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REVIEW ARTICLE

Bioactive Compounds of Fennel Seeds: Their Current Status, Biofunctional Properties, Novel Processing Technologies, and Application

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Abstract: Fennel seeds are well known for their aromatic qualities. They have a rich history of culinary and pharmaceutical use, dating back to ancient civilisations, such as the Romans and Egyptians. These seeds are native to the Mediterranean region and available in diverse varieties worldwide; they are a nutritional powerhouse, containing significant quantities of carbohydrates, proteins, and dietary fibre. They are also a rich source of bioactive compounds, including anethole, fenchone, and limonene, which contribute to their therapeutic potential. Fennel seeds have demonstrated their effectiveness in addressing multiple digestive disorders and shown promise in combating severe ailments, like cancer and cardiovascular diseases. Different extraction methods, including cold plasma, ultrasound, and critical fluid extraction, hold promise for extracting fennel seed oil. In the culinary sphere, fennel seeds are prized for their ability to enhance the flavour of foods, like bread and yoghurt. The essential oil derived from fennel seeds is used for a wide range of applications and can function as a preservative, extending the shelf life of various food products. This review aimed to provide a detailed overview of the botanical traits, dietary makeup, and different medicinal effects of fennel seeds, which can further help to explore the relevant gaps and open doors to the research and exploration of the potential applications of fennel seeds. Additionally, this study aimed to investigate emerging extraction technologies that could enhance the yield of fennel seeds' oil, further paving the way to new explorations in the area of novel food product development.

Keywords: Bioactive compounds, extraction technology, fennel seeds, oil, pharmaceutical application, anti-inflammatory.

1. INTRODUCTION

Throughout history, spices have transcended their culinary origins to play an important role in both gastronomy and medicine. Today, in the modern food industry, they are revered for their ability to enhance food's colour, impart diverse flavours, and extend shelf life with their natural preservative properties. Spices being abundant in bioactive compounds and their nutritional advantages have rendered them essential in tackling numerous health issues resulting from fast-paced living and unbalanced dietary practices [1]. Spices are plant-derived compounds that provide unique aromas and fragrances, improving the overall palatability of the food [2]. The most popular and widely used spices include turmeric, cumin, and coriander. Turmeric is known for its vibrant yellow colour, anti-inflammatory properties, antioxidative properties, and immunoprotective effects [3]. Cumin seeds are known to impart a warm, earthy, and slightly nutty flavour that enhances the depth and aroma of dishes, whereas spices, like coriander, are known to promote a citrusy flavour to food [4]. These spices not only contribute to the sensory appeal of food, but also possess bioactive compounds that support health and wellness [5]. Among the array of health-promoting spices, fennel, called saunf in India, is scientifically known as *Foeniculum vulgare* and is a member of the Umbelliferae family, grown in Asia, the Mediterranean region, and Europe [6]. To the ancient Greeks and Romans, it was a badge of success and glory, whereas Vedic texts crowned it as Madhurika in Sanskrit [7]. Fennel leaves, stalks, and seeds are commonly used in culinary preparations, imparting unique flavours to pickles, pastries, sauces, and soups. They are utilized prominently in pharmaceutics and phytotherapy due to their therapeutic potential [3]. The volatile oil obtained from fennel seeds through various extraction methods has found diverse applications in the food industry for flavour enhancement of food and in therapeutic sectors due to its rich phytochemical profile. Since ancient times, fennel has been used to treat various conditions, such as mouth ulcers, stomach aches, liver disease, arthritis, and leucorrhea. It has been traditionally used as a laxative for treating constipation, kidney disorders, insomnia, gastritis, flatulence, fever, diarrhoea, cancer, and abdominal disorders, such as colitis [8]. Previously, various reviews have primarily focused on the fennel plant as a whole; still, more detailed and comprehensive scientific literature is required to delve

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into the nuances of fennel seeds and their wide-ranging applications [9]. This review has comprehensively explored the diverse applications, processing technologies, pharmacological effects, and functional benefits of fennel seeds, as well as their essential oil, multifold extraction techniques, and various techniques employed to obtain the essential oil. It has also provided an overview of current and potential processing technologies.

2. MATERIALS AND METHODS

An extensive search using various keywords, including fennel, fennel seeds, and fennel seed oil extraction, was carried out using multiple search engines, such as Google Scholar, ScienceDirect, Scopus, as well as Web of Science, and the most relevant and novel information relating to fennel seeds was included.

3. CULTIVATION OF FENNEL SEEDS

Foeniculum vulgare is a herbaceous plant whose height ranges from 1 to 2 meters. It is a perennial plant with feathery, dissected leaves and characteristic yellow flowers with furrowed stems and sheathed petioles, as shown in Fig. (**1**). Its flowers have umbilical inflorescence and a short pedicel (4-5 mm by 1-3.5 mm) consisting of 20-50 bisexual flowers; the flowers are ovular in shape [10].



Fig. (1). Fennel plant at the flowering stage. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

The schizocarp of fennel is elliptical, consisting of a short conical stylopodium at the end. The mericarps are attached to a divided carpophore and separate easily, as shown in Fig. (**2**). Each of the mericarps that remain attached to the carpophore has an elliptical and curve shape; fennel fruits, on drying, are used as fennel spice [11]. The fennel plant and its seeds are fragrant and have a pleasant flavour; their seeds reach 8 mm in length and 3 mm in width (Fig. **3**). There are three significant varieties of fennel produced worldwide, classified as sweet fennel, bitter fennel, and florence fennel [12]. They are grown for different potential uses, as shown in Table **1**. Sweet fennel needs to be cultivated, while bitter fennel grows wild and is considered a weed in some parts of the world, such as the USA and Australia. To directly sow in the field, 8-10 kg/ha of fennel seed is necessary, whereas to raise the seedling in a nursery of 1000 m^2, the required amount of seeds is 2.5-3.0 kg. Nitrogen, P_2O_5 (phosphorus pentoxide), and the use of different microorganisms, like phosphate-solubilising bacteria, such as *Azospirillum*, are known to increase the yield of fennel seeds and their essential oil [13]. *Azospirillium* has been known to contribute to nitrogen fixation, the release of phytohormones, as well as protection from plant pathogens, soil salinity, and toxic components that may be present in the soil [14]. Intercropping has been found to be a technique to improve the yield of fennel seed, as well as its essential oil [15]. Fennel is organically farmed in various parts of the world [1] due to increased awareness of the need for sustainable agriculture [16-18]. Crop rotation and green manure can be utilised to meet the nutritional demands of organically grown fennel [19-22]. Green fennel is obtained by harvesting the umbels when they have grown to about half their full length, typically around 30-40 days after flowering. By following proper agricultural practices, a yield of approximately 2 to 2.5 tonnes per hectare can be achieved. The harvesting process involves multiple rounds to ensure all the umbels have fully matured. It is essential to avoid stacking the harvested umbels. Afterwards, the green fennel is dried in the shade, and the seeds are cleaned by winnowing [4].

