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Review

Unlocking Essential Oils' Potential as Sustainable Food Additives: Current State and Future Perspectives for Industrial Applications

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Abstract: Essential oils (EOs) comprise a relevant bioactive fraction from diverse plant sources and vegetable tissues. Their beneficial properties have been mainly related to the presence of bioactive molecules such as monoterpenes and sesquiterpenes, among others, with beneficial properties against critical issues in the food industry that could promote sustainable production beyond organoleptic boosters. This review collects up-to-date information concerning EOs and their bioactive applications in the food field. In addition, a bibliometric analysis was applied to scientific and intellectual property databases to elucidate the current technological trends for EOs in the food sector. Thus, the current information on the evaluation of EOs in food systems has demonstrated that their application guarantees safe and high-quality foods, as they have the potential to partially replace some of the conventional synthetic antioxidants and antimicrobial agents according to sustainable trends.

Keywords: green additives; bioactive compounds; natural preservatives; sustainable food supply chain

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1. Introduction

Essential oils (EOs) comprise a volatile, aromatic, oily liquid fraction extracted from plants, containing small, lipophilic, and non-polar molecules of industrial interest [1]. Their application dates back 6000 years to aromatherapy [2]. EOs are primarily associated with the aroma sector and have beneficial and auxiliary properties against disorders such as anxiety and stress [3]. However, it is widely recognized that EOs possess properties beyond their aromatic characteristics. For example, traditional medicine has utilized EOs to combat common illnesses, including microbial and viral infections, inflammatory processes, and gastrointestinal disorders [2,4]. Moreover, the application of EOs is not only restricted to the health sector. Several studies have started significant results in the food field when incorporating EOs into food products. In recent decades, the potential applications in the food field have been elucidated, mainly highlighting their remarkable antioxidant and antimicrobial properties to extend the shelf-life by retarding the microbial growth or oxidation processes [5–7].

Alongside this, current trends have shifted their focus toward sustainability, aiming to develop production processes with greater environmental awareness, resource efficiency, and social responsibility. Thus, the EOs have been highlighted as a potential novel sustainable additive for the food industry. Consequently, the scientific literature has identified three well-defined areas of research: (1) the search for new sources of essential oils (EOs) such as chemical characterization, bioactivities, and toxicity, as evidenced by studies conducted on *Atractylodes macrocephala* Koidz and *Bassia muricata* [4,8]; (2) the development of novel chemical stabilization technologies (such as emulsions, encapsulations, among others) without evaluating their application within a food matrix; and finally, (3) the evaluation of their application in food matrices through encapsulations, microemulsions, new packaging, or novel formulations, thereby generating innovative proposals across different production areas [9,10], with the objective of fostering the development of more sustainable production methods.

The development of these new integrative methods will allow the efficient application of the beneficial activities, particularly antioxidants and antimicrobials associated with EOs. This is a significant issue, as the incorporation of “green additives” has garnered considerable consumer interest in recent years.

Thus, EOs present a green and environmentally friendly alternative for the development of food additives, providing desired characteristics or incorporating properties that stabilize food products against unfavorable conditions such as microbiological contamination and oxidation. This review encompasses a compilation of studies carried out on EOs for their application in foods, highlighting current technological advancements and potential areas of research for the future under a sustainable vision.

2. Materials and Methods

2.1. Data Sources and Research Method

This review was conducted by considering those papers available in scientific databases (ScienceDirect www.sciencedirect.com and Scopus www.scopus.com, accessed on 2 March 2024), primarily focusing on publications between 2020 and 2023. The search utilized the following keywords: “essential oil”, “essential oil food product”, “essential oil chemical composition”, and “bioactive properties of essential oils”. Furthermore, to assess trends in the intellectual property applications of essential oils, a search for patents was conducted in databases “PATENTSCOPE” (www.wipo.int/patentscope/en/, accessed on 2 March 2024) and “Google patents” (https://patents.google.com/, accessed on 2 March 2024), using the same keywords.

2.2. Trends Analysis by VOS Viewer

The trend analysis applied the VOS viewer software version 1.6.8 to visualize research information obtained from Scopus database (as of 2 March 2024) using the keywords “Essential oil” and “Food product”. The database search showed 576 research documents. To develop the co-occurrence analysis, a thesaurus file was created to avoid repetitions and synonyms in keywords (e.g., essential oil/essential oils or antioxidant activities/antioxidant activity).

2.3. Essential Oils Historical Trade Data

For this point, the data were obtained from OEC website (https://oec.world/) using the following codes: SITC 705513 for a general perspective, 330113 (HARMONIZED SYSTEM 1992 FOR 6-DIGIT) for lemon essential oils, 330124 (HARMONIZED SYSTEM 1992 FOR 6-DIGIT) for peppermint essential oil and 330112 (HARMONIZED SYSTEM 1992 FOR 6-DIGIT) for orange essential oils. The products are classified under Section

VI (chemical products), specifically 33 (perfumery and cosmetics), with the code 33.01 (essential oils). The most recent available data cover the period from 2008 to 2018. The data were downloaded and analyzed using both a spreadsheet and the "stacked" tool on the OEC website.

3. Extraction and Production of Essential Oils: Sustainable Vision

3.1. Current State of Sustainable EO Production

The production of EOs is a topic of significant interest for the industry due to various factors impacting their production. The main challenges include: (1) The extraction method, and (2). Productive conditions (biotic and abiotic). Additionally, factors such as genetics and onto-genetics can influence the chemical composition of EOs, potentially compromising their bioactive potential [11].

3.1.1. Sustainable Extraction Methods

In the field of extraction processes, recent trends have focused on adhering to principles recommended by Chemat et al. [12]: (1) use renewable resources, (2) alternative solvents (beyond organics), (3) lower energy consumption, (4) generate by-products with potential applications into agro-refinery, (5) reduce unit operations, and (6) biodegradable extracts without contaminants. Moreover, Majid et al. [13]) emphasized the "e3 concept", which encompasses three principles: energy efficiency, environmental sustainability, and recovery of natural additives. These principles align closely with sustainable practices: (1) defined recovery processes, (2) low use of organic solvents, (3) reduced energy consumption, (4) valorization of by-products, (5) short production times, and (6) recovery of natural additives. Generally, the extraction process starts with the removal of impurities (e.g., dirt, insects, or other external material) followed by a drying process. The recovered dried sample is suitable according to standard procedures for extraction, which could employ different extraction times and techniques, as well as plant parts (leaves, flowers, seeds, or the whole plant). Regarding the extraction techniques, conventional techniques (hydro and steam distillation) have been the most widely applied methodologies for obtaining EOs (Table 1). However, non-conventional techniques such as supercritical fluid extraction "SFE", microwave-assisted extraction "MAE", and ultrasonic-assisted extraction "UAE" have been successfully applied to obtain EOs from several plant materials with higher yields compared to the conventional methods [14–17]. For example, the higher recovered EO yields from *Rosmarinus officinalis* obtained from SCFE (3.03%) than hydro distillation (0.6%); the lower yield is based on the contact of plant material with hot water, which could lead to losses of the volatile portion if there is not a well-controlled extraction process [14]. Additionally, the sustainability of conventional methods such as HD has been evaluated by Katekat et al. [16]; their findings highlighted that the carbon footprint of conventional HD is higher compared with non-conventional or hybrid methods.

Further, non-conventional techniques can promote a better disruption of the cell walls of the plant, facilitating the extraction of internal components or allowing higher extraction yields [17]. Ongoing efforts focus on hybridizing extraction methods to achieve better operational benefits. For example, incorporating a cold plasma pretreatment has been shown to enhance extraction yield and antioxidant activity due to cellular damage induced by the pretreatment, which improved the extraction capacity [18]. Other researchers have highlighted the various technological advantages of hybrid methods, such as integrating UAE and SFE. These advantages include cost-effectiveness, durability, selectivity, and scalability potential to meet current market demands [19,20]. However, it is important to highlight that the scalability of the process englobes a critical challenge; Belwal et al. [21] elucidated the challenges for UAE and SFE technologies such as vessel geometry, solvent type, batch/flow mode, solvent/biomass ratio, and dissipation factor, among others. Thus, beyond good lab-scale results, the next barrier to sustainability in EO extraction will be scale-up.

Regarding the chemical composition, although no consistent correlation has been observed between chemical components in studies using the same extraction technique, it was observed that monoterpenes and sesquiterpenes are the main compounds identified in the reviewed studies. Table 1 shows five of the main compounds identified in each study, with the most common compounds being as follows: terpinene isomers > caryophyllene isomers and derivatives > pinene isomers > thymol > *p*-cymene > linalool > limonene > carvacrol = α-terpineol > other uncommon components. The differences in the chemical composition and quantities of EOs extracted from various plant materials can also be attributed to genetic factors among the species, as well as climate conditions, harvest time, and geographic origin, which all have a strong impact on the quality of the EOs [17,22,23]. While the scientific community has made significant efforts in developing new hybrid methods to enhance EO extraction, it is crucial to expedite the incorporation of advanced equipment in production facilities, increase technical knowledge, and reduce the potential high production costs.

