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Review

Antioxidant Activity of Essential Oils Extracted from Apiaceae Family Plants

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Abstract: The importance of antioxidants has gained much attention due to the increase in the prevalence of various non-communicable diseases such as cancer, diabetes mellitus, and cardiovascular diseases, which occur due to excess reactive species. The widespread use of synthetic antioxidants in the food industry has raised concerns about their potential harmful effects on health. As a result, the utilization of natural antioxidants to preserve food and as a source of dietary antioxidants has gained attention. Essential oils extracted from Apiaceae family plants are an excellent source of antioxidants. In this review, research findings regarding the antioxidant activity of selected Apiaceae family members and their applications are discussed.

Keywords: antioxidant activity; Apiaceae family; essential oil

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1. Introduction

The Apiaceae family, which was previously named Umbelliferae, are angiosperms (flowering plants); they are common and widely grown in many parts of the world. This family has 300–455 genera and 3000–3750 species. Asia is the main ground for most of the genera, followed by Europe and Africa. Nearly half of the genera are endemic to the Asian region. The most common and well known Apiaceae plants are celery (*Apium graveolens* L.), carrot (*Daucus carota* L.), Indian pennywort/Vallarai/Gotukola (*Centella asiatica* L. Urb), parsley (*Petroselinum crispum* (Mill.) Fuss), parsnip (*Pastinaca sativa* L.), wild celery (*Angelica archangelica* L.), coriander (*Coriandrum sativum* L.), cumin (*Cuminum cyminum* L.), fennel (*Foeniculum vulgare* Mill), anise (*Pimpinella anisum* L.), dill (*Anethum graveolens* L.), and caraway (*Carum carvi* L.) [1].

Most of the Apiaceae plants have various uses, are served as foods, herbs, and spices, and are also well known for their economic importance [1]. Various parts of Apiaceae plants such as the roots, leaves, leaf stalks, pseudo-blubs, and seeds are used and the selection of the plant part depends on the species [2]. Many spices used in Indian cuisine including ajowan, asafetida, cumin, coriander, caraway, dill, and fennel are from the Apiaceae family.

Traditional Indian spices are identified as an assortment of many important phytochemicals [3]. Furthermore, Apiaceae plants are abundant in bioactive compounds which offer positive therapeutic actions including antioxidative, anti-inflammatory, cardioprotective, nephron-protective, antidiabetic, antihypertensive, and antimicrobial effects [3].

Apiaceae plants are recognized as a valuable source of essential oils (EOs) [4]. EOs are produced by plants through different biosynthetic pathways as a response to various biotic or abiotic stress conditions, as a defense action against bacteria, viruses, fungi, insects, and herbivores, and to attract pollinators [3,5]. Some Apiaceae plants are composed of more than 760 different chemical compounds and identified as excellent EO sources. However, their chemical composition is subjected to variations according to the extraction method, specific plant part, harvest period, plant maturity, the properties and composition of the soil, and other environmental factors [4].

The imbalance of reactive oxygen species (ROS) can lead to many pathologies such as hypertriglyceridemia, cancer, neurodegenerative diseases, diabetes, skin diseases, aging, wound healing, and cardiovascular diseases [1]. Antioxidant enzymes and natural dietary antioxidants can minimize the negative effects on health due to the imbalance in ROS and oxidative stress [1]. Currently, most consumers seek healthy diets rich in natural sources of antimicrobial and antioxidant potential such as essential oils. Many aromatic plant extractions have antimicrobial, antioxidant, and other beneficial biological activities, and thus can be widely used. Furthermore, aromatic plant extracts have many other benefits such as less polluting effect on the environment and subtle impacts on consumers' health [6]. The study of EOs and their components as potential substitutes for additives in the food industry has highlighted the benefits compared to synthetic antioxidants, which frequently cause adverse health implications [7].

Apiaceae plants contain EOs, and their antioxidant activity has been tested in many studies. This review provides comprehensive information on the antioxidant activity of essential oils of the Apiaceae family, tests to measure antioxidant activity, and potential uses and future trends of the usage of Apiaceae EOs.

2. Importance of Natural Antioxidants

An antioxidant is defined as a substance which is capable of significantly delaying or completely inhibiting the oxidation of substrate molecules, even in minute quantities [8]. Antioxidants find application in numerous industries and hold significant importance in human health. Furthermore, antioxidants play an important role in the body. The balance between free radicals and antioxidants within the human body is crucial for the healthy functioning of the body. Imbalance between antioxidants and reactive oxygen species may lead to many negative consequences [9]. The exposure of the human body to reactive oxygen species can result in oxidative stress which can eventually lead to lipid peroxidation, protein glycation or oxidation and nitration, enzyme inactivation, and DNA damage. These reactions can cause many pathological conditions such as diabetes mellitus and neurodegenerative diseases. However, the usage of endogenous or exogenous antioxidant systems is identified to be effective in preventing pathological conditions [10].