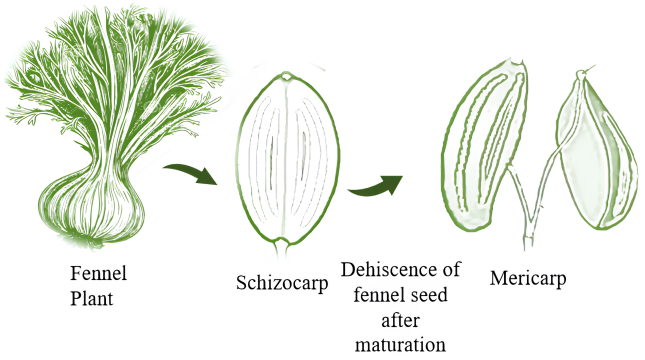


Fig. (2). Schizocarp and mericarp of fennel seeds. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).



Fig. (3). Fennel seeds. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 1. Different potential uses of bitter, sweet, and florence fennel.

S. No.	Aspect	Bitter Fennel	Sweet Fennel	Florence Fennel	References
1.	Essential oil production	Extracted for its potent essential oil and used in aromatherapy and as a natural remedy for colic and pain relief.	Essential oil is used for its pleasant aroma and medicinal properties, including stress relief and skin care.	Essential oil is used in perfumes, skincare, and calming therapies.	[22]
2.	Culinary uses	Used in Middle Eastern and Mediterranean cuisine to add taste and flavour.	Commonly used for its seeds in cooking, baked goods, and confectionery items.	Consumed as a vegetable; used in salads and soups.	[63]
3.	Medicinal applications	Used in traditional medicine for digestive issues, respiratory health, and as a diuretic.	Often used for relieving indigestion, bloating, and cough.	Used for its anti-inflammatory properties and to treat digestive discomfort.	[63]
4.	Aromatic and flavoring	Strong, pungent flavor with a slight bitterness; used in pickle and spice mixes.	Sweet and licorice-like flavor; used in teas, desserts, and as a flavor enhancer.	Mild and sweet flavor, often added to dishes for a subtle taste.	[64, 67]
5.	Nutritional value	Contains dietary fiber, vitamins (e.g., vitamin C), and minerals (e.g., calcium, potassium).	Rich in vitamins A, C, and E, plus essential minerals, like iron and calcium.	High in vitamin C, potassium, and antioxidants, beneficial for overall health.	[65]
6.	Cosmetic uses	Used in homemade skin care products for its antibacterial and antioxidant properties.	Added to skin care products for its moisturizing and soothing effects.	Commonly used in facial masks and skin treatments for rejuvenating properties.	[66]
7.	Agricultural uses	Used as a companion plant to repel pests and improve soil quality.	Acts as a companion plant, especially for repelling aphids and attracting beneficial insects.	Can be grown in gardens for pest control and as an ornamental plant.	[64]
8.	Cultural and traditional uses	Important in some Mediterranean and Middle Eastern rituals and traditional remedies.	Widely used in Italian and Indian cuisines; integral in certain cultural recipes and rituals.	Frequently used in Mediterranean cuisine; symbolic in some cultural dishes and festivals.	[68]

4. TRADITIONAL APPLICATION OF FENNEL SEEDS

Fennel seeds are used in traditional cuisine worldwide, notably in countries, such as Bangladesh, India, Pakistan, Spain, and Italy. Fennel seed-based mukhwas are consumed in India and Pakistan as a digestive aid, alleviating gas, and a mouth refreshener after meals [23]. The seeds are also used in the management of women's health [24] and in the preparation of natural toothpaste; furthermore, fennel oil is used as a flea and mosquito repellent in stables [11]. Fennel seeds are also widely used in the kitchen in the preparation of meat, fish, and vegetable dishes; in addition to their use in savoury and sweet dishes, they are also commonly incorporated into tea preparations, imparting a unique aromatic taste. Traditionally, fennel seeds are employed in making fennel seed syrup. This remedy is known for its effectiveness in alleviating issues, such as flatulence, and is commonly called gripe water. Fennel tea, prepared from fennel seeds, has a carminative effect on the body, helps fight bacterial infections, and efficiently eliminates hookworm [25]. In India, fennel seeds are also considered to promote eyesight. Traditional practices also recognize their efficacy in countering the effects of snake and scorpion poisons [26]. They are also a galactagogue for nursing mothers, as fennel helps enhance milk production. The fennel seeds are also used as a major ingredient in licorice powder and act as a carminative agent [27].

5. NUTRITIONAL COMPOSITION OF FENNEL SEEDS

The moisture content in fennel seeds ranges from 6.24-8.04% [28]. Table **2** shows the nutritional composition of fennel seeds reported by the USDA; however, their composition can differ based on geographical location, soil fertility, soil nutrients, and variety. Fennel seeds contain approximately 52-60 grams of carbohydrates per 100 grams, with a significant portion comprising dietary fibre. Fennel seeds also comprise 15-18 grams of protein per 100 grams, making them a valuable source of plant-based protein. In addition, fennel seeds contain 14-17 grams of lipids per 100 grams, comprising a good amount of unsaturated fats, as well as omega-3 and omega-6 fatty acids [29]. The seeds are also a notable source of several essential vitamins and minerals, such as vitamin C, which acts as an antioxidant and supports immune function, and B vitamins, which are integral to energy metabolism and neurological health. Fennel seeds also

Table 2. Nutritional composition of fennel seeds (USDA).