Table 1. Extraction, characterization, and main component of essential oils.

EO Origin	Plant Tissue	Extraction Method	Time (Min)	Extraction Yield (%)	Total Compounds	Main Components	% from the Extracted Oil	Class of Compound	Reference
Zataria multiflora	NI	NI	NI	NI	35	Carvacrol Thymol Linalool Carvacrol methyl esther Trans-Caryophyllene	47.65 17.52 12.93 1.72 1.34	monoterpene monoterpene monoterpene monoterpene sesquiterpene	[24]
Thymus daenensis	Aerial parts	Hydrodistillation	180		32	Thymol γ-terpinene *p*-Cymene α-Terpinene β-Myrcene	40.69 30.28 11.13 5.52 2.47	monoterpene monoterpene monoterpene monoterpene monoterpene	[25]
Satureja hortensis	Aerial parts	Hydrodistillation	180		18	Thymol γ-terpinene *p*-Cymene α-Terpinene β-Myrcene	41.28 37.63 12.2 3.59 1.42	monoterpene monoterpene monoterpene monoterpene monoterpene	
Cymbopogon citratus	Aerial parts	Hydrodistillation	240	NI	24	Geranyl acetate Geraniol Citronella Patchouli alcohol Citronellyl acetate	19.72 19.02 17.83 7.46 6.5	monoterpene monoterpene monoterpene sesquiterpene monoterpene	[26]
Ocimum africanum	Aerial parts	Hydrodistillation	240	NI	10	Estragole Linalool α-Bisabolene β-Caryophyllene Geranial	69.93 22.64 2.48 1.22 1.03	monoterpene monoterpene sesquiterpene sesquiterpene monoterpene	
Sysygium aromaticum	Floral buds	Steam distillation	180	1	3	Eugenol Caryophyllene α-Caryophyllene	56.06 39.63 4.31	monoterpene sesquiterpene sesquiterpene	[27]
Cannabis sativa	Aerial parts	Hydrodistillation	180	2.7	24	*E*-Caryophyllene α-Humulene Caryophyllene oxido Myrcene Linalool	35 12.8 10.6 4.5 3	sesquiterpene sesquiterpene sesquiterpene monoterpene monoterpene	[28]
Ferulago angulete	NI	Steam distillation	NI	NI	30	*Cis*-Ocimene α-Pinene Trans-β-ocimene γ-terpinene Germacrene-D	30.17 15.43 5.74 5.57 5.03	monoterpene monoterpene monoterpene monoterpene sesquiterpene	[29]

Table 1. *Cont.*

EO Origin	Plant Tissue	Extraction Method	Time (Min)	Extraction Yield (%)	Total Compounds	Main Components	% from the Extracted Oil	Class of Compound	Reference
Trachyspermum ammi	Whole commertial plant	Hydrodistillation	180–240	NI	14	Thymol para-cimene γ-Terpinene α-Terpinene α-Thujene	40.4 23.1 21.4 3.4 2.7	monoterpene monoterpene monoterpene monoterpene monoterpene	[30]
Foeniculum vulgare	Organic seeds	Hydrodistillation	240	1.37–4.3	9	*E*-Anethole Limonene Methyl chavicol (Estragole) Fenchone *p*-anisaldehyde	81.21 5.17 3.97 2.14 1.44	monoterpene monoterpene monoterpene monoterpene other	[31]
Foeniculum vulgare	Conventional seeds	Hydrodistillation	240	1.37–3.24		E-Anethole Methyl chavicol (Estragole) Limonene Fenchone *p*-anisaldehyde	65.61 10.81 6.78 5.12 2.3	monoterpene monoterpene monoterpene monoterpene other	
Curcuma longa	Leaves	Steam distillation	320	NI	20	α-Phellandrene α-Terpinolene 1,8 Cineole Benzene 2-β-Pinene	46.7 17.39 8.78 4.24 3.64	monoterpene monoterpene monoterpene other monoterpene	[32]
Origanum majorana	NI	NI	NI	NI	10	Terpinen-4-ol α-Terpineol Linalool Caryophyllene γ-terpinene	28.92 16.75 11.07 5.09 3.49	monoterpene monoterpene monoterpene sesquiterpene monoterpene	[33]
Laurus nobilis	Flowers	Hydrodistillation	150	1.06	25	1,8 Cineole α-Caryophyllene germa-cradienol Limonene α-Pinene	45.01 7.54 6.13 4.69 3.04	monoterpene sesquiterpene sesquiterpene monoterpene monoterpene	[34]

Table 1. *Cont.*

EO Origin	Plant Tissue	Extraction Method	Time (Min)	Extraction Yield (%)	Total Compounds	Main Components	% from the Extracted Oil	Class of Compound	Reference
Elettaria cardamomum	Fruits	Hydrodistillation	180	3.74	22	α-Terpinyl acetate	42.65	monoterpene	[35]
						α-Terpineol	2.98	monoterpene	
						Linalool	2.72	monoterpene	
						Limonene	2.32	monoterpene	
						4-Terpineol	1.85	monoterpene	
Curcuma longa	Rhizome	Hydrodistillation	180	0.25	44	β-Turmerone	25.77	sesquiterpene	
						Ar-Turmerone	12.28	sesquiterpene	
						β-sesquiphellandrene	10.44	sesquiterpene	
						α-zingibernene	5.13	sesquiterpene	
						α-Phellandrene	1.33	monoterpene	
Zingiber officinale	Rhizome	Hydrodistillation	180	0.29	NI	α-zingibernene	22.69	sesquiterpene	
						β-sesquiphellandrene	10.08	sesquiterpene	
						Limonene	7.9	monoterpene	
						D-germacrene	2.79	sesquiterpene	
						α-farsesene	2.26	sesquiterpene	
Alpinia officinarum	Rhizome	Hydrodistillation	180	0.35	53	α-Terpineol	11.11	monoterpene	
						β-pinene	3.85	monoterpene	
						α-Pinene	3.56	monoterpene	
						Limonene	2.76	monoterpene	
						4-Terpineol	2.29	monoterpene	
Zataria multiflora	Commercial				6	Thymol	39.14	monoterpene	[36]
						Carvacrol	26.61	monoterpene	
						p-Cymene	7.88	monoterpene	
						γ-terpinene	6.57	monoterpene	
						α-Pinene	3.34	monoterpene	
Cinnamomum zeylanicum	Commercial				5	*E*-Cinnamaldehyde	97.83	other	
						Eugenol	0.48	monoterpene	
						Menthol	0.26	monoterpene	
						Menthone	0.15	monoterpene	
						Camphor	0.16	monoterpene	

Table 1. *Cont.*

EO Origin	Plant Tissue	Extraction Method	Time (Min)	Extraction Yield (%)	Total Compounds	Main Components	% from the Extracted Oil	Class of Compound	Reference
Syzygium aromaticum	Commercial				11	Eugenol	78.42	monoterpene	
						Caryophyllene	11.49	sesquiterpene	
						Eugenol acetate	6.23	monoterpene	
						α-Humulene	1.32	sesquiterpene	
						α-Copaene	0.85	sesquiterpene	
Zataria multiflora	Commercial				20	Carvacrol	48.19	monoterpene	[37]
						Linalool	23.91	monoterpene	
						Cymene	5.52	monoterpene	
						Thymol	4.13	monoterpene	
						γ-terpinene	2.56	monoterpene	
Mentha longiflora	Leaves	Hydrodistillation	240		19	Pulegone	47.2	monoterpene	[38]
						Eucalyptol	22.72	monoterpene	
						Menthone	13.44	monoterpene	
						β-pinene	2.79	monoterpene	
						Sabinene	1.5	monoterpene	
Thymus vulgaris	NI	Steam distillation	NI	NI	19	Thymol	30	monoterpene	[39]
						p-Cymene	13.78	monoterpene	
						cis-a-Bergamotene	6.7	sesquiterpene	
						γ-terpinene	4.51	monoterpene	
						Anethole	4.33	monoterpene	
Thymus vulgaris	NI	NI	NI	NI	15	Thymol	43.63	monoterpene	[40]
						p-Cymene	22.86	monoterpene	
						Bornyl acetate	8.7	monoterpene	
						γ-terpinene	6.56	monoterpene	
						β-Caryophyllene	5.65	sesquiterpene	
Cuminum cyminum	NI	NI	NI	NI	16	Cuminaldehyde	30.9	other	
						Sabinene	14.3	monoterpene	
						p-Cymene	13.9	monoterpene	
						γ-Terpinene	12.6	monoterpene	
						Cuminyl alcohol	11.5	monoterpene	

Table 1. *Cont.*

EO Origin	Plant Tissue	Extraction Method	Time (Min)	Extraction Yield (%)	Total Compounds	Main Components	% from the Extracted Oil	Class of Compound	Reference
Coriandrum sativum	Fruit	Hydrodistillation	240	0.28	32	Linalool	62.2	monoterpene	[41]
						Geranyl acetate	10.9	monoterpene	
						γ-Terpinene	10.2	monoterpene	
						decanal	3.8	aldehyde	
						α-Pinene	3.2	monoterpene	
Rosmarinus officinalis	Aerial parts (leaves and flowers)	Hydrodistillation	240	0.6	25	α-Pinene	33.5	monoterpene	[14]
						Eucalyptol	16.6	monoterpene	
						Limonene	10.123	monoterpene	
						β-Linalool	7.9	monoterpene	
						Camphor	6	monoterpene	
Rosmarinus officinalis	Aerial parts (leaves and flowers)	Supercritical fluid extraction (CO_2)	120	3.03	21	α-Pinene	38	monoterpene	
						Eucalyptol	21	monoterpene	
						Camphor	8.5	monoterpene	
						Camphene	5.9	monoterpene	
						Bornyl acetate	4.4	monoterpene	
Carum copticum	Commercial				18	Thymol	62.5	monoterpene	[42]
						γ-terpinene	19.4	monoterpene	
						p-Cymene	10.7	monoterpene	
						Carvacrol	1.16	monoterpene	
						β-pinene	1.05	monoterpene	

NI: No information.