Active free radicals which are responsible for oxidative stress can be converted to more stable or less harmful compounds by the action of potent antioxidant compounds [11]. Therefore, antioxidants are identified as protectors of cellular organs from oxidative deterioration [11]. Furthermore, antioxidants are also identified as a health care product which can be sold worldwide without a prescription [9].

Oxidation is identified as one of the primary causes of food deterioration and spoilage. Synthetic antioxidants are used in food products to delay the oxidation of fats and to prevent microbial growth [12]. Excess oxidation can cause food spoilage and reduce customer acceptability [13]. Adding Eos as an ingredient or directly mixing them in food can be used to achieve antioxidative properties [14].

The usage of synthetic additives has gained much attention due to many adverse health outcomes [12]. Recent reports have encouraged the use natural antioxidants such

as EOs, because of the adverse outcomes for human health of synthetic antioxidants including butylated hydroxy anisole (BHA) and butyl hydroxytoluene (BHT) [11]. The commonly used BHA and BHT are subjected to restrictions because they are considered as possible carcinogens [15].

Therefore, natural alternatives are being studied for use as antioxidants. Phenolic compounds are identified as a potential source of natural antioxidants and can be extracted from plants. Phenolic compounds are synthesized by plants and are identified as functional compounds [9]. Phytochemicals mitigate oxidative stress by increasing the antioxidant levels while decreasing lipid peroxidation [3]. EOs are identified as potential antioxidants and the food industry is increasingly interested in using natural EOs as antioxidants instead of synthetic antioxidants, which are introduced to prolong the shelf life of food products.

3. Essential Oils from Apiaceae Plants as a Source of Natural Antioxidants

Essential oils are produced as secondary metabolites by plants and the positive health effects of EO extracts have been recognized since ancient times [16]. EOs are mixtures of organic ingredients, and provide plants with their unique fragrance [11]. The composition of EOs is complex and contains a combination of sesquiterpene and monoterpene hydrocarbons and alcohols, ketones, and aldehydes (their oxygenated derivatives), fatty acids, oxides, and sulfur derivatives [14]. Phenylpropane and phenolic constituents and their derivatives are aromatic compounds in EOs [17]. The chemical composition and the quantity of EOs present in a plant may vary based on the environment, the maturity level of the plant, and geographical location [11].

Some EOs are identified as "Generally Recognized as Safe" (GRAS) [16]. Eos are used in diverse applications in multiple industries including food flavoring, industry perfumery, coloring, soap, and detergents [2]. Furthermore, EOs have attracted both scientific and widespread attention due to (a) their ability to act synergistically with preservation techniques, (b) the fact that EOs are GRAS, and (c) the fact that they are bioactive compounds in foods with antioxidant, antibacterial, antidiabetic, antimutagenic, non-toxigenic, and antimycotic properties [14].

Apiaceae plants are identified as a rich source of antioxidants, mainly with phenolic acids and flavonoids which are identified to have therapeutic effects [1]. Generally, EOs are pale yellow or colorless, but some may vary, for example, green European valerian and blue chamomile [11]. The performance of EOs is a result of the interaction between EOs and the oxidizable material to be protected. Furthermore, antagonistic and synergistic effects occur between individual components of EOs [14]. Antioxidant compounds are capable of inhibiting, altering, or halting oxidative reactions at relatively low concentrations. In this context, EO constituents assume a vital role in exerting antioxidant activity [13]. Most spices are composed of natural antioxidants, which can extend shelf life and prevent the spoilage of seasoned food. Therefore, natural antioxidants are widely applied in the food industry [18].

Phenols are mainly responsible for the antioxidant capacity of EOs and are identified as chain-breaking antioxidants. Phenols are capable of donating an H-atom from the phenolic hydroxyl group to peroxyl radicals. This process can lead to a lower rate of peroxidation of unsaturated lipids [14]. Usually, the antioxidant capacity of EOs is analyzed though various physical and chemical in vitro studies [14]. EOs have gained their antioxidant potential from redox properties which make them adsorb and neutralize free radicals, quenching singlet and triplet oxygen, and decomposing peroxides [19]. The antioxidant capacity differs in various types of EOs due to the differences in chemical structures [20].