S. No.	Nutritional Value	Amount	Unit
1.	Calories	345	kcal
2.	Protein	15.8	g
3.	Fat	14.9	g
4.	Ash	8.22	g
5.	Carbohydrate	52.3	g
6.	Fibre	39.8	g
7.	Calcium, Ca	1200	mg
8.	Iron, Fe	18.5	mg
9.	Magnesium, Mg	385	mg
10.	Phosphorus, P	487	mg
11.	Potassium, K	1690	mg
12.	Sodium, Na	88	mg
13.	Zinc, Zn	3.7	mg
14.	Copper, Cu	1.07	mg
15.	Manganese, Mn	6.53	mg
16.	Vitamin C	21	mg
17.	Thiamin	0.408	mg
18.	Riboflavin	0.353	mg
19.	Niacin	6.05	mg
20.	Vitamin B-6	0.47	mg
21.	Vitamin A, RAE	7	µg
22.	Vitamin A, IU	135	IU
23.	Fatty acids (total saturated)	0.48	g
24.	SFA 16:0	0.48	g
25.	MUFA 18:1	9.91	g
26.	PUFA 18:2	1.69	g

contain calcium and magnesium, promoting bone health [28-30].

6. FENNEL SEED POWDER AND FENNEL SEED OIL

Fennel seed powder is the finely ground form of *Foeniculum vulgare* seeds, distinguished by its sweet, aromatic profile with prominent liquorice flavour. It acts as a nutritionally rich functional ingredient in a variety of culinary applications. It is commonly used to enhance the flavour and aroma of savoury dishes, desserts, baked goods, and beverages, and is also used in the formulation of spices and related products [31]. Different milling tools, including hammer mills, rotor mills, and ball mills, can be used to produce fennel seed powder. Several grinding techniques, such as low-temperature grinding with the use of cryogens, have the potential to enhance the quality of fennel seed powder [32-34]. Table **3** depicts the advantages of cryogrinding over room-temperature grinding [35-37]. Fennel seed powder is used as a spice in various regions of the world, such as China and Egypt, as well as the Indian states of Bengal and Orissa [38]. When its decoction is rubbed over the eyes, it aids in the treatment of several eye conditions, including eye irritation and dry eyes [39]. Fennel seeds, their powdered form, and essential oil have also found applications in confectionery products, as well as in the production of soaps, assorted sweets, liqueurs, pickles, meat sauces, and candies. Fennel seed oil is an essential oil extracted from fennel seeds, mostly employing steam distillation. The essential oil extracted is highly concentrated and has a strong, sweet, liquorice-like

Table 3. Normal grinding versus cryogrinding.

S. No.	Aspect	Cryogenic Grinding	Normal Grinding
1.	Grinding type	Grinding is performed at very low temperatures (-50ºC –80ºC) using liquid nitrogen or other cooling agents.	Grinding is performed at ambient temperature, typically using mechanical methods.
2.	Physical impact	Maintains material integrity, resulting in finer particles and a more consistent particle size distribution.	May cause particle size variations due to the heat generated during the process.
3.	Chemical impact	Preserves sensitive compounds, reducing the risk of oxidation and degradation.	The heat generated can lead to chemical changes, oxidation, and possible loss of volatile compounds.
4.	Nutritional impact	Helps retain heat-sensitive nutrients and bioactive compounds, improving nutritional quality.	Nutrient loss is more likely due to heat exposure, which can degrade vitamins and other sensitive elements.
5.	Applications	Ideal for materials prone to heat damage, such as herbs, spices, and certain food products.	Commonly used for general grinding of grains, seeds, and other materials that are less heat-sensitive.
6.	Advantages	Enhances preservation of flavor, aroma, and bioactive properties; produces finer and more uniform powder.	Simpler and more cost-effective; suitable for a wide range of materials.
7.	Disadvantages	Requires specialized equipment and higher energy input due to cooling requirements.	Higher risk of heat-induced degradation and less control over particle size uniformity.

aroma. The bioactive compounds present in the fennel are anethole, fenchone, and estragole, promoting therapeutic effects. Due to its anti-inflammatory, antibacterial, and anti-oxidant effects, fennel seed oil is used extensively in the pharmaceutical, cosmetic, and aromatherapy industries. In the food sector, it is also utilized as a flavouring additive to give food and beverages a distinct, fragrant flavour [39]. It is also used in the cosmetics sector, particularly in soaps and perfumes. The exposure of fennel seed oil to oxygen leads to the transformation of its primary fatty acid component, petroselinic acid, into lauric and adipic acids. These converted acids are in high demand within the soap and cosmetics sectors for their various applications [40].

7. BIOACTIVE COMPOUNDS PRESENT IN FENNEL SEED AND OIL

Fennel seeds are rich in bioactive compounds, encompassing various flavonoids and phenolic compounds. These beneficial compounds are found in both fennel's essential oil and its seeds. The vital bioactive constituents that impart the distinctive flavour to fennel include anethole, fenchone, and limonene, with concentrations ranging from 1.2% to 88.4%, 1.1% to 14.7%, and 5.3% to 15.7%, respectively. The amount of bioactive compounds and their proportion can vary depending on the variety of the seeds as well as their geographical origin [32, 33]. The presence of flavonoids and phenolic compounds promotes a wide range of health benefits. The key flavonoids present in fennel seeds include quercetin, kaempferol, rutin, and chlorogenic acid. The antioxidative action of these compounds plays a crucial role in scavenging free radicals and reducing oxidative stress [41]. Quercetin also has strong anti-inflammatory and immune-boosting properties. It modulates the inflammation pathways, improving cardiovascular health and protecting cells against oxidative damage. Quercetin also improves respiratory function and reduces allergy symptoms, which makes it a multifaceted bioactive component of fennel seeds [42]. Kaempferol is known for its anti-carcinogenic and cardioprotective effects. It inhibits oxidative stress, supports vascular function, and reduces the risk of chronic diseases [43]. Rutin improves circulation and strengthens the blood vessels. It has been found beneficial for managing conditions, like varicose veins, haemorrhoids, and wound healing [44]. The medicinal potential of chlorogenic acid is further enhanced by its ability to fight inflammation and oxidative stress.