3.1.2. Sustainable Production Systems

In the framework of sustainability, certain factors have been identified as critical for the production and quality of EOs, such as environmental conditions and the production process [11,43]. In response, recent years have seen the study and development of new production systems, such a "greenhouse" production, aimed at optimizing resources (water, fertilizers, time, temperature, etc.) to enhance production and quality. While conventional greenhouse systems involve soil-based cultivation, there is growing interest in hydroponic systems. Farvardin et al. [44] highlighted several benefits of this technology, including (1) reduced cultivation area, (2) lower water consumption, (3) environmental parameters control, (4) improved quality, (5) reduced fertilizer use, and (6) better plant nutrition management. This last aspect is particularly important for production because plants require specific concentrations of nutrients to maximize biomass or secondary metabolite production. For example, Chrysargyris and Tzortzakis [45] demonstrated the impact of varying nitrogen, potassium, and phosphorus concentrations on the production of phenolic compounds, antioxidant activity, and specific metabolites (carvacrol and p-cymene) in Origanum dubium. They found that under specific conditions, carvacrol and p-cymene production could increase and also had the potential health benefits.

Additionally, in crops such as basil (*Ocimum basilicum* L.), hydroponic systems have been used to achieve greater economic value due to the presence of target metabolites (methyl chavicol). However, field methods yielded higher concentrations of bioactive components [46]. This indicates that production systems can be selected based on specific market demands, and it is possible to develop future research aimed at optimizing the specific production of biomass, EO, or particular chemical components.

Furthermore, the sustainability of EO production has also been explored through research focused on process development by incorporating residual materials. For example, lemongrass (*Cymbopogon citratus*) leaf waste has been evaluated as a new source of EOs, using different methods to enhance recovery and quality [47]. Another approach involves dual-purpose methods, such as recovering pectin and EOs from *Citrus maxima* peel waste, which could offer a solution for agro-industrial waste management [48].

Thus, sustainable EO production represents a key area of interest for the current scientific community, which seeks not only to utilize EOs as sustainable components in the food industry but also to develop a sustainability chain from production to application.

4. Functional Properties

The search for sustainable bioactive compounds has highlighted the potential of EOs as a bioactive fraction of interest to the food industry, particularly for novel food development. However, among the functionalities of EOs, their antimicrobial and antioxidant properties comprise the most extensively studied within the food field.

4.1. Antioxidant Potential

In the industry, antioxidants are attractive compounds due to their protecting capacity against oxidative processes that affect the food matrix. These unwanted changes are responsible for reducing sensorial attributes by altering flavor (rancidity) and color. Nowadays, the search for novel green antioxidants has been a hot topic to find alternatives for conventional synthetic industrial antioxidants, which may have adverse effects [49]. The EOs, mainly due to the presence of compounds such as terpenes (thymol and carvacrol) and oxygenated terpenes with remarkable antioxidant synergy, are a potential source of interest for novel antioxidants. Thus, in the last decade, evaluations of crops well-known as EO sources have increased, including examples such as laurel (*Laurus nobilis* L.) and Greek oregano (*Origanum vulgare*) [34,50]. Additionally, research efforts have highlighted other compounds in EOs with antioxidant potential beyond thymol and carvacrol. For example, the EOs in the ginger family have been identified as a source of antioxidants, containing compounds such as α-terpinyl acetate, β-turmerone, α-zingiberene, and 1,8-cineol [35]. Similarly, other EOs with the presence of juniper camphor, α-sinensal, and 6-epi-shyobunol as major components have shown strong antioxidant activity [51].

However, the antioxidant mechanism can vary. For example, López et al. [52] and Amorati et al. [53]) defined three antioxidant classes according to their action mechanisms: the "preventive antioxidants", where the antioxidant interfere with the initiation process; the "chain-breaking antioxidants" (phenolic terpenes), where a phenolic group in the chemical structures donates a hydrogen atom to a lipid radical; and the "termination-enhancing antioxidants", which involve the production of a non-phenolic terpene radical that interact with a radical leading to a termination reaction. Understanding the antioxidant mechanism involved in EO compounds is an alternative area to research to identify the best chemical interactions for optimal antioxidant food protection.

4.1.1. EO as Potential Novel Sustainable Antioxidant Additives

The application of synthetic antioxidant additives (e.g., BHA and BHT) has been a debatable topic in the consumers' opinion due to the growing awareness of healthy food choices [54]. Current research efforts are evaluating new natural antioxidants as alternatives to synthetic or conventional antioxidants. The EO from Eucalyptus (*Eucalyptus globulus*), rich in eucalyptol, α-pinene, and γ-terpinene (compounds associated with antioxidant properties), showed a higher activity as Fe^{+2} chelator (IC_{50} = 8.43 ± 0.03, mg/mL) than BHA (IC_{50} 104.73 ± 7.30, mg/mL) [55]. Additionally, EO from citron (*Citrus medica* L.) was applied to sunflower oil to improve the stabilization and reduce oxidative damage. The result of applying citron (EO, 800 mg/mL) showed changes in the oxidative stability index (OSI) similar to those obtained by applying BHT (200 mg/mL). In the same manner, several studies have reported comparable antioxidant capacities from EOs (oregano and mentha). Thus, the application of natural antioxidant components could be a good substitute for synthetic antioxidants [56]. These results could be explained by the different chemical compositions (both quantity and quality) in EOs. The potential future substitution of conventional antioxidants with natural antioxidants presents an interesting scope for research. However, a challenge to overcome is the lack of development and/or specification of the current legislative framework regarding the incorporation of natural antioxidants in foods. In the case of EO, Gutiérrez-Del-Rio et al. [57] highlighted the lack of specified information about the case of European regulations because there is no specific category for natural antioxidants related to the amounts and permissions for the use of natural additives in official tables according to European Food Safety Authority (EFSA).

4.2. Antimicrobial Potential

In the last century, human activities have grown drastically, leading to the emergence of new infectious diseases (bacterial, fungal, or viral) with the capacity to develop resistance strategies against conventional treatments. Thus, it is necessary to find new antimicrobial compounds with the potential to combat pathogens [58]. This situation is not exclusive to the health sector, as pathogens can also be found in the food and agricultural sectors. In this sense, EOs have been evaluated in numerous studies for their bioactive activities. The most studied EOs are those from species such as oregano, laurel, ginger, cinnamon, and citrus (lemon, mandarin) [2,59,60], which have been previously associated with antimicrobial activity. Additionally, Bhavaniramya et al. [61] associated the antimicrobial activity with the main components of EOs, such as cinnamaldehyde, citral, carvacrol, eugenol, thymol (phenols), and other compounds (ketones such as β-myrcene, α-thujone, or geranyl acetate).

The main action mechanisms of EOs involve membrane permeability, apoptosis, leakage of intracellular molecules, and DNA damage, among others [62,63], with the specific mechanism depending on the chemical composition of the EOs.

4.2.1. EOs as Novel Sustainable Antimicrobial Additives

Contemporary trends in the food field encompass the search for natural components as novel antimicrobial additives. Thus, plant bioactive fractions (such as essential oils, phenolic compounds, and bioactive peptides, among others) have become highly interesting sources. Recently, novel carrier methods such as nanostructures, active packaging, and emulsions have been the main approaches explored. In the field of active packaging, the addition of EOs into films has been extensively studied technique, with multiple formulations showing antimicrobial potential. For example, a cassava starch film containing oregano EO showed activity against the spoilage yeast strain *Zygosaccharomyces bailii* [64]. Similarly, a combination of guar gum, calcium caseinate, and clary sage EO exhibited good antimicrobial activity against *Pseudomona aeruginosa* and antioxidant activity [65]. Otherwise, emulsions represent an attractive technology due to their capacity to retain bioactive compounds from EOs and prolong their effectiveness [66]. For instance, Badr et al. [67] reported the application of lavender EO nano emulsions with antimicrobial potential against *Staphylococcus typhimurium* (minimum inhibitory concentration; MIC, 3105 mg/L) and *Staphylococcus aureus* (3000 mg/L), as well as antifungal activity against *Aspergillus flavus* and *Aspergillus niger*. However, other aspects related to the technologies, such as size, shape, structure, and co-additives, among others, must be considered to achieve higher activities.