4. Methods to Evaluate the Antioxidant Potential of Essential Oils

Antioxidant activity is measured based on various tests, and it is advised to use more than one method to measure it [21]. Various chemical-based in vitro methods are widely used to measure the antioxidant activity of EOs and natural or synthetic derivative chemical

compounds [22]. Some methods which are used to determine the antioxidant activity of EOs are listed in Table 1.

Table 1. Some techniques used to measure antioxidant activity [23].

Antioxidant Capacity Test	Principle of the Method	End Product Determination
Oxygen radical absorption capacity (ORAC)	Antioxidant reaction with peroxyl radicals, induced by 2,20-azobis-2-amidino-propane (AAPH)	Loss of fluorescence of fluorescein
Hydroxyl radical antioxidant capacity (HORAC)	Antioxidant capacity to quench OH radicals generated by a Co (II)-based Fenton-like system	Loss of fluorescence of fluorescein
Tartrate-resistant acid phosphatase (TRAP)	Antioxidant capacity to scavenge luminol-derived radicals, generated from AAPH decomposition	Chemiluminescence quenching
Cupric ion-reducing antioxidant capacity assay (CUPRAC)	Cu (II) reduction to Cu (I) by antioxidants	Colorimetry
Ferric-reducing antioxidant power (FRAP)	Antioxidant reaction with a Fe (III) complex	Colorimetry
Potassium ferricyanide-reducing antioxidant power (PFRAP)	Potassium ferricyanide reduction by antioxidants and subsequent reaction of potassium ferrocyanide with Fe^{3+}	Colorimetry
ABTS	Antioxidant reaction with an organic cation radical	Colorimetry
2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity	Antioxidant reaction with an organic radical	Colorimetry

5. Antioxidant Activity of Some Apiaceae Plants

5.1. Coriander

Coriander *Corriandrum sativum* L. (*C. sativum*) is a well-known spice and medicinal herb. EO can be extracted from coriander leaves, stems, flowers, and fruits or seeds. The main constituents of coriander oil are linalool (64.2–79.9%), γ-terpinene (5.8–13.6%), neryl acetate (2.3–8.4%), α-pinene (2.8–7.1%), and p-cymene (1.1–3.6%) [3]. The major component of coriander EO, linalool, is identified to have an antioxidant capacity. Coriander fruit EO contains petroselinic acid and is therefore called "triglyceride oil" [17]. Coriander is cultivated mainly to harvest the seeds, which contain EO, fatty acids, coumarins, flavonoids, and polyphenols [17]. Coriander is grown in countries including the USA, the UK, Argentina, India, France, Italy, Morocco, Myanmar, Mexico, the Netherlands, Pakistan, Turkey, Spain, and Romania [5]. Numerous bioactive compounds in coriander are primarily utilized in the food and cosmetic sectors due to its fragrance and antioxidant properties [10].

Coriander contains EO in its leaves, flowers, stem, seeds, roots, and bark; however, the composition of EO changes depending on the part which was used for the extraction (Table 2). There are specifications identified in the characteristics of the EO of coriander according to the Food Chemical Codex (FCC). Generally, matured fruits and leaves have a more pleasant odor than immature ones. Coriander contains 0.2–1.5% of EO and 13–20% of fixed oil, but there are several cultivars with EO up to 2.6%. Different cultivars and regions have an impact on the EO concentration [17]. The study findings of Raveau et al. [24] suggest that marginal lands polluted by trace elements can be used for the production of EO as it exhibits antioxidant activity, which can be used in non-food applications [24].

Table 2. Different compositions of *C. sativum* essential oil from different parts of the plant [25].

Source	Composition	Geographical Location
Seeds	Linalool (58.0–80.3%), γ-terpinene (0.3–11.2%), α-pinene (0.2–10.9%), p-cymene (0.1–8.1%), camphor (3.0–5.1%), and geranyl acetate (0.2–5.4%)	Europe
Flowers	Benzofuran,2,3-dihydro (15.4%), hexadecanoic acid, methyl ester (10.32%), 2,4a-epioxy-3,4,5,6,7,8,-hexahydro-2,5,5,8a-tetramethyl-2h-1-benzofuran (9.35%), 2-methyoxy-4-vinylphenol (8.8%), 2,3,5,6-tetrafluroanisole (8.62%), 2,6-dimethyl-3-aminobenzoquinone (6.81%), and dodecanoic acid (5%)	India
Leaves	Decanal (19.09%), trans-2-decenal (17.54%), 2-decen-1-ol (12.33%), cyclodecane (12.15%), cis-2-dodecena (10.72%), dodecanal (4.1%), and dodecan-1-ol (3.13%)	Brazil

Various parts of the coriander plant such as the flowers, bark, seeds, stems, roots are used for the extraction of EO. However, the composition of the EO may vary depending on the part of the plant used for the extraction. For example, the EO compositions of *C. sativum* seeds, flowers, and immature leaves are different. Thus, the diversity of the EO composition enhances its versatility. EOs from immature plants are used for the preparation of curries, soup, and sauces, whereas EOs from the fruits of coriander are used for the preparation of spice blends for cold meats [25]. The typical composition of coriander is given in Table 3.