8. COMPOSITION OF ESSENTIAL OIL

The wide range of therapeutic properties and distinctive aroma of fennel's essential oil are attributed to its complex composition of bioactive compounds. Anethole, estragole, fenchone, D-limonene, and α-pinene are the significant compounds found in fennel oil [45].

The topography, the season of harvest, and the techniques of extraction employed, along with various agricultural and genotypic factors, determine the composition of chemical compounds present in fennel [46]. The chemical composition of fennel seed essential oil has been scientifically studied, as shown in Table **4** in the form of percentage ranges. The yield can vary depending on the geographical location and the different cultivars.

9. PHENOLIC COMPOUNDS PRESENT IN FENNEL SEEDS

A total of 33 phenolic compounds have been identified in fennel seeds, and their chemical structures are illustrated in Fig. (**4**).

Table 4. Chemical composition of fennel seed essential oil (each component is calculated as % of the total essential oil content).

S. No.	Chemical Components	Percentage Range
1.	α-pinene	0.30 -0.50%
2.	Camphene	0.07-0.12 %
3.	Sabinene	0.11-0.17%
4.	β-pinene	0.03 -0.10%
5.	β-myrcene	0.08-0.26%
6.	I-phellandrene	0.04-0.12 %
7.	p-cymene	0.09-0.26%
8.	Limonene	3.88-6.322%
9.	Trans-β-ocimene	0.14-0.33%
10.	γ-terpinene	0.08-0.16%
11.	L-fenchone	2.82-12.09%
12.	Eucalyptol	0.42%
13.	Carveol	0.21-0.22%
14.	Camphor	0.10-0.31%
15.	Terpinen-4-ol	0.09%
16.	p-anisic aldehyde	0.16-0.50%
17.	Cis-limonene oxide	0.12-0.14%
18.	Trans-limonene oxide	0.15-0.16%
19.	D-carvone	0.14-0.33%
20.	Cis-anethole	0.14-0.25%
21.	Estragole	7.62-88.92%
22.	Trans-anethole	0.14-78.26%
23.	α-fenchyl acetate	0.08-0.22%
24.	Trans-2,8-p-mentha-dien-1-ol	0.09%
25.	Monoterpene hydrocarbons	5.50-7.76%
26.	Oxygenated monoterpenes	3.21-12.62%
27.	Phenylpropanoids	80.64-89.06%

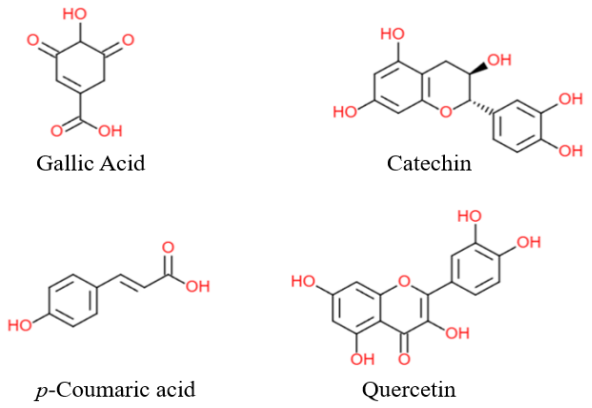


Fig. (4). Chemical structures of some phenolic compounds present in fennel seeds.

The historical use of fennel seeds for enhancing physical and mental well-being is rooted in the pharmacological effects attributed to their numerous bioactive components (Table **5**). This quality positions them as a valuable resource for potential applications in the pharmaceutical industry, and several studies have already delved into their health-promoting benefits. Strong antioxidant activity is one of the fennel seeds' notable qualities; it shields cells from oxidative damage and lowers the risk of chronic illnesses, like cancer and cardiovascular conditions. Their bioactive ingredients, like anethole, have anti-inflammatory properties that help manage respiratory problems, gastrointestinal inflammation, and arthritis. Anethole and fenchone, which have carminative and muscle-relaxing properties, help reduce indigestion, flatulence, and bloating. Fennel seeds are also well known for being beneficial for digestive health. Additionally,

Table 5. Pharmacological effects of the fennel seed and the associated bioactive compounds.

S. No.	Health Protective Activity	Various Related Disease Conditions	Major Bioactive Compounds Responsible for Protection from the Respective Disease	Mechanism	References
1.	Antifungal, antibacterial, and antiviral activities	Periodontitis, severe acute respiratory syndrome (SARS), COVID-19	Fenchone, oleic acid, estragole	Bactericidal activity by swelling of the bacteria, followed by leakage of the DNA (*P. gingivalis*); antiviral activity by blocking the receptor protein, like ACE-2, preventing entry of the virus (COVID-19)	[45, 69]
2.	Antioxidant activity	-	Monoterpene hydrocarbons, including limonene, α-pinene, sabinene, camphene, β-pinene	Free radical scavenging activity	[38, 70]
3.	Anti-inflammatory activity	Allergic reactions, arthritis, asthma, colitis	Quercetin glycoside	Increment of anti-oxidant enzymes (catalase and superoxide dismutase), inhibiting the prostaglandin synthesis of cyclooxygenase-2 and 5-lipoxygenase	[71, 72]
4.	Anti-anxiety and anti-depressant effect	Anxiety and depression	*Trans*-anethole	Increasing the serotonin activity and its levels by activating serotonergic receptors (5-HT) and dopamine receptors	[73, 74]
5.	Gastrointestinal protection	Indigestion, flatulence, and diarrhoea, and peptic ulcer	-	Inhibition of mucosal lesions in the case of peptic ulcer, protective against transepithelial electrical resistance in T84 colonic cells	[61, 75, 76]
6.	Estrogenic-related activities	Lactation problems, menstrual disorders, infertility	Dianethole, photoane, and diosgenin	Increase in the follicular-stimulating hormone	[77, 78]
7.	Cardiovascular activity	Thrombosis, atherogenic dyslipidemia	Anethole	Inhibited platelet aggregation and reduction in the plasma levels	[79]
8.	Anti-diabetic and anti-obesity activity	Diabetes, hyperglycemia, obesity	-	Increase in glutathione peroxidase (GSHPx) activity, reducing oxidative stress in the body	[80, 81]
9.	Anti-cancer activity	Cancer	a-pinene and D-limonene	Apoptosis of cancer cell lines, binding of oncoproteins	[82, 83]
10.	Hepatoprotective activity	Liver cirrhosis, fatty liver	*Trans*-anethole	Increase in the enzymatic antioxidants, like sodium dismutase (SOD); reduction in lipid levels	[84, 85]