5. Sustainability and Functionality: The Role of Essential Oils in Food

EOs have industrial potential for use in the development of new products or improving the quality of processes due to their bioactive properties. In recent years, several authors have explored the possible application of EOs in different sectors of the food industry (dairy, bakery, beverage, and packaging development), resulting in the development of sustainable technologies with novel scopes.

5.1. Dairy Products

The dairy industry is an important part of the food sector, which produces a high quantity of “Dairy products, DPs” that are staples in the human diet (milk, cheese, yogurt, etc.). Recently, incorporating EOs into DPs has been explored to provide technological advantages such as long storage times and enhanced flavor and sensorial properties (Table 2). In addition, current trends also explore DPs as carrier matrices for bioactive compounds [68].

Table 2. Trends in the novel application of essential oils in food products.

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
Dairy	Thyme (TEO)	Thymol (30%) *p*-cymene (13.78%)	Coated Liposomal chitosan-based emulsion	Karish cheese	Antimicrobial	The application of TEO (1–2%) maintained the appearance and microbial count until 3rd week. The chitosan emulsion kept the microbial count and appearance acceptable up to 4th week.	[39]
	Cumin (CEO)	Cuminaldehyde (30.9%) Sabine (14.3%) *p*-cymene (13.3%) *y*-terpene (12.6%)	Raw EO	White soft cheese	Antimicrobial Increase storage-time	The application of CEO encapsulation (0.5–0.75%) has the potential to improve antimicrobial and chemical properties. The overall acceptability of the product improves during the storage period (60 days)	[40]
	Spearmint Lemongrass Clove Cinnamon	----	Nano emulsion (<30 nm)	Stirred yogurt	Antimicrobial Flavoring agent	The addition of encapsulated EOs improves the preferred score. This addition did not affect the physicochemical evaluation (moisture, ash, protein, and fat). Furthermore, the application did not show mold and yeast growth when clove and cinnamon EOs were used at concentrations of 0.05 and 0.25%, respectively.	[69]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Origanum vulgare (L.) (OEO)	----	Raw EO	Minnas cheese	Antimicrobial	Adding (0.02%) Mina cheese with EO reduces contamination by undesired microorganisms. The EO did not significantly affect pH and moisture values compared to the control.	[70]
	Cinnamon (CIEO)	----	Nanostructured lipid carries (NLC)	Enriching milk	Antioxidant	The addition of EO demonstrated a reduction in malondialdehyde (a byproduct of lipid oxidation). It showed a lower peroxide value than the control during the first 2 weeks of storage.	[71]
	Thyme (*Thymus vulgaris*)	Thymol (43.63%) *p*-cymene (22.86%) Bronyl acetate (8.70%) *γ*-terpinene (6.56%)	Nano emulsion	Labneh	Antimicrobial Flavoring agent	The enriched labneh (0.1%) maintained its quality for up to 6 weeks in cold storage, with acceptable taste and aroma.	[72]
Bakery	Tahiti lemon	Limonene	Antifungal ingredient	Bread	Antifungal storage protection	The application of Tahiti EO contributes to inhibiting *Aspergillus niger* and *Penicillium sumatrense*.	[73]
	Carvacrol	----	Active packaging	Bread/butter cake	Antifungal storage protection	Films enriched with carvacrol showed enhanced antifungal activity. The application resulted in an increase of 2.0–2.3 times the shelf-life of bread.	[74]
	Thyme oil	----	Active packaging	White bread	Antifungal storage protection	Active films (thyme oil, 30% *v*/*w*) extended shelf-life compared to pure film (1–4 days).	[75]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Rosmarinus officinalis L.	α-pinene (42.8 ± 0.3%) eucalyptol (5.4 ± 0.6%)	Improve chemical and organoleptic properties	Bread	Organoleptic properties	The EOs contain bioactive compounds such as terpenes, which have the ability to impact desirable organoleptic properties and enhance the pleasant odor of bread.	[14]
Meat	*Zataria multiflora* Boiss.	Carvacrol (48.19%) linalool (23.19%) cymene (5.52%) thymol (4.13%)	Active gelatin-nano chitosan film	Chicken breast meat	Antimicrobial	The application of the EO reduces microbial growth during the storage period (14 days). The films reduced the total volatile base nitrogen value (indicative of protein degradation) and peroxide value (indicative of lipid oxidation). There was not significant negative impact on the sensory properties of chicken meat.	[37]
	Ajowan (*Carum copticum*)	Thymol (62.5%) γ-terpinene (19.4%) *p*-cymene (10.7%)	Virgin olive oil (VOO) nano emulsion + Ajowan EO (AEO)	Lamb loins	Antimicrobial	The combination of VOO + AEO (1–2%) increases the shelf-life of lamb loins (16 days) under chilled conditions. The application reduced chemical changes such as protein, lipid, and hemoglobin degradation. The color and sensory properties were higher in treatments with VOO + AEO (1–2%) compared to controls (water and VOO).	[42]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Shirazi-thyme Cinnamon Clove	Thymol (39.14%) Carvacrol (26.61%) p-cymene (7.88%)/E-cinnamaldehyde (97.83%)/Eugenol (78.42%) Caryophyllene (11.49%)	Synergistic triple combination	Chicken breast meat	Antimicrobial	The triple combination of EOs showed a synergistic effect (reduced 6–8 folds the MIC value). The application in chicken breast meat determined a bacteriostatic action and inhibition of *Pseudomonas fluorenceis*, and the higher concentration (20 mg/kg) showed a bactericidal activity.	[36]
	Mentha longifolia L. (MEO)	Puleogone (47.20%) Eucalyptol (22.72%) Menthone (13.44%)	Electrospun carboxymethyl cellulose-gelatin nanofibrous filmencapsulated with MEO	Peeled giant freshwater prawn	Antimicrobial	The incorporation of MEO in packaging extends the shelf-life of prawns until 14 days (2%). Reduces the presence of bacterial populations related to off-odor (H_2S bacterial and LAB). The sensorial evaluation determined that the addition of 2% MEO stayed stable at the acceptable consumption value until the end of the study.	[38]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Thyme (*Thymus vulgaris* L.)	Carvacrol (54.5%) O-cymol (26.9%) 4-carene (4%)	Meat sausage preservative	Meat sausage	Antimicrobial	The TEO incorporation showed lightly antimicrobial activity against coagulase-positive *Staphylococcus* in comparison with control + (nitrite). The combination of TEO + a half-normal concentration of nitrite preserving showed antibacterial activity against aerobic mesophiles. The TEO application demonstrated a good sensorial acceptance (lower concentrations 0.00095%)	[76]
Beverages	Lemongrass (0.1–1%, *v*/*v*) Mandarin (1–2%, *v*/*v*)	----	Nano emulsion	Apple juice-based beverage	Antimicrobial antioxidant storage protection	The nano emulsion applied in apple juice-based beverage model showed higher antioxidant activity. The antimicrobial potential of nano emulsion decreased in the complex model.	[77]
	Garlic	----	Encapsulation β-cyclodextrin sugar beet pectin microencapsulates	Orange juice	Functional beverage development	The encapsulation improved the thermal stability of GEO. The release of GEO in simulated gastrointestinal conditions showed 3% (120 min) in the stomach phase and 100% in the intestine condition.	[78]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Carvacrol	----	Functional addition	Carrot juice	Improve storage life	The study revealed the potential of Themo sonication and carvacrol to inactivate microorganisms. Optimal conditions: Carvacrol + low frequency (13.3 W/mL, 2.6 μM, 40 min) and Carvacrol high frequency (2.6 mm, 13.3 W/mL, 52 °C, 40 min). The treatments maintained fresh, color and β-carotene content in juice.	[79]
	Cinnamon bark Thyme thymol	----	Separate addition and combination	Tomato juice	Inhibition activity against *Listeria monocytogenes*	The study demonstrated a synergistic effect with cinnamon bark and thyme thymol essential oil. The combination reduced the number of *L. monocytogenes* by about 2.2 log CFU/mL (25 °C, 24 h).	[80]
	Litsea cubeba	----	Addition	Vegetable juices, carrots Bittergourd Cucumber Spinach	Natural antibacterial against *E. coli* 0157: H7	The study showed that using concentrations near MIC (minimum inhibitory concentration), the viable count of (*E. coli*) decreased by 99.1, 99.92, 99.4, and 99.6% in juices at 4 days in storage.	[81]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
Vegetables	Oregano Lemongrass Cinnamon	-------	Microemulsion	Iceberg lettuce	Antimicrobial activity against *Lactobacilli casei* and *Salmonella Newport*	The microemulsion using 0.3% oregano EO was the most effective treatment against pathogens and microorganisms. The visual inspection demonstrated that lettuce treated with microemulsions improved the visual appearance by the reduction of browning and other unwanted visual changes.	[82]
	Oregano Cinnamon Carvacrol	----------	Cellulose stickers impregnated with EOs	Green peppers	Antimicrobial activity against Listeria	The vapor-phase concentrations of carvacrol (241 µL/mL), oregano (363 µL/mL), and cinnamon (556 µL/mL) showed a lower MID (Minimum inhibitory doses) against *Listeria grayi*. The application of EOs on green peppers resulted in reductions in the *Listeria* population as follows: oregano EO (1.22 log CFU/G on the 5th day), carvacrol (1.22 log CFU/g on the 4th day) and cinnamon EO (1 log CFU/g, 2nd day); the control reached 8.60 log CFU/g by the 5th day.	[83]