Table 3. The typical composition of *C. sativum* essential oil [25].

Chemical Group	Composition
Alcohols	Linalool (60–80%), geraniol (1.2–4.6%), terpinen-4-ol (3%), α-terpineol (0.5%)
Hydrocarbons	γ-terpinene (1–8%), r-cymene (3.5%), limonene (0.5–4.0%), α-pinene (0.2–8.5%), camphene (1.4%), myrcene (0.2–2.0%)
Ketones	Camphor (0.9–4.9%)
Esters	Geranyl acetate (0.1–4.7%), linalyl acetate (0–2.7%)

Coriander EO is used as a substitute for synthetic antioxidants mainly due to its favorable characteristics such as stability at high temperatures and high antioxidant potential [25].

According to a study by Jeya et al., the EO of *Coriandrum sativum* L. seed showed significant antioxidant activity, and the percentage of inhibition was 66.2% and 87.8% for standard ascorbic acid. According to the study, the respective IC_{50} values were 0.147 mg/mL and 0.108 mg/mL [26]. In this study the antioxidant activity was evaluated using DPPH scavenging activity and FRAP. In the DPPH assay, 500 µg of coriander seed EO showed the highest radical-scavenging activity of 66.48% when compared to 500 µg of coriander leaf EO with a radical scavenging activity of 56.73%. Furthermore, in the same study, the results of the FRAP assay showed an absorbance of 0.734 for coriander seed oil and 0.815 for coriander leaf oil [26].

According to a study conducted by Kačániová et al. [18], coriander EO's radical scavenging activity was 51.05% of the inhibition of purchased EO. EO distilled from the aerial parts of coriander possesses a greater effectiveness in antioxidant activity [24]. Recent studies have tested coriander EO as an antioxidant in cakes and suggested it as a suitable alternative for synthetic antioxidants in food preservation. mMoreover, salami with the addition of the coriander EO had reduced lipid oxidation; therefore, the EO increased the shelf life [18]. An EO concentration of 0.1 g/mL has the capability to scavenge free radicals (DPPH and galvinoxyl), which is effective in preventing oxidative damage in foods containing lipids [5]. It acts as a natural substitute for synthetic antioxidants such as BHA, BHT, TBHQ, and propyl gallate which are used in the food industry [5].

5.2. Caraway

Caraway (*Carum carvi)* is a biennial herb and commonly used as a spice. The dried fruit has an intense flavor and pleasant odor. Caraway fruit essential oil includes approximately 30 components [27]. Caraway EO is mainly composed of carvone (44.5–95.9%) and limonene (1.5–51.3%), and minor amounts of β-myrcene, transdihydrocarvone, transcarveole (0–0.2%), α-pinene, sabinene, n-octanal, trans-β-ocimene, δ-terpinene, linalool, cis- and trans-limonene oxide, cis-dihydrocarvone, cis-carveol, perillaldehyde, trans-anethole, and trans-β-caryophylle [3]. The utilization of caraway has a historical background, and it has been used to alleviate constipation, offer control over urination, and avoid phlegm. Lactating mothers use caraway to enhance the flow of breast milk [10]. The EO and caraway extracts are proven to have antidiabetic, antioxidant, hepatoprotective, antiulcerogenic, antimicrobial, insecticidal, diuretic, analgesic, renoprotective, molluscicidal, anti-cholinesterase, and immunomodulatory activities [27,28].

In accordance with a study by Hajlaoui et al. [10], the antioxidant activity of EOs from the seeds of caraway and coriander alone and in combinations was investigated using five assays, namely, DPPH, superoxide anion, reducing power, chelating power, and β-carotene methods (Table 4). The results can justify the fact that the antioxidant compounds in caraway and coriander increase the antioxidant content of the food.

Table 4. Antioxidant activity of caraway, coriander, and combinations of coriander and caraway compared with authenticated standards (BHT and EDTA) [10].