they have antibacterial qualities that successfully prevent the growth of several types of yeasts, fungi, and bacteria. The phytoestrogens and anethole in fennel seeds contribute to hormonal modulation, offering relief from menstrual irregularities and menopause symptoms and supporting lactation. Flavonoids and phenolic acids have been associated with potential anti-cancer actions, such as the suppression of cancer cell proliferation and the alteration of cell signaling pathways. Additionally, fennel seeds exhibit anti-diabetic qualities by improving insulin sensitivity and supporting cardiovascular health by lowering cholesterol and oxidative stress. Their therapeutic usefulness is further enhanced by their neuroprotective and antispasmodic properties, which help with ailments, like muscular spasms and neurodegenerative illnesses.

10. APPLICATION OF ESSENTIAL OILS

Essential oils are highly concentrated, aromatic oils extracted from plants and byproducts, including herbs and spices, by various methods, like steam distillation, hydrodiffusion, or supercritical fluid extraction [47]. The demand of consumers in the market for minimally processed foods,

Table 6. Extensive applications of fennel seed essential oil.

S. No.	Aspect	Mode of Action	Key Benefits	Active Compounds	Research Highlights	Industrial Applications	References
1.	Hypoglycaemic activity	Enhances insulin sensitivity, improves glucose uptake, and modulates glucose metabolizing enzymes, like glucokinase	Lowers blood glucose and improves glucose tolerance	Anethole, fenchone, estragole	Animal studies have shown significant blood glucose reduction and improved insulin sensitivity	Used in natural dietary supplements for diabetes management	[86]
2.	Antioxidant properties	Neutralizes free radicals and reduces oxidative stress, protecting pancreatic β-cells and reducing inflammation	Prevents oxidative damage and supports cellular health	Anethole, flavonoids	Shown to lower oxidative stress markers and protect against diabetes-related damage in studies	Added to functional foods and drinks for antioxidant benefits	[87, 88]
3.	Anti-inflammatory effects	Modulates inflammatory pathways and reduces pro-inflammatory cytokines, improving insulin sensitivity	Reduces chronic inflammation associated with diabetes	Anethole, terpenes	Reduces systemic inflammation, aiding in the management of insulin resistance	Included in skincare products and topical treatments	[89]
4.	Antimicrobial activity	Exhibits antimicrobial and antifungal effects by disrupting microbial cell membranes and metabolic pathways	Protects against harmful microorganisms and spoilage	Anethole, estragole	Demonstrated *in vitro* effectiveness against various bacterial and fungal strains	Used in food preservation and natural disinfectants	[90, 91]
5.	Anticancer potential	Contains compounds that may inhibit cancer cell proliferation and induce apoptosis in certain cancer types	May help in cancer prevention and support treatment.	Anethole, flavonoids	Some studies have shown inhibition of cancer cell growth, though more research is needed	Potential use in functional health products and research	[92]
6.	Pain relief (analgesic)	Acts on pain receptors and reduces inflammation, providing analgesic effects	Alleviates pain and discomfort	Anethole, fenchone	Shown to reduce pain perception in animal studies and used in massage blends	Formulated into creams, gels, and oils for topical use	[93, 94]
7.	Aromatherapy and relaxation	Provides a calming effect on the nervous system and helps reduce stress by promoting a sense of well-being	Reduces stress and anxiety, and promotes relaxation	Anethole, terpenes	Widely used in aromatherapy to relieve stress and support mental health	Incorporated in essential oil blends and diffusers	[95]
8.	Flavoring and food industry	Adds a natural anise-like flavor, enhancing the taste profile of foods and beverages	Improves the flavor and sensory properties of food	Anethole, estragole	Commonly used as a flavoring agent in various culinary applications and beverages	Used in confectionery, beverages, and baked goods	[95]
9.	Cosmetic applications	Antioxidant, anti-inflammatory, and antimicrobial properties, benefiting skin health and hygiene	Promotes clearer, healthier skin and protects against infections	Anethole, flavonoids, terpenes	Proven to have anti-inflammatory and antimicrobial effects, suitable for acne-prone and sensitive skin	Included in creams, serums, and cleansing products	[96, 97]

as well as the decreasing indulgence of people in artificial flavours due to health consciousness, has driven the use of EOs as flavouring agents, natural preservatives, and functional food components [48]. Essential oils derived from cumin, fennel, and cardamom provide concentrated seasoning oils that improve the flavour of snack foods as