Table 2. *Cont.*

Industry	Essential Oil (EO)	Main Component	Technological Application	Target Food Product	Activity	Relevant Result	References
	Galangal	---------	Carboxymethyl chitosan-pullulan edible films enriched with EO	Mango (*Mongifera indica* L.)	Storage preservative	The film with 8% EO showed the best preservative effect, with lower weight loss (8.72 0.28%), highest firmness (3.82 0.76 N), and higher triable acidity (0.185 0.07%). The films with EO could be described as effective antimicrobial and oxygen barriers. In addition, the film extended the shelf-life of mangoes by 9 days at room temperature compared to the control.	[84]

Abbreviations: TEO: Thyme essential oil; CEO: Cumin essential oil; OEO: Oregano essential oil; CIEO: Cinnamon essential oil; AEO: Ajowan essential oil; Voo: Virgin olive oil; MEO: Mentha essential oil.

5.1.1. Direct Application

The incorporation of EOs has been explored in different DPs. Direct application has been particularly successful in cheese products. For example, a liposomal chitosan-base emulsion of thyme EO (TEO) was added to karish cheese to improve its shelf-life, resulting in lower microbial growth (mesophilic and psychotropic bacteria) [39]. Similarly, De Campos et al. [70] evaluated the oregano EO (OEO) against bacterial and fungal growth during the maturation process of Minas cheeses (30 days). OEO (0.02%, v/v) inhibited pathogenic strains *E. coli* and *S. aureus* similarly to standard additives like nisin and natamycin, and sensory evaluation indicated that the panelists appreciated the addition of EOs. Previous studies highlighted the main presence of thymol (a monoterpene) in these EOs, which has been reported as a potential antimicrobial natural additive due to its interactions with extra- and intracellular components, negatively affecting normal bacterial metabolism [85,86]. In addition to thymol-rich content EOs, other EOs have shown shelf-life prolongation effects [40]

The application of EOs is not limited to solid products. Their use in beverages is an interesting trend. For instance, yogurt enriched with nanoencapsulated EOs showed an inhibitory effect against *E. coli* and *S. aureus* with good sensorial acceptability [87]. Additionally, milk was functionalized with cinnamon EO using chitosan-coated nanostructured lipid carriers, resulting in a reduction in malondialdehyde production (a secondary product in lipid oxidation) during the first 2 weeks of storage [71]. However, beyond the technological advantages, the application of EOs in DPs is also being researched to develop novel functional products and elucidate EOs' effects as native components in fermented DPs (e.g., yogurt). Relevant studies conducted by Salama et al. [69] and S. M. El-Sayed and El-Sayed [72] highlighted the combination of EOs, lactic acid bacteria, and the impact of EOs on fermented products, respectively. Thus, EOs and probiotics could be novel alternatives for the market, appealing to consumers seeking natural and novel products for a healthier diet.

5.1.2. Indirect Application

A critical aspect to consider for EO application is the potential impact on sensorial properties. Previous studies have reported a potential negative impact associated with higher concentrations of EOs [88,89].

Thus, another approach involves developing active packaging. Recently, an edible coating made with quince mucilage and thyme EO was developed for potential application in Kasar cheese, showing suppression of microbial growth and potential as a shelf-life booster [89]. In addition, the incorporation of EOs and another bioactive component has been tested. In this context, Nourmohammadi et al. [90] evaluated a whey protein/nano clay bio-composite with *Thymus fedtschenkoi* EO (thymol, 40.67%; carvacrol, 46.61%; and endo-borneol, 1.68%) and resveratrol in Liqvan cheese, highlighting the antimicrobial and antioxidant impact as a new method of cheese packing.

5.2. Bakery Products

The bakery comprises an important market with a growing economic expectation of USD 12.39 billion and an annual growth rate of 8.5% from 2021 to 2026 [91]. The bakery industry develops a large quantity of basic products (bread, cookies, cakes, muffins, among others) involved in the daily diet. Bakery products (BPs) face issues related to microbial spoilage, which represents a critical problem due to undesirable changes in texture, taste, and color, as well as possible toxicological impacts. In this context, the search for novel natural antimicrobial components could be a more attractive alternative for extending the shelf-life of BPs, with the extra benefits of providing potential extra flavor and integrating components with other possible functionalities (such as antioxidants) [14].

5.2.1. Direct Application

The direct application of EOs has been explored as a technological booster in food with different carrier technologies. Studies have evaluated the addition of raw essential oils to bakery products. For example, enriched bread formulations have received positive sensory scores such as green, fresh, and citric, with the addition of *Rosmarinus officinalis* L. EOs within safe concentration ranges [14]. Similarly, Dos Reis Gasparetto et al. [73] applied Tahiti lemon (*Citrus latifolia Tanaka*) EO rich in limonene and its fractions (solubilized and fractionated) against the predominant molds (*Penicillium sumatrense* and *Aspergillus niger*); their findings suggested that EO application may positively contribute to fungal inhibition in bread. Moreover, the use of carrier technologies has been a remarkable approach in recent years to improve the capacities of EOs in food matrices. For example, oleogels have shown promise for enhancing bakery products. Da Silva et al. [92] integrated olegels with orange EO, resulting in bread with decreased hardness, high storage stability (20 days), and reduced mold growth related to the chemical composition (limonene, 95.95%; β-myrcene, 1.76%; β-linalool, 0.98%). Thus, oleogels could be a potential alternative to conventional vegetable fat in bread development. Another interesting carrier technology involves EOs loaded fibers technology, which has conserved antioxidant and antifungal activities, with potential application in bread formulation or active packaging development for bread [93].

5.2.2. Indirect Application

Current applications have been focused on integrating of EOs (or their main compounds) into biopolymers to develop new natural packaging methods with shelf-life-booster properties. For example, carvacrol (a main compound in oregano) was applied in the formulation of biodegradable blend films for packaging bread and butter cake. The control samples showed fungal growth on the 4th day, while treatments enhanced with carvacrol at 2–5% extended the shelf-life by 2–4 days [74]. Similarly, Sharma et al. [75] used a bacterial biopolymer (poly (3-hydroxybutyrate-co-4-hydroxybutyrate) and thyme oil in the formulation of active films. The evaluation showed that bread sealed with active films (30%, v/w) had a shelf-life extended by at least 5 days compared to the control film. Other recent examples include studies conducted by Sripahco et al. [94], who developed biodegradable antifungal films (*Anethum graveolens* EO and pineapple nanocellulose-gellan gum) that inhibited *A. niger* during storage (3 weeks); and the study by S. Fan et al., [93] who used a non-contact application of a composite film (clove EO, and corn starch). Thus, the technological application of EOs in the baking industry represents an area of important benefits for the development of new products with improved shelf-life and safety.

5.3. Non-Dairy Beverages

In the beverage sector, EOs have been explored as additives for the development of functional beverages and/or provide technological advantages (antioxidant and antimicrobial). Thus, novel functional drinks or plant-based beverages provide suitability, affordability, and health benefits with the potential to integrate polyphenols and probiotics, among other bioactive components [95–98].

Recently, the potential to boost shelf-life in vegetable juices (such as tomato) has been highlighted through the incorporation of EOs like cinnamon and thyme, which exhibit synergistic inhibitory activity against *L. monocytogenes* [80]. Similarly, Dai et al. [81] reported that *Litsea cubeba* EO shows potential against other pathogenic bacteria such as enterohemorrhagic *E. coli* 0157:H7 in four vegetable juices (bitter gourd, cucumber, carrots, and spinach) stored at 4 °C for 4 days; the study suggests that citral (Main component) can impede bacterial nucleic acid replication. More recently, Sangroula et al. [99] have found the potential of cardamom EO as a potential green preservative in "ready-to-eat" beverages, offering technological advantages such as lower total microbial and yeast counts and higher antioxidant activity.

On the other hand, Molet-Rodríguez et al. [77] found that the interaction between EOs and the food matrix (apple juice) englobes a complex mechanism. Their study found that the nutritional components (fructose, sucrose, and glucose) could help bacteria mitigate the negative impacts of added antimicrobial EOs. Therefore, novel procedures could be developed to enhance the technological advantages of EO applications. For example, the integration of complementary technologies could increase effectiveness. A study conducted by Fan et al. [100] implemented carvacrol, a main component found mainly in oregano species, to improve storage life in carrot juice using thermo-sonication (high and low frequency) as complementary technology against aerobic bacteria, yeast, and mold at a low frequency (24 kHz). The authors reported a reduction in microbial counts (5 log reductions) and that treatment with carvacrol and high frequency could extend the shelf-life by 25 days (at 6 °C). Thus, the application of EOs and their main compounds may serve as a natural alternative to increase shelf-life in food and beverages.