	DPPH IC_{50} (μg/mL)	**Superoxide Anion IC_{50} (μg/mL)**	**Reducing Power EC_{50} (μg/mL)**	**Chelating Power EC_{50} (μg/mL)**	**β-Carotene IC_{50} (μg/mL)**
C. sativum	38.83 ± 0.76^{a}	37.00 ± 1.73^{a}	24.00 ± 1.53^{a}	23.00 ± 1.00^{a}	25.70 ± 1.02^{a}
C. carvi	34.00 ± 3.46^{b}	28.00 ± 7.00^{b}	18.00 ± 1.00^{b}	36.33 ± 4.10^{b}	19.00 ± 2.16^{b}
Mixture	19.00 ± 1.00^{c}	10.33 ± 0.58^{c}	11.33 ± 1.53^{c}	31.33 ± 0.47^{b}	11.16 ± 0.84^{c}
BHT	11.5 ± 0.62^{d}	1.60 ± 0.20^{d}	23.00 ± 1.00^{a}		4.60 ± 1.60^{d}
EDTA				32.50 ± 1.32^{b}	

[a–d]: each value represents the average of three repetitions. Means (three replicates) followed by the same letter are not significantly different at $p < 0.05$.

In a similar study, combinations of cumin and caraway were studied by Yakoubi et al. [29], and it was concluded that essential oil mixtures showed higher antioxidant activities than the crude essential oils of cumin and caraway.

A study by Ghannay et al. [30] also showed that caraway essential oil exhibits antioxidant activities. In a DPPH assay, caraway EO showed potent antioxidant effects such as an IC_{50} value of 15 ± 0.23 mg/mL. However, its antioxidant capacity was significantly ($p < 0.05$) lower than that of BHT and ascorbic acid standards. Reducing power test results showed that caraway EO exhibited a higher redox property (2.95–3.2 times) than to the commercial standards, BHT and ascorbic acid [30]. Compared with EDTA ($IC_{50} = 32.50 \pm 1.32$ mg/mL, positive control), caraway EO had 4.7 times significantly ($p < 0.05$) higher chelating power. Furthermore, the findings of the research proved that there is no significant difference between caraway EO and BHT in inhibiting linoleic acid oxidation [30].

A study by Gajić et al. [27] investigated the antioxidant activity of ripe and disintegrated caraway fruit isolated using Clevenger-type hydrodistillation. In this study, the antioxidant activity was investigated using a DPHH assay, and caraway essential oil at a concentration of 50 mg/mL neutralized 90% of the DPPH radical after 40 min of incubation, 85% after 20 min of incubation, and 20% without incubation. The best antioxidant activity was shown at 40 min of incubation with $EC_{50} = 4.6$ mg/mL, but caraway EO had a weaker antioxidant activity than L-ascorbic acid and BHT [27].

The potential antioxidant activity of caraway EO is attributed to its rich content of highly oxygenated monoterpenes, with carvone being a prominent constituent (58.2%).

Furthermore, carvone, with its two enantiomeric forms of, (−)-carvone and (+)-carvone, is an oxygenated monoterpene possessing a greater capacity to capture free radicals and to reduce power [30]. Caraway EO has the capability to quench hydroxyl radicals and lipid peroxides [28]. Therefore, caraway EO finds broad use in the food, beverage, and cosmetic industries [30].

5.3. Celery

Celery (*Apium graveolens* L.) is a member of the Apiaceae family, distributed widely in Europe, Africa, and Asia [31]. Celery is consumed as a raw material in salads or used in cooking as a condiment [32]. The medical benefits of celery were identified many years ago and include the prevention of coronary and vascular diseases. The phytochemicals of celery comprise bergapten, flavonoids, glycosides, furanocoumarins, furocoumarin, limonene, psoralen, xanthotoxin, and selinene. A few of its identified medicinal characteristics are anticancer, antioxidant, antimicrobial, antifungal, nematocidal, anti-rheumatism, antiasthma, anti-bronchitis, hepatoprotective, appetizer, anticonvulsant, antispasmodic, breast milk inducer, anti-jaundice, antihypertensive, and anti-dysmenorrhea activities, the prevention of cardiovascular diseases, and spermatogenesis induction [33].

Celery is composed mainly of water (95%) and dietary fiber; additionally, it contains significant amounts of antioxidants [32]. The usage of the celery plant as a food preservative has increased in recent years, mainly due to its antioxidant attributes. Secondary metabolites of phenolic acids in celery are important as antioxidants [32]. Different EOs such as terpenes, phthalides, and aldehydes contribute to the unique smell and taste of celery. Celery contains a variety of phytochemicals, amongst which limonene, phthalides, β-salinene, coumarins, spathulenol, and flavonoids (apiin) are the primary constituents of celery EOs. The intense fresh-like smell of celery EO is a result of the high concentration of limonene. Enantiomer (R)-(+)-limonene gives a citrusy odor while enantiomer (S)-(−)-limonene gives a pine-fresh odor. Due to its distinct smell, celery EOs are widely utilized in the cosmetic industry, particularly in perfumery, as a fragrance component [34]. Based on the chemical constituents of celery EO, the five major chemical categories are identified as monocyclic terpenes (77.10%), bicyclic terpenes (14.69%), aliphatic hydrocarbons (1.70%), ketones (0.20), and sesquiterpene (2.97%) [35]. Sedanolide, sedanonic anhydride, 3-n-butyl phthalide, and other minor phthalides are reported as primary constituents in celery seed oil [15]. Celery oil and large doses of the seeds can act as a uterine stimulant; therefore, it must be avoided during pregnancy [15].