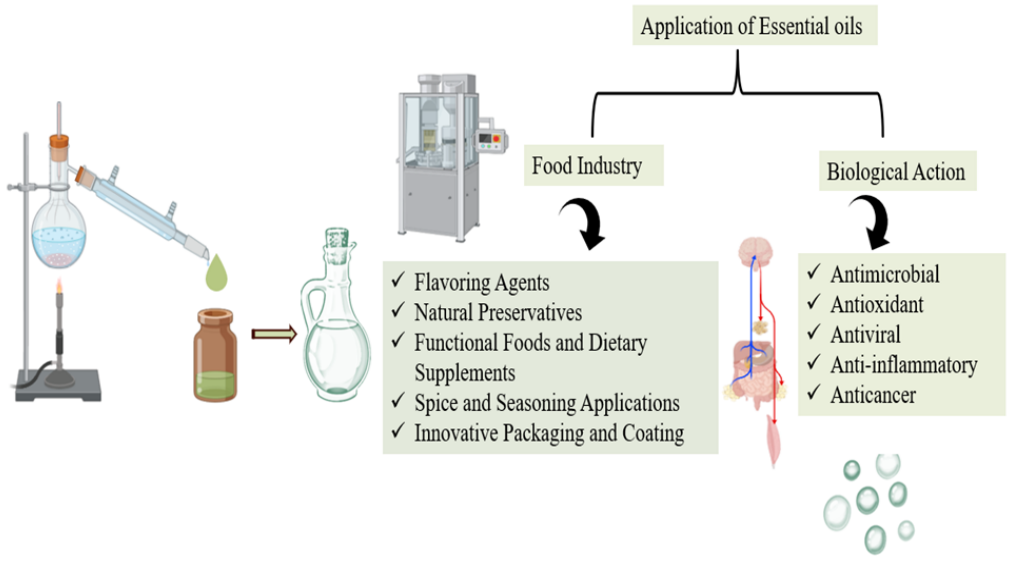


Fig. (5). Application of essential oils. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

well as ethnic cuisine. Essential oils are an effective choice for culinary applications since they are easier to utilize, have a more robust taste, and have been consistently found to be of higher quality than whole spices. Fig. (**5**) represents the application of essential oils.

While essential oils extracted from spices, like clove, cinnamon, and oregano, add powerful flavours to savoury foods and sauces, citrus oils, like lemon and orange, are popular in drinks, pastries, and confections because of their pleasant smell.

Fennel seeds are increasingly being utilized in functional food formulations because of their numerous health benefits, namely their anti-inflammatory, digestive, and stress-relieving effects. In herbal teas, nutraceuticals, and fortified beverages, essential oils (EOs) blend flavour with therapeutic properties to appeal to consumers who are health-conscious as well as provide them with a posh experience. EOs have a substantial effect on food products' visual and sensory appeal [49]. The essential oil derived from fennel seeds also has a wide range of applications, as presented in Table **6**.

11. POTENTIAL EXTRACTION TECHNIQUES FOR FENNEL SEEDS' ESSENTIAL OIL

The extraction process is used to isolate valuable bioactive compounds from natural sources, such as plants, seeds, as well as herbs. It plays a significant role in various industries, like food, pharmaceuticals, and aromatherapy, by enabling the recovery of various functional ingredients, including essential oils and phytochemicals. The choice of extraction method significantly impacts the yield, purity, and chemical composition of the extracted product, making it essential to select a technique suited to the target compounds and their intended applications. Techniques, such as steam distillation, solvent extraction, cold pressing, and modern innovations, like supercritical fluid extraction, have been widely employed to obtain high-quality essential oils from botanicals. Among these, the extraction of essential oil from fennel seeds (*Foeniculum vulgare*) stands out due to the seeds' rich bioactive profile and their extensive use in culinary, therapeutic, and industrial applications. Various conventional and non-conventional techniques may be used to extract the fennel essential oil having abundant bioactive compounds. These extracted essential oils may have multiple applications in both the pharmaceutical and food sectors. Microwave-assisted extraction, a novel technique, utilises rapid heating technology, vibrating the compounds and molecules present in the spice, causing an increase in the temperature and pressure, which, in turn, ruptures the cell, releasing essential oils from the damaged surface. Microwave-assisted extraction is characterized by a low extraction cost, and it is known to cause an increase in the yield of essential oil [50]. Microwave-assisted hydrodistillation of fennel seeds (characterized by a cheap extraction cost) was found to increase the yield of the oil more quickly and using less energy when compared to the traditional hydrodistillation technique [51]. Coaxial microwave-assisted hydrodistillation extraction is another cheap extraction technique applied to spices and herbs, like lavender, rosemary, fennel seeds, and clove buds; it increased the yield of phytochemicals, like oxygenated monoterpenes, in fennel essential oil [52]. Microwave hydrodistillation increased the yield of fennel essential oil by 7.5% when compared to the conventional hydrodistillation technique [53]. The other known techniques that can be used to extract fennel seed essential oil are supercritical fluid extraction (SFE) using CO_2, hydrodistillation (HD), cold atmospheric-pressure plasma (CAPP), and ultrasonic extraction [54-56]. Microwave-assisted extraction (MAE) and supercritical fluid extraction (SFE) improved the efficiency of essential oil extraction from fennel fruits and decreased the total extraction time [54]. The SFE technique extracts essential oils using solvents with pressure and temperature above

the critical point [55]. Enzymatic extraction, which is a novel technique, has been found to increase the yield of essential oil by 11-22.5% in comparison to the control sample [57, 58]. An accelerated solvent extraction technique under optimal conditions leads to a reduction in cost, as well as an increase in the volatile oil compounds of fennel [58]. Cold atmospheric-pressure plasma (CAPP) is a non-thermal technology. The mechanism of atmospheric plasma involves the formation of a substantial, short-lived, stable bubble during plasma bubbling, leading to distilled water disintegration, which causes the uniform distribution of the volatile compounds [56]. This technology has been employed for some spices and can also be explored for fennel essential oil extraction. Ultrasound-assisted extraction (UAE) is a mechanical method based on changing the frequency and amplitude of sound waves. The shock waves produced during ultrasound treatment, including micro-jets, shear, and turbulence, destroy the cellular matrix, which causes an instant release of essential oil and its rapid firing. This technology has already been explored for the extraction of clove essential oil [59-61]. Table **7** represents the various advantages and disadvantages of different extraction technologies [62]. Cryogenic grinding, by applying temperatures ranging between -50ºC and –80ºC and using liquid nitrogen or other cooling agents, in particular, has been instrumental in retaining the quality of essential oils by minimizing the thermal degradation of volatile constituents, further amplifying fennel's commercial potential [35-37, 57]. The cryogenic grinding technique and the supercritical fluid extraction using CO_2 are expensive and suggested for high-priced commercial products.