The application of EOs in the beverage market has mainly focused on their incorporation as shelf-life boosters through encapsulation or as complementary components in emerging conservation technologies. Furthermore, the conventional approach to incorporating EOs for functional beverage development is still under study, with efforts to include new essential oils and new encapsulation technologies.

5.4. Meat Products

Meat is a significant source of protein in the human diet but is highly susceptible to foodborne diseases due to its short shelf-life and its high susceptibility to microbiological and chemical degradation. In this line, effective preservation strategies are needed to inhibit the growth of undesirable microorganisms. Currently, these strategies include freezing, refrigeration, and the development of new packaging methods (e.g., vacuum) to prevent contamination or limit it to acceptable levels [101,102]. Recently, the incorporation of bioactive components has been proposed for the development of active (functional) packaging to inhibit food deterioration (lipid oxidation, protein degradation, and unwanted changes in organoleptic properties) [103–106]. These changes could negatively impact consumer acceptance and the quality of food products by altering color, odor, and flavor [104–106].

5.4.1. Direct Application

The direct application of EOs can serve as a "natural" preservative. Lages et al. [76] evaluated an alternative to synthetic chemical preservatives (nitrites) in meat sausage using thyme EO with a high carvacrol content (54.5%) and o-cymol (26.9%). It showed a similar antimicrobial behavior to common food preservatives at normal concentrations. In the same approach, other studies have evaluated the application of EO (both free and by encapsulation) in other food matrixes, such as mortadella using OEO against *Salmonella* spp. and *L. monocytogenes* [107]. Additionally, EO application has not only a positive effect on microbial control; Fan et al. [79] demonstrated that oregano oil nanoparticles could inhibit lipid oxidation, retain flavor and organoleptic properties, and extend the shelf-life of Harbin red sausages. However, the authors highlighted that determining the ideal concentration is crucial to avoid negative impacts on organoleptic properties. Thus, current research highlights the potential combination of EOs with other bioactive compounds (e.g., phenolics) to improve the bioactivity at lower concentration, indicating a promising area for new product development.

5.4.2. Indirect Application

The potential of EOs as active components has been tested in active packaging using different technologies, such as nanofibrous films (0.5, 1, 2%) encapsulated with *Mentha longiflora* L. EO with main components such as Pulegone 47.20%, Eucalyptol 22.72%, and Menthone 13.44%, which showed a reduction in bacterial counts (e.g., *Enterobacteriaceae*) associated with disruption of DNA expression, lower lipid oxidation, protein degradation and better sensorial scores when compared to controls (without active films) [38]. Another recent technology involves coating with emulsions. In this context, gelatin-nano chitosan films have been reported to decrease *Pseudomonas* spp. growth, reduce TVB-N (total volatile basic nitrogen) to 22.68 mg/100 g (with *Zatatia multiflora* essential oil at 0.9%), and lower the peroxide value in chicken breast meat [37]. In addition, EO-emulsions in an alginate coating system using thyme, oregano, and pimento have shown a reduction in pathogenic bacterial strains (*Pseudomonas* spp., H2S-producing bacteria, and *Enterobacteriaceae*); extending the quality and shelf-life of chill-stored carps' fillets by 2–4 days [108].

Similarly, ginger EO in oil-gelatin coating showed a reduction in microorganisms under storage conditions and inhibited the production of off-flavor volatile compounds in fish [109]. Closely, the nano emulsion with Ajowan (*Carum copticum*) EO rich in thymol (62.5%) and γ-terpinene (19.40%), and virgin olive oil revealed lower microbiological growth, TVB-N, and peroxide values, compared to control groups, with sensory attributes acceptable for 16 days of storage versus 8 days for the control [42]. Other systems have shown similar results in reducing storage damage, such as a novel protein complex nanoparticle system added with hemp (*Cannabis sativa* L.) EO, which extended the shelf-life of Rainbow trout fillets from 8 to 14 storage days [7]. Thus, the application of EO in the meat sector has emerged as an interesting area for developing methods to boost shelf-life under new green and novel trends.

5.5. Vegetable Products

The fruits and vegetables sector faces challenges during storage periods due to the high prevalence of pests that could affect the quality of food products (e.g., fungi). Similar to other food sectors, the conventional application of chemical preservatives is a common solution. However, the potential incorporation of natural compounds could lead to better consumer acceptance by offering a sustainable and eco-friendly product with less artificial preservatives [110,111].

In the last years, remarkable results have been achieved in inhibiting fungal pests such as *Aspergillus* spp. (*A. flavus*, *A. niger*, *A. versicolor*) and *Penicillium italicum*, among other species. In the citrus industry, the application of chitosan nano emulsion functionalized with *Valeriana officinalis* EO showed a reduction in weight loss and degradation of soluble solids and phenolic compounds in *Citrus sinensis* L.; that could be related to the antioxidant properties of the main component found in the EO as: Valerianol (77.59%) and borneol (13.79%) [60]. Similarly, Chen et al. [112] showed the potential of films prepared with *Syringa* EO, which inhibited spore germination and mycelium elongation of *Penicillium* spp., positively impacting the physical characteristics of fruits (firmness, reducing vitamin C and total soluble solids loss).

Additionally, the antimicrobial potential of EOs in the fruits and vegetable market has been tested in different studies on various food matrices targeting specific pests, including Carica papaya (against *Lasiodiplodia theobromae* and *Rhizopus stolonifera*), banana (*Colletotrichum musae*), and the evaluation of microbial spoilage in date fruits, strawberries, guavas, and lettuce, among others [82,113–115]. A novel approach beyond active packaging involves the ready-to-eat (RTE) market, which presents a potential research area for EO application. Tao et al. [83] applied EOs (oregano and cinnamon) into cellulose stickers against Listeria grayi in green peppers for 5 days (22 °C), showing a reduction in microbial growth (Control: 8.60 log CFU/g, Oregano: 4.22 log CFU/g; and Cinnamon: 1 log CFU/g). Additionally, its application has been studied for reducing bacterial production of nitrite content during the storage period in RTE vegetable products. The data showed that microencapsulates of garlic essential oil reduced nitrite content to 7.09 mg/kg compared with 17.33 mg/kg (control) after 7 days [116]. Thus, the findings suggest a viable alternative for applying EOs in active packaging in the vegetable industry, with the capacity to inhibit pathogenic bacteria and improve food safety. This technology could also be applied to other matrices such as strawberries, berries, mangoes, or other fruits.

6. Bibliometric Networks Visualization (Essential Oils and Food Applications) by VOS Viewer

The analysis determined the trending scientific topics of current research in the EO field. The analytical program showed the most used terms and their connection. The results were presented graphically (Figure 1), emphasizing the cluster compilation (Figure 1a) and time distribution (Figure 1b) between 2019 and 2024.

The findings organized the research information (576 documents from 2019–2024) in six clusters (Figure 1a).

- The first cluster (red) is mainly related to plant sources and general bioactivities of EOs with the following keywords: “bioactive compounds”, “chemistry”, “plant extracts”, and “citrus”.
- The second cluster (green) focuses on the active application of EOs, as revealed by the keywords: “edible films”, “active packaging”, “active additives”, and “shelf-life”.
- The third cluster (blue) is related to extraction techniques and specific compounds of EOs with keywords “plant extracts”, “thymol”, “carvacrol”, and “hydro-distillation”.
- The fourth cluster (yellow) pertains to the antifungal properties of EOs with keywords such as “antifungal agents”, “contamination”, “*Aspergillus niger*”, and “anti-infective agents”.
- The fifth cluster (purple) encompasses new strategies as novel carriers with keywords “nano emulsions”, “emulsion”, “waxes”, and “capsule”.
- The sixth cluster (cyan) focuses on nanomaterials with keywords “nanocellulose”, “nanofibers”, and “silver-nanoparticles”.

The analysis of trends over time (Figure 1b) showed that the clusters related to “active applications”, “antifungal applications”, “novel carriers” and “nanomaterials” encompasses areas with recent publications and lower density (green/yellow $\geq$ 2022). The lower density indicates an opportunity for new research aimed at increasing the novel potential applications of EOs in the food field. Conversely, clusters 1 and 3 revealed studies before 2022. Thus, the information suggests that current trends are more focused on applied technologies research studies than basic research studies. The above can be explained by the shift in focus regarding the study of essential oils. The current perspective, aligned with sustainability trends and the search for new sustainable additives, promotes application and evaluation studies in food products, in contrast to the conventional (still necessary) approach of seeking new sources of bioactive compounds (e.g., EOs).