Many studies have been conducted to find the antioxidant activity of celery EO. EO extracted from the leaves of celery has been tested for in vitro antioxidant and in silico antioxidant activity. The results for the DPPH-induced FRS capacity of the EO ranged from 1.580% ± 0.21% to 32.45% ± 0.2% at concentrations ranging from 0.25 mg/mL to 5 mg/mL Furthermore, the range of absorption in ferric chloride increased from 0.043 ± 0.01 to 0.279 ± 0.02 as the concentration increased from 0.25 mg/mL to 5 mg/mL The antioxidant activity of celery EO was lower than that of the ascorbic acid, which was used as the standard [34]. In another study, celery seed EO composition and antioxidant activity were studied in twelve populations of *Apium graveolens* L. collected from Iran. The results showed that the antioxidant activity of the EO differed in the studied seeds, in the range of Urmia (P12) and Sanandaj (P1) EOs [21]. The plant part which is used for the EO extraction has an impact on the antioxidant activity, as is shown in Table 5.

In another study, the antioxidant activity and chemical compounds of essential oils isolated from celery leaves were investigated. The test results of the DPHH radical scavenging assay showed that the oil isolated from celery has a natural antioxidant capacity [39].

Table 5. Differences in the antioxidant activity of EO obtained from different celery plant parts.

Part	Antioxidant Activity	Reference
Aerial part EO	DPPH radical 84 ± 0.4% at a concentration of 1000 µg/mL	[15]
Celery seed	DPPH radical scavenging activity EC_{50} (mg/mL) with 10.04 ± 0.39	[36]
Celery seed EO from waste celery seeds	Concentration causing 50% inhibition of DPHH is IC_{50} = 89.1 g/L	[37]
Sonicated celery seeds	EO at concentrations between 2.5 and 100 g/L quenched the stable free radical DPPH in a range between 34 and 52%, and 50% inhibition of DPPH radical at 81.63 g/L	[38]
Whole plant	The value of IC50 concentration that inhibits 50% of the DPPH radical was 88.2 mg/mL FRAP test results showed no reducing capacity at concentrations lower than 2.5 mg/mL inhibition of the formation of TBARs 88.15% of EO concentration of 20 mg/mL	[19]

The effect of irradiation on the EO was investigated by El-Beltagi et al. [33], and the results showed an enhanced antioxidant activity of celery EO at different irradiation dose levels, while increasing the oil concentration used from each treatment (in µL) proved that the highest antioxidant activity resulted in the irradiation dose level 10.0 kGy with 88.30, 90.51, and 93.86% for concentrations of 10, 15 and 25 µg oil, respectively, compared to the control samples with 77.15, 81.35, and 84.09% at the same concentrations. Furthermore, the IC_{50} for the essential oil ranged from 54.17 µg/g oil in the control sample to 127.23 µg/g oil in the dose level of 5.0 kGy [33].

5.4. Fennel

Fennel (*Foeniculum vulgare* L.) is an significant spice plant member of the Apiaceae family and is widely grown in many parts of the world [40]. Native regions for the growth of fennel are the Mediterranean region and Southern Europe. Presently, tropical and temperate regions have become cultivation grounds [41,42]. Fennel comprises two subspecies, *F. vulgare* subsp. Piperitum and *F. vulgare* subsp. Vulgare. Some of the common varieties of fennel are var. *azoricum* (Mill.), var. *dulce* (Mill.), and var. vulgare (also known as common fennel) [43]. Fennel is a famous spice in cooking, and its roots, stalks, leaves, and many other plant parts are edible. The dried seeds of fennel are best known for their pleasant smell and taste [43].

EOs from fennel are now used in many industries due to their richness in antioxidants. For example, wild fennel EO extracts are used in the food and pharmaceutical industries. Fennel EOs are extracted for the food industry as a flavoring agent (in bread, pickles, pastries, cakes, biscuits, and sweets), and facilitate the inhibition of the growth of pathogenic microorganisms in products such as cheese, meat, and fish [43].