12. PROCESSING AND ENCAPSULATION TECHNIQUE FOR FENNEL AND ITS ESSENTIAL OIL

Spices are mainly consumed in the form of powder rather than whole seeds; various methods are used to grind the seeds into powder. Fennel seed oil is also extracted for further application in the food and fragrance industry. After grinding, the powder must be stored in cool, dry, airtight conditions to preserve it and extend its shelf life [57]. The volatile oils extracted from the spices are encapsulated in the form of powders to prevent the loss of bioactivity as they are thermolabile and can potentially be incorporated into various food products. The various encapsulation methods employed for essential oil are shown in Table **8**.

Owing to its various health benefits, flavor, and aroma, there is a trend for the encapsulation of fennel essential oil. Currently, various encapsulation techniques are being explored for the extraction of fennel essential oil and its extracts, which are being applied to foods for preservation and flavouring (Fig. **6**). Fennel powder, its oil, and its extracts have huge potential for application in various food products.

Table 7. Advantages and disadvantages of different extraction technologies.

S. No.	Extraction Technique	Advantages	Disadvantages
1.	Solvent extraction (SE)	Protects heat-sensitive substances	Time-consuming, low efficiency
2.	Hydrodistillation (HD)	Low cost, easy to operate	Longer extraction time, low efficiency
3.	Microwave technology (MT)	Low cost, low extraction time	Not available for industrial production
4.	Supercritical fluid extraction (SFE)	Low extraction time, low energy consumption	Expensive equipment, increased production cost
5.	Enzyme-assisted extraction (EAE)	High efficiency, decreased cost	Nil
6.	Ultrasound technology (UAE)	Decreased cost, decreased extraction time	Difficult to guarantee the safety of the device

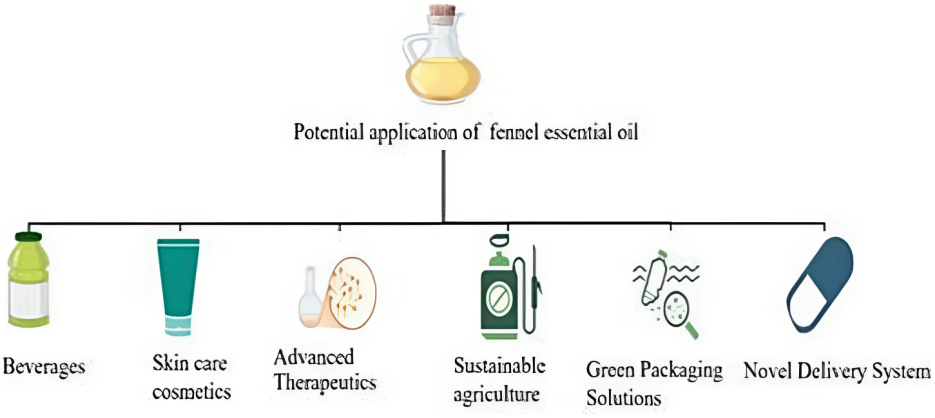


Fig. (6). Potential application of fennel essential oil. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 8. Microencapsulation methods for essential oils.

S. No.	Encapsulation Methods	Encapsulation Techniques
1.	Mechanical methods	• Fluidised bed coating • Spray drying • Freeze drying • Vibrating nozzle • Coaxial electro-spray system
2.	Chemical methods	• Interfacial cross-linking • Interfacial polycondensation • Emulsification
3.	Physicochemical methods	• Coacervation • Use of polyelectrolytes • Complexation • Supercritical fluid technology

A value-added product of *Aonla supari* with various spice powder blends, including fennel seed powder, has been developed [53].

A yoghurt formulation using reconstituted whole milk powder with various concentrations of fennel seed extract was prepared and compared with untreated yoghurt, which showed increased shelf life and improved antioxidant activity [58]. A fortified bread has been developed with fennel seeds and found to enhance bread crumbliness and antioxidant activity when up to 7% fennel was added to the flour [63-65].

The quality of fish was found to be improved with lower lipid oxidation and enhanced antioxidant and antimicrobial properties when 2% of fennel essential oil was applied to the edible nanocomposite coating of the fish. A composite film was created by combining starch sodium octenyl succinate with fennel essential oil and chitosan, demonstrating beneficial effects on preserving and enhancing apple fruit quality during storage. These effects included antifungal properties and improved colour retention [66]. Different mixtures of gum arabic for the encapsulation of fennel oleoresin have been developed [67, 68]. Freeze drying is a recently explored technology for the encapsulation of essential oils due to its many advantages, as shown in Table **9**.

Different processing methods and encapsulation technologies can be employed in the future to preserve the volatile oil compounds, and their application in various food products still needs to be explored.

13. POTENTIAL APPLICATIONS OF FENNEL SEED, FENNEL SEED POWDER, AND ESSENTIAL OIL

As the demand for natural and sustainable products is increasing, the future scope of fennel-based products is poised to expand across various industries. Fennel seeds and their powdered form have been used traditionally for flavouring and as digestive aids. Their integration into functional foods and beverages is set to increase due to their health-promoting properties.