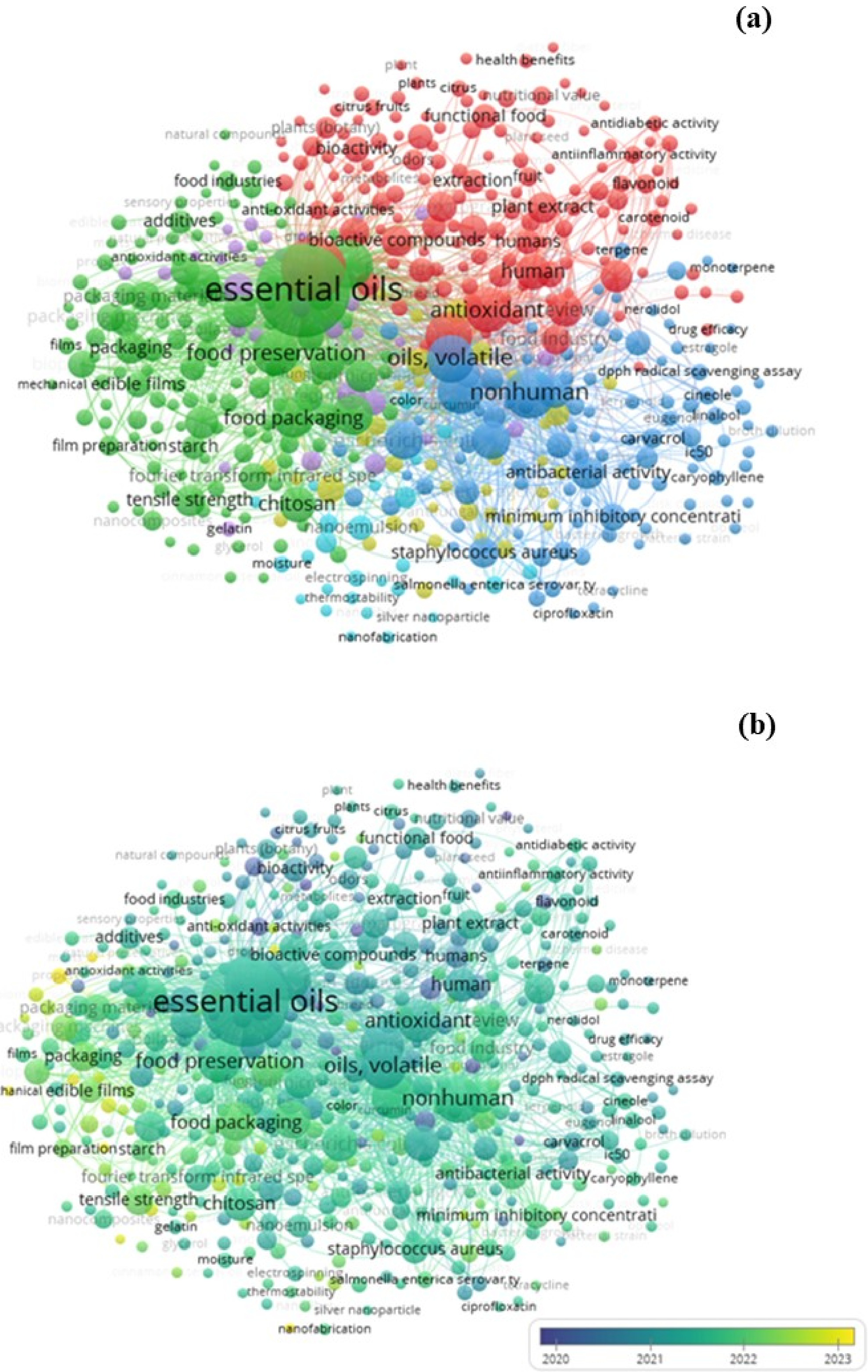
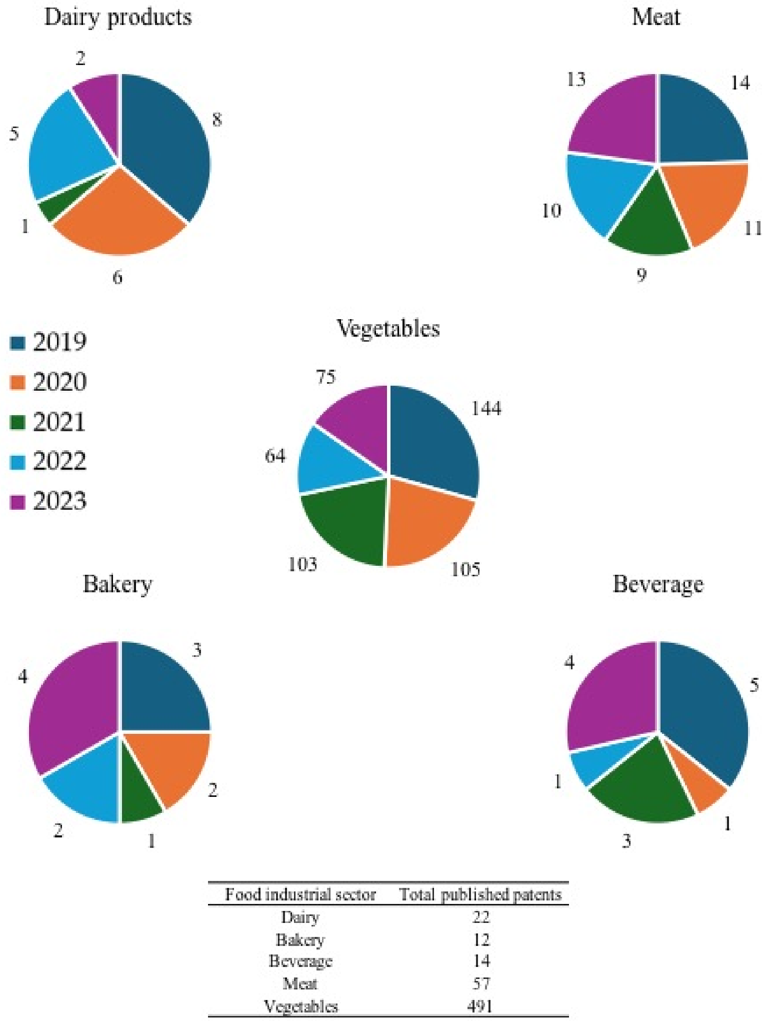


Figure 1. Network graph of essential oil trends from 2019 to 2024 by VOSviewer. (**a**) Cluster distribution of research information in essential oil trends; (**b**) Time distribution of research information in essential oil trends between 2019 and 2024.

7. Intellectual Property

7.1. Intellectual Property Screening in Food Sectors

A critical point in technological development is the generation of intellectual property, as numerous investigations fail to make the technological leap and remain only as laboratory tests. A world intellectual property database (PATENTSCOPE) has been applied to search for technological growth in EO applications in terms of "food products". According to the search made in "WIPO-PATENTSCOPE" (accessed 2 March 2024) using the keyword "essential oil" and each food sector, the obtained data were divided by sector over the last 5 years from 2019 to 2024 (Figure 2). The analysis showed that the sectors with lower intellectual property include bakery (12) < beverage (14) < dairy (22) = meat (22). The highest number of patents was published for the vegetables/fruits sector (491).



Food industrial sector	Total published patents
Dairy	22
Bakery	12
Beverage	14
Meat	57
Vegetables	491

Figure 2. Representative graph of patents published from 1 January 2019 to 1 January 2024 on the topic of essential oils and food industrial sectors (dairy, bakery, beverage, meat, and vegetables).

A possible explanation for the lower amount of intellectual property in sectors like bakery, dairy, beverages, and meat, could be the result of the organoleptic impact of EOs on food products. Thus, the development of food products in these sectors could involve a more complex procedure to ensure beneficial impacts on the food matrix without reducing consumer acceptability. Otherwise, the application in vegetable products is mainly as an extended shelf-life additive where the EOs are primarily incorporated into active packaging with a lower impact on organoleptic properties. The aforementioned establishes a significant area of opportunity for developing intellectual property that seeks to create processes and products to address the lack of technology in these sectors (baking, meat, dairy, and beverages).

7.2. Current Application of Essential Oils

According to the result obtained in Section 6 and the higher research interest in active packing according to VOS viewer analysis, the novel trends in essential oil application in the food industry have been focused mainly on the addition of EOs as active components (emulsion, encapsulation, or active additive). Thus, active EOs provide a natural and interesting alternative to traditional processes that also attract higher consumer attention under the labels of "natural" or "environmentally friendly" products.

As summarized, the patents are related to the development of new active coating by the incorporation of EOs to provide antimicrobial and antioxidant capacities and extend the shelf-life of the products. The patent CN113755968 encompasses a polysaccharide nanofilm based on a combination of plant essential oil (green pepper, lemon, citronella) and organic acid. The nanofilm has excellent antioxidant activity and effectively prevents microbial contamination, slows down lipid and protein oxidation, and improves the sensory properties of the food, which can be applied to food preservation. Another patent, CN113080249, describes an edible spray for prolonging the shelf-life of vegetables and fruits using *Zingiber corallinum* Hance EO. The invention provides a slow-release mode, a protective role against bacteria and oxidative processes, thereby extending the shelf-life. Similarly, the patent CN114145335 discloses an oregano essential oil chitosan coating liquid. The combined use of the oregano essential oil and the chitosan coating can effectively inhibit bacterial growth, slow down the lipid oxidation rate, and prolong the shelf-life to more than 7 days.

