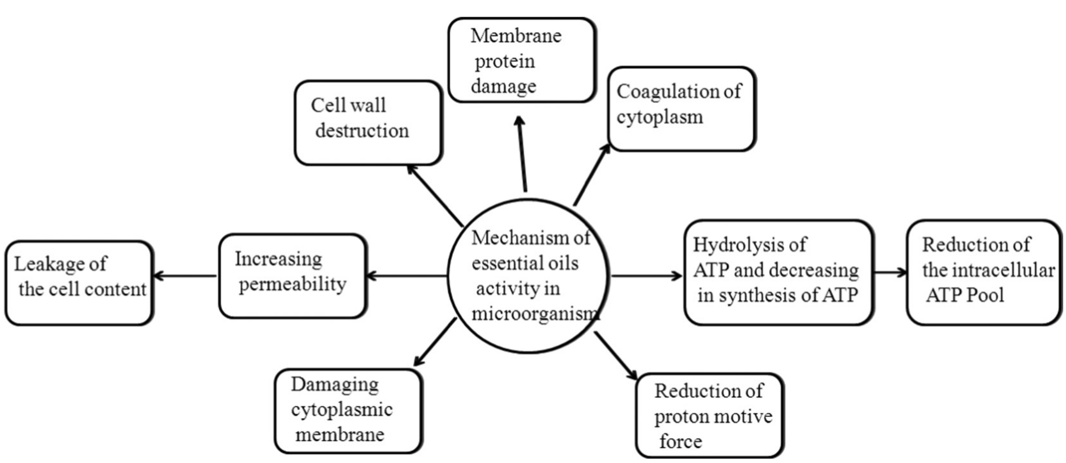


Fig. 2. Different kind of mechanism of EOs activity on microorganisms.

carvacrol, has a benzene ring, and shows high affinity for microbial membranes and can perturb the cell membrane potential. However, it does not affect the membrane permeability, but it significantly decreases the enthalpy and melting temperature of the membrane. Several studies reported its antimicrobial activity individually and in combination with other carvacrol derivatives. In the combination study, *p*-Cymene increased the antimicrobial activities of other compounds [31]. Thymol also induces the release of lipopolysaccharides, but it does not affect the chelation of cations and integrates within the polar head groups of the lipid bilayer, which leads to cell membrane alteration. At low concentrations, the cell membrane can adapt to maintain its structure and function. It can interact with cell membrane proteins at different sites within cell and affect a variety of cellular functions. Like thymol, carvacrol is another phenolic monoterpenoid, which could act on microbial cells and cause cell membrane damage both at structural and functional levels and result in increased permeability [58–60]. Some other studies also reported that the components of EOs could lead to loss of microbial viability by destabilization of phospholipid bilayer, especially, the destruction of plasma membrane function and structural composition through inactivation of enzymatic mechanisms. In some cases, EOs have altered the membrane permeability by another kind of mechanism, i.e., they have destroyed the electron transport system, which led to increase in the intracellular ATP concentration. Inhibition of electron transport system subsequently leads to energy production, synthesis of proteins and translocation, and disrupting proton motive force, and synthesis of other cellular components that result in cell lysis and death [58]. Recently, researchers focus to investigate the antimicrobial effects of herbal products to find new, less or nontoxic, therapeutic and antipathogenic inhibitors of quorum sensing [61]. Cell membrane integrity is playing a crucial role in cell survival and fundamental biological activities of bacteria. Cell membrane acts as an effective barrier between the cytoplasm and its environment; in the presence of antimicrobial compounds around the microorganisms, it may alter the synthesis of fatty acids and membrane proteins to modify the membrane fluidity as a defense mechanism [62]. At a specific cell density, bacteria can communicate and coordinate both bacterial interactions and associations through unique intracellular communication, known as quorum sensing. Quorum sensing system regulates the production of chemical signaling molecules. EOs and volatile compounds such as cinnamaldehyde, have been investigated from diverse points of view. Brackman et al. [63] reported that 60 μmol concentration of cinnamaldehyde and cinnamaldehyde derivatives reduced virulence of *V. anguillarum, V. harveyi*, and *V. vulnificus* by decreasing the DNA-binding activity of the quorum sensing response regulator LuxR.

8. Antioxidant activity of EOs

The antioxidant potential of EOs mainly depends on their chemical compositions. Phenolic and other secondary metabolites bind with double bonds, which is responsible for the substantial antioxidant activity of EOs [64]. EOs extracted from traditional plants such as *Achillea filipendulina*, *Galagania fragrantissima*, *Anethum graveolens, A. rutifolia, Hyssopusseravschanicus, Mentha longifolia,* and *Ziziphorac linopodioides* are rich sources of oxygenated monoterpenes such as aldehydes, ketones, and esters. In addition, monoterpene hydrocarbons (*A. absinthium* and *A. scoparia*) and phenolic terpenoids, such as thymol or carvacrol (*O. tyttanthum* and *Mentha longifolia*) are the major chemical compounds, which result in the strongest antioxidant activities.