Fennel seeds can be incorporated into specialty teas, digestive supplements, or snack products aimed at supporting gut health and alleviating bloating. Their natural carminative properties make them ideal for such applications [59]. The powder obtained after the grinding of the fennel seeds can be added to baked goods, energy bars, and meal replacement powders, providing both flavour as well as nutritional benefits. The fennel essential oil can be utilised as a natural preservative because of its anti-oxidant and antimicrobial effects, as well as a flavour enhancer in various processed foods and beverages, extending their shelf life and enhancing sensory profiles [60]. The therapeutic properties of fennel seeds, powder, and essential oil make them promising candidates for use in pharmaceuticals and nutraceuticals. Fennel seed powder can be formulated into dietary supplements or capsules aimed at promoting respiratory health, managing hormonal balance, and supporting digestion. The essential oil derived from fennel may be incorporated into plant-based pharmaceutical products targeting inflammation, microbial infections, and oxidative stress-related disorders [61]. Fennel seeds and powder can also be included in natural exfoliating scrubs, face masks, and anti-aging creams. Fennel essential oil can be incorporated into creams, serums, and hair care products that aim to soothe and promote scalp health, reduce inflammation, and combat skin irritations [62]. The bioactive qualities of fennel seed extracts and essential oils make sustainable packaging alternatives possible. The extracts obtained from fennel seeds can be infused into bio-based films and coatings to enhance food preservation and reduce microbial growth, thereby extending the shelf life of packaged foods.

Fennel seeds can be researched for advanced therapeutic uses owing to their benefits related to cardiovascular health as well as combating many non-communicable diseases, including diabetes. They may be focused for their role in

Table 9. Comparative analysis of freeze-drying: advantages and disadvantages.

S. No.	Property	Advantages	Disadvantages	References
1.	Preservation of nutritional and bio-active compounds	Ensures minimal degradation of heat-sensitive and volatile components due to low-temperature operation	Requires prolonged process times, which may limit its application for time-sensitive needs	[98]
2.	Thermal impact	Minimal thermal degradation, preserving the integrity of bioactive compounds and sensitive materials	Limited by the need for a vacuum system and low operational temperatures, increasing system complexity	[98]
3.	Shelf-life	Produces highly stable, low-moisture products with extended storage life	High energy demand for achieving low moisture levels impacts overall cost efficiency	[99]
4.	Physical and sensory properties	Maintains product shape, color, texture, and flavor, making it ideal for premium applications	End products are brittle and prone to damage, requiring careful handling and specialized packaging	[100]
5.	Rehydration characteristics	Excellent rehydration due to the porous structure, ensuring quick water absorption	A porous structure can make products more susceptible to oxidative damage if improperly stored	[101]
6.	Operational costs	Produces high-quality, premium products suitable for niche markets	Substantially high capital investment and operational costs restrict broader application	[102]
7.	Time requirements	Controlled sublimation ensures optimal quality preservation	Long processing times reduce throughput, making it unsuitable for large-scale operations	[103]
8.	Scalability	Ideal for small-batch, high-value products in pharmaceuticals, biotechnology, and food industries	Batch processing limits scalability for continuous or mass production	[104]
9.	Applications	Extensively used in high-value sectors requiring preservation of sensitive materials	Limited adoption in cost-sensitive sectors due to high economic barriers	[105]

managing chronic diseases, such as diabetes, cardiovascular disorders, and metabolic conditions, leveraging their anti-inflammatory and antioxidant effects. The eco-friendly nature of fennel seed and its oil can make valuable contributions to sustainable farming practices. Fennel seed powder could be employed for soil fertility and to improve pest resistance. The essential oil can be improvised as a natural pesticide and herbicide, acting as a natural alternative to chemical fertilisers. Fennel seed powder can be encapsulated for controlled, sustained release in nutraceuticals or functional foods, ensuring optimal absorption and efficacy, and serving as a novel delivery system. Nano-encapsulation of the fennel essential oil can enhance the stability, bioavailability, and targeted delivery of the essential oil in both food and pharmaceutical applications, improving its effectiveness and safety profile.

CONCLUSION

Fennel seeds have garnered significant attention for their rich phytochemical profile, comprising flavonoids, phenolic acids, and dietary fibres, as well as essential oil. These compounds have a variety of bio-functional qualities. The antibacterial, anti-inflammatory, antioxidant, and digestive health-promoting properties of fennel seeds make them an invaluable natural resource for the culinary, pharmaceutical, and nutraceutical industries. Fennel seed and its essential oil have many potential applications and can easily be produced worldwide for culinary and therapeutic purposes. Its unique flavour allows for its incorporation into various food systems, such as vegetable preparation and pasta. Fennel seeds have the ability to treat multiple ailments, like gastric disorders, and prevent grave diseases, such as cancer and cardiovascular conditions. Innovative techniques, such as microwave and ultrasonic extraction, can lead to efficient oil extraction with minimal energy consumption. At the same time, a range of encapsulation technologies, such as freeze-drying, offer opportunities to enhance shelf life and facilitate the incorporation of bioactive components, essential oils, and oleoresins into various food systems, such as yoghurt. However, other potential applications of fennel still need to be explored. Cryogenic grinding, in particular, has been instrumental in retaining the quality of essential oils by minimizing the thermal degradation of volatile constituents, further amplifying fennel's commercial potential. Bioactive compounds from fennel have demonstrated exceptional promise for increasing the shelf life, enhancing sensory qualities, and providing health advantages when added to food products. However, issues, including scalability, the affordability of sophisticated extraction techniques, and the stability of bioactive compounds throughout the processing and storage, limit industrial use. The bioavailability and functionality of fennel bioactive compounds can be greatly improved by addressing these constraints through optimization research and the creation of novel delivery methods, like encapsulation. For the optimisation of fennel,

future studies should focus on cost-effective extraction, industrial scalability, and the investigation of synergistic effects with other bioactive components. Ongoing technological advancement, as well as research processes, has opened up enormous potential for fennel to be explored as a healthy, sustainable ingredient for a wide range of industrial uses. The gaps in the literature and potential biases in existing research are related to the need to extend the research in different geographical areas of the world.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: original draft preparation: CL; writing, review, and editing: MM, AMG. All authors have reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

CAPP	=	Cold atmospheric-pressure plasma
EO	=	Essential oil
EOs	=	Essential oils
HD	=	Hydrodistillation
MAE	=	Microwave-assisted extraction
SFE	=	Supercritical fluid extraction
UAE	=	Ultrasound-assisted extraction
USDA	=	United States Department of Agriculture

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CONFLICT OF INTEREST

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