The following patents are related to non-contact components:

- The patent CN113632827 comprises clove EO microcapsules for non-contact strawberry preservation. The clove EO has a certain slow-release capacity, and the shelf-life of strawberries can be prolonged.
- The patent CN113907240 relates to a fresh-keeping adhesive sticker with the ability to release natural antibacterial and antioxidant active additives, reducing rot caused by pathogenic bacteria infection and prolonging the shelf-life of fruits and vegetables.
- The patent CN114097866 is aimed at developing an environment-friendly water absorption pad capable of prolonging the shelf-life of fresh meat. It is composed of non-woven fabric, a ginger essential oil composite film, and a water absorption resin with the capacity to inhibit deterioration indices.

Finally, the following patents are related to preservation methods.

- The patent CN114128747 discloses a chilled beef fresh-keeping method based on composite plant essential oil, which prolongs the shelf-life of the product, improves the appearance, and enriches the taste.
- The patent CN114431281 discloses a preservation method for prolonging the shelf-life of crayfish tails through combined irradiation sterilization and the synergistic effect of essential oil microcapsules, which slow down bacterial growth with a long-acting effect.

The intellectual property of EO applications in the food industry encompasses the development of recent technologies aimed at incorporating antimicrobial and antioxidant properties into preservation areas.

8. Essential Oils Historical Trade Data

According to the OEC database and the Standard International Trade Classification (OEC, 2023), in 2018, essential oils (SITC 705513) were worth $4.67 billion in global trade, ranking 410th among the most-traded products out of 764, with a growth of 11.2% from 2017 to 2018. The trade of essential oils represented 0.024% of global trade in the same year. India was the largest net exporter, with exports worth $369 million, followed by

China ($222 million), Argentina ($222 million), Brazil ($220 million), and Italy ($132 million). On the other hand, the main importers were the US ($387 million), followed by the Netherlands ($233 million), Japan (142 million), Ireland ($136 million), and Germany ($132 million) (Figure 3). Analyzing the decade from 2008 to 2018, exports from countries such as Mexico, Brazil, Argentina, China, Madagascar, Bulgaria, Belgium, Italy, and Spain grew by more than 100%. Mexico exported $120 million, representing 2.58% of the world's trade in essential oil. The SITC 705513 classification, in general, encompasses any product considered an essential oil. The OEC database does not provide specific information about the types of essential oils traded and their quantities. However, there is data on specific essential oils such as lemon, orange, and peppermint.

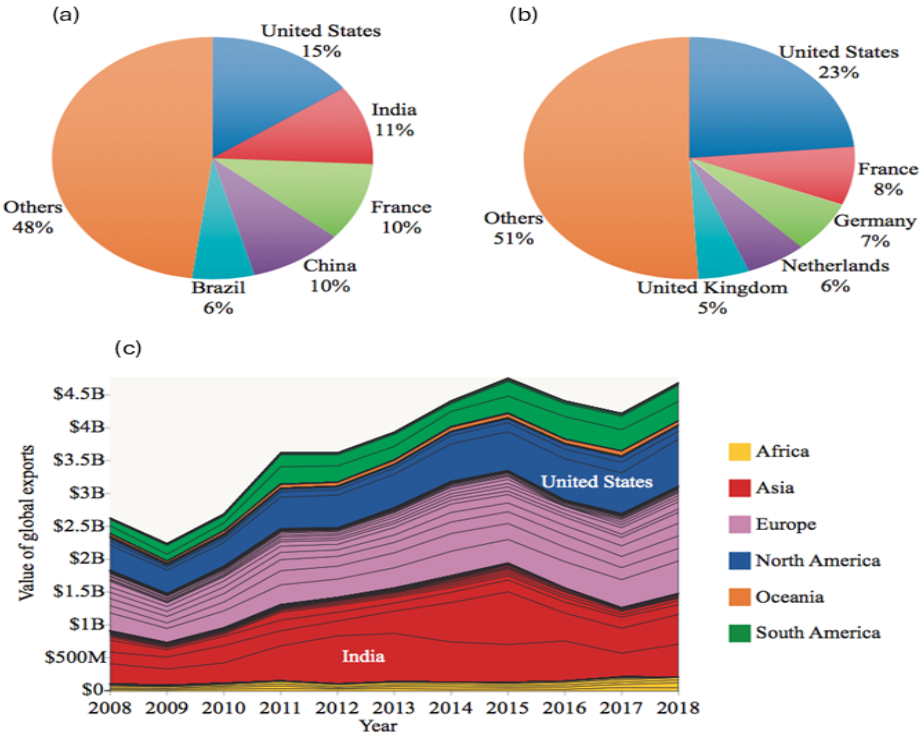


Figure 3. Trade data. (**a**) Principal exporter countries in 2018; (**b**) principal importers countries in 2018; (**c**) trend of world net trade 2008–2018.

In 2020, the main exporter of lemon essential oil was Argentina, accounting for 42.9% of the total $547 million market, while Ireland was the largest importer with 38.3% of the market. A decrease in product transactions was observed from 2019 to 2020. Brazil was the greatest exporter of orange essential oil in 2020, with 37% of the total $440 million market, while the United States was the main importer with 23.4% of the total transactions. The consumption of this product decreased in most registered countries from 2019 to 2020. Brazil also led in net exports ($160 million), while the Netherlands was the largest importer ($35 million). Furthermore, in 2020, the United States was the greatest exporter of peppermint essential oil, with 40.4% of the total $209 million market, followed by India with 33.8%. The largest importer was the United States with 15.2%, followed by China with 9.99%. From 2019 to 2020, most countries presented a growth in their transactions, with the United States increasing its exports by 11.1% while its imports decreased by 10.7%. India had the highest net trade as an exporter of peppermint essential oil.

Trade information only registers the price and quantity of essential oils transactions with corresponding authorities. There is no information about the earnings of the producer companies. However, a process using residues as initial feed should generate more revenue than using raw materials. Therefore, research into essential oil production from residues is encouraged within the scientific community.

9. Authors' Viewpoint

The current sustainability trends have promoted interest in natural products (e.g., essential oils) as potential green and sustainable additives, which enable sustainable primary production (optimization of productive resources), support the economy of producer communities, and encourage the consumption of natural additives, leading to more responsible production and consumption.

Additionally, the incorporation of EOs into food products opens the field to new questions, some related to the field of engineering aimed at optimizing process efficiency through renewable energy or linked to their application in food, such as determining the adequate concentration for good bioactivity and consumer acceptance, evaluating possible chemical changes during the gastrointestinal process (hydrolysis, protein interactions), elucidating the possible impact on gastrointestinal microbial strains (prebiotic effect), and exploration of other possible health benefits. The innovation and development field of active packing provides a new trend with valuable perspectives, such as the incorporation of new EOs, changes in concentration, or the synergetic activity of multiple EOs.

The interest in the incorporation of EOs in the food industry is accompanied by scientific literature supporting their potential application as green additives (antioxidants and antimicrobials) [117]. However, food regulation and safety represent one of the biggest challenges in achieving their full acceptance and application in the market. As Donsi et al. [118] pointed out, the complexity of standardizing EOs is due to their variable and complex mixture of multiple components. However, Tamburlin et al. [119] conducted a toxicological study on EOs used as food supplements (Oregano, Eucalyptus, peppermint, among others), highlighting 100, 150, and 225 mg/day (60 kg consumer) as recommended daily doses. Meanwhile, Synadiet (Syndicat National des Compléments Alimentaires) establishes similar values: 150, 150, and 300 mg/day (70 kg/consumer).

Finally, it is important to highlight the lack of information on other EOs, as well as the need to further investigate the area of toxicology, ensuring consumer safety. Additionally, some essential oils, such as *Citrus aurantium* L., have already been explored in the area of animal feed, determining the maximum safe concentrations for animals in human food [120]. This highlights an area of interest in the food industry for the potential application of EOs as additives in animal feed.

10. Conclusions

Essential oils are a sustainable bioactive fraction with potential applications in the food field. Their applications are mainly based on their antioxidant and antimicrobial properties, serving as potential shelf-life or flavoring enhancers. They can be applied to different food sectors (meat, bakery, dairy, fruits, and beverages, among others) according to the remarkable results published in scientific databases. However, the application method is a critical aspect of the technology due to the potential negative impact on organoleptic characteristics. Thus, the selection of EOs is a critical step for successful application, as is the choice of the carrier method. In response, novel carriers (e.g., encapsulation and emulsions) or indirect applications (active packaging) have been studied in the last 5 years. According to the bibliometric networks visualization (576 research documents), the current research approach has focused on applications and carrier methods beyond chemical characterization or bioactive evaluation, highlighting the current trends for essential oils. Furthermore, intellectual property data showed that between 2019 and 2024, a total of 596 patents were developed, with a higher number relating to the vegetable market (due to the lower organoleptic impact). Finally, the current information related to the EOs highlights their potential as a new frontier for the food field to incorporate green and friendly components in the food industry.

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