EO content varies depending on the part of the plant used for the extraction, ranging from 0.21% in stems to 0.83% in leaves and 3.5–6% in seeds. Essential oil of fennel seeds was isolated from *Foeniculum vulgare* Mill. var. dulce with a yield of 1.84 ± 0.04% (*w*/*w* on the dry weight basis) [41]. However, minor variations are seen in fennel umbels during different growth and developmental stages in terms of the oil content and composition [43].

Fennel EO contains more than 30 different types of terpene chemicals [44]. Some significant components are α-pinene, estragol, trans-anethole, α-phellandrene, and fenchone [9]. A GC-MS analysis identified the quantities in percentages of the main components of fennel oil as follows: trans- anethol (84.1–86.1%), fenchone (7.13–8.86%), limonene (3.0–3.3%), and methyl chavicol (2.5–2.7%) [3]. (E)-anethole, fenchone, methyl chavicol, and α-phellandrene

are identified as the main components of the essential oil from fennel umbels. Furthermore, fennel contains many phenolic substances, namely, tannin, coumarin, hydroxycinnamic acids, flavonoids, and phenolic acids [44]. Polyphenols and flavonoids in fennel can prevent the formation of free radicals, thus exhibiting antioxidant properties [44]. Some phenolic components of fennel that showed antioxidant action are caffeoylquinic acid, rosmarinic acid, eriodictyol-7-orutinoside, quercetin 3-O-galactoside, and kaempferol-3-O-glucoside [44]. The antioxidant content in fennel EO is significant for its potential to use as a cardioprotective and anticancer compound [40].

The fennel genotype used can also have an effect on antioxidant activity. In a study by Yaldiz et al., the antioxidant activity of USDA genotypes and local genotypes of fennel were tested. Local gene types of fennels showed a lower content of antioxidant activities compared to USDA genotypes. USDA genotypes showed higher essential oil components compared to local genotypes [40].

According to a study by Abdellaoui et al., the cultivation of fennel under specific conditions or domestication led to a notable decrease in seed yield, seed essential oil yield, and antioxidant activity. Additionally, domestication caused alterations in the phytochemical composition of fennel EO compared to the EO extracted from wild fennel seeds [45].

Wild fennel had the highest seed yield (10.98 $\pm$ 0.4 g/plant) compared to the cultivated plant (9.14 $\pm$ 0.5 g/plant), and the researchers remarked that domestication has not increased the EO yield. The antioxidant activities of EO of wild and domesticated plant seeds were evaluated using an inhibition of β-carotene bleaching assay and a TBARS test. The results showed that the wild fennel seed EO exhibited higher antioxidant activity compared to the domesticated plant seed oil. This can be explained as wild plants are subjected to more natural stresses than cultivated plants, which has enhanced the release of secondary metabolites, hence the wild plant seed EO has a higher antioxidative power [45].

In another study, Ahmed et al. [46] investigated the antioxidant activities of fennel seed EO from Egypt and China. The Chinese fennel essential oil showed high activity in DPPH radical scavenging with an IC_{50} value of 15.66 mg/g, while the Egyptian fennel essential oil showed very low activity with an IC_{50} value of 141.82 mg/g, which shows a great variation according to the geographical location. A similar study showed that fennel EO has considerable antioxidant capacity with IC_{50} values in the range of 11.83–36.90 mg/mL in the DPPH assay, 7.65–20.13 mg/mL in the $ABTS^{+}$ test, and 3.65–15.24 mg/mL in the reducing power assay [47].

The antioxidant activity can also be influenced by the method of extraction. Fennel fruit EO, extracted using the double-condensed microwave-assisted hydro distillation method, showed a higher antioxidant capacity with an IC_{50} value in the DPHH assay of 14.05 µL/mL, compared to EO extracted using the hydro distillation method (18.58 µL/mL). This is due to the fact that the content of oxygenated compounds separated under microwave irradiation is comparatively high [48].

In a study conducted by Milenković et al., the DPPH-radical scavenging capacity assay was performed on EO extracted from fennel, with 40 min of incubation time. The antioxidant activity of fennel stem EO was higher (2.58 mg/mL) than that of fennel leaf EO (6.91 mg/mL). This is due to the higher phenolic content in fennel stem EO [49]. In a similar study, EOs from leaves, umbels, and seeds were tested using a DPHH assay, and the results showed that EOs from different parts showed varying antioxidant capacities, and the best antioxidant capacity was shown by the EO extracted from leaves, followed by umbels, and then seeds [43].

5.5. Anise

Pimpinella anisum is a traditional medicinal herb of the Apiaceae family and is commonly used in the Mediterranean region, Europe, and Africa [36]. Most of the plants of the genus *Pimpinella* are annuals and perennials, and it is a collection of more than 180 species. This plant naturally occurs in South America, Africa, Europe, and Asia [50]; however, the Mediterranean region is identified as the center of the highest diversity [50].