Thymol and carvacrol are important monoterpenes present in several types of EOs extracted from *O. tyttanthum*, *Mentha longifolia* and *Thymus serpyllus*, and they play a key role in the antioxidant properties [65]. The oils extracted from the medicinal plants such as cinnamon, nutmeg, clove, basil, parsley, oregano, and thyme show significant antioxidant activities due to the presence of major constituents such as thymol and carvacrol [66]. Mainly, their activities are related to the presence of phenolic compounds that have significant redox properties and play important roles in neutralizing free radicals and in peroxide decomposition [2]. The other components such as certain alcohols, ethers, ketones, aldehydes, and monoterpenes: linalool, 1,8-Cineole, geranial/neral, citronellal, isomenthone, menthone, and some monoterpenes also play a key role in the antioxidant properties of EOs [67].

9. Role of EOs on cereal disease control

Pathogenic fungi mediated crop diseases mainly affect cereal production. In addition, these pathogenic fungi are able to produce a huge number of mycotoxins, which pose highly negative effects on health of animals and humans. According to Morcia et al. [68], it has been estimated that more than 23 million kg per year of chemical based fungicides are used in the Western and developing countries. Numerous reports demonstrated the use of EOs and their value added metabolites to control the pathogenic fungi to improve the quality and safety of crop protection. The antimicrobial properties of natural biocides with nontoxic features can be consequently used to at different ratios to estimate crop diseases and their quality characteristics in open field trials. Table 2 illustrates that EOs based commercial products. The effects of a natural biocide are different from that of the traditional pesticide in the field crops. Indeed, the trial performance of chemical pesticides can demonstrate a high level of effectiveness in contrast with the EOs.

However, EOs based biocides can be used in combination with traditional pesticides, allowing more flexible treatment periods, rising the shelf lives of traditional fungicides and assuring safety working environment to the farmers. In addition, EOs have few drawbacks such as instability and volatility but have even distinctive features and profits, such as reduced preharvest restrictions, less toxic to human and animal health, possibility of utilization even in sensitive environmental areas, suitability for all types of farming, including certified organic production system. EOs based fungicides play a key role on different crop production farms as evaluated by the Integrated Pest Management System, in which some different strategies act in a synergic way to guarantee high quality and high value yield.

10. Future aspects

EOs are vital and play crucial roles in crop protection and food industry with a wide range of applications. EOs significantly inhibits the growth and reduction in density of more serious pathogens such as *Salmonella* spp., *E. coli, Candida* spp., and improve the crop protection against plant pathogenic microbes. Hence, there is a need for understanding the mechanisms behind the antimicrobial, antioxidant and antifungal effects of EOs and their interactions. The usage of one or more synergists can produce the desirable aroma and flavor without any ill effects to the food products; hence, the use of EOs in food industries and in consumer goods is expected to increase in the future [69]. The use of clove and oregano oils may produce a dark pigmentation when in contact with iron and this may lead to adverse effects. Hence, the understanding of the basis for microbial resistance or sensitivity, the stability of EOs during food processing and the study of bacterial adaptation ion in the presence of EOs in food are also important for further evaluation.

Table 2
EOs based commercial products for crop protection.

EOs source	Commercial name
Allium sativum	GC-3™
Azadirachta indica	Trilogy™
Gossypium hirsutum	GC-3™
Melaleuca alternifolia	Timor™, Timorex™
Mentha	Fungastop™
Reynoutria sachalinensis	Milsana™
Rosmarinus officinalis	Sporan™
Rosemary, thyme and clove oils	Sporatec™
Sesame	Organocide™
Simmondsia californica	*E*-Rase™
Thymus vulgaris	Promax™

11. Conclusion

Several types of EOs and their individual components are used as natural antimicrobial compounds in order to reduce the impact of microbial activities in food products. Mostly, the phenolic components of the EOs are effectively acting as membrane permeabilizers. Compared to the gram-negative bacteria, the gram-positive bacterial strains are more sensitive to EOs and their bioactive compounds. Thymol, carvacrol and cinnamaldehyde are the major components present in EOs, which are responsible to maximize the antimicrobial activity through various aspects including alteration of the membrane permeability, changes of membrane fatty acids and inhibition of the protons motive force. In some cases, the microencapsulated edible film or coating with EOs along with antimicrobial agents, effectively enhance the safety and quality of cereals and food products, which need to be investigated in future studies.

Declaration of Competing Interest

All the authors confidently declare that there is no conflict of interest.

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