P. anisum is commercially cultivated in many regions as Asia, Europe, Iran, and America [36]. Species of anise are used as wild vegetables and in various other applications, due to its carminative, expectorant, antifungal, antidepressant, mutagenic, insecticidal, estrogenic, antispasmodic, nematocidal, antiseptic, analgesic, sedative, antibacterial, diuretic, antiviral, anti-inflammatory, and antimalarial properties; it is also used as a pectoral stimulant in the treatment of flu, cold, and asthma [36].

The EO of anise seeds has been used as a flavoring agent, and an ingredient in perfumes and toothpastes [51]. The principle active compound of anise EO is trans-anethole. Trans-anethole is identified as the agent for the antioxidant activity and smell of anise EO [51,52]. Furthermore, the antioxidant activity of anise seed extracts is due to the total phenolic composition [53].

Many studies have tested for the antioxidant potential of anise EO. Ghada et al. tested for the DPPH radical scavenging activity of *P. saxifrage* EO and found an IC_{50} value of 6.81 µg/mL. The ability to reduce ferric EC_{50} was 35.20 µg/mL, and for β-carotene basis, the IC_{50} value was 206 µg/mL [36]. In another study by Antonella et al., EOs from flowers and stems of *P. tragium* were tested using DPPH and FRAP assays to determine the capability to activate or inhibit free radicals. The obtained results were compared with relevance to ascorbic acid, gallic acid, and BHT, which are known antioxidant compounds. According to the results, EOs extracted from flowers and stems had higher antioxidant potential than gallic acid [36].

In accordance with the results of a study conducted to evaluate the antioxidant activity of anise EO, a higher scavenging activity of free DPPH (88.3 ± 0.5%) at a concentration 1000 µg/mL was observed. In the same concentrations as anise EO, ascorbic acid gave 97.40 ± 3.65% and catechin gave 93.96 ± 2.63%, which shows that the radical scavenging activity of anise EO was closer to ascorbic acid and catechin [52]. The IC_{50} of anise EO was catechin 14.26 ± 0.2 µg/mL and ascorbic acid 17.21 ± 0.3 µg/mL, which were used as the positive controls [52].

As reported by the researchers in another study, the free radical scavenging activity of DPPH was determined with BHA as the reference. The antioxidant activity of anise EO at the concentration of 10 and 20 µL/mL was nearly 36.02 ± 2.033% and 43.62 ± 1.071%, respectively. The antiradical activity of anise EO at the concentrations of 30, 40, and 50 µL/mL resulted as 58.12 ± 1.238%, 68.42 ± 2.007%, and 77.58 ± 1.044%, respectively. Furthermore, 50 µL/mL of anise EO showed the maximum percentage of radical scavenging activity (77.58%), followed by a concentration of 40 µL/mL (68.42%) [54].

The plant material characteristics, such as the part of the plant used for the extraction and plant maturity, have a direct effect on antioxidant activity. The results of chelating and reducing power assays have shown that the extraction of EO from mature plant parts is related to a higher antioxidant potential [53].

6. Applications of Antioxidants of Essential Oils from the Apiaceae Family and Future Trends

The antioxidant activity of EOs from the Apiaceae family has many practical food and nonfood applications. Fennel EO is widely used in the cosmetics industry and medicine. Current works have shown that fennel essential oil (EO) has bioactive properties, such as antioxidant and antimicrobial activities, which makes fennel EO suitable as a potential ingredient in bioactive packages [55]. Coriander EO serves as a preservative in processed meat products by inhibiting lipid peroxidation [5]. Oxidative spoilage can be controlled in foods such as bakery products, fish, and meat products by incorporating EOs [14]. *C. sativum* EO (0.05–0.15%) inhibited the rate of primary and secondary oxidation with effects almost equal to BHA (0.02%) in cakes [25]. The amount of sodium nitrate used can be reduced (60 mg/kg) when combined with coriander EO (0.12 µL/g), with higher redness and retarded lipid oxidation activity within 52 days of refrigerated storage for cooked pork sausages [56]. Good-quality cumin EO can be utilized in the cosmetic and pharmaceutical industries [57]. However, there can be negative impacts of using EOs, which need further

study. For example, furocoumarins used to treat skin diseases can increase the risk of cancer with long-term usage [58]. More studies are required to identify the antioxidant potentials and their synergistic effects, the activity in the human body, and other potential negative or positive effects of the antioxidants of EOs extracted from Apiaceae plants.

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