Nutritional, Therapeutic and Food Industrial Aspects of Fennel Seeds (Foeniculum vulgare): A Comprehensive Review

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Fennel (Foeniculum vulgare), a perennial aromatic herb belonging to the family Apiaceae, has been valued since ancient times for its medicinal, nutritional, and culinary properties. Originating from the Mediterranean region, fennel is now cultivated globally, particularly in India, Egypt, and Italy. It is rich in essential nutrients such as potassium, calcium, iron, vitamin C, and dietary fiber, which contribute to digestive health, metabolic balance, and cardiovascular support. Phytochemically, fennel seeds contain volatile compounds like anethole, fenchone, and estragole, along with phenolic acids and flavonoids, including quercetin and rosmarinic acid, that exhibit strong antioxidant, antimicrobial, and anti-inflammatory activities. These bioactive constituents are responsible for fennel's diverse therapeutic benefits, such as relieving gastrointestinal disorders, reducing oxidative stress, and regulating hormonal balance. Moreover, fennel has shown potential anti-diabetic, anti-obesity, and anticancer effects in various experimental studies. In traditional medicine, it is widely used to promote lactation, alleviate menstrual discomfort, and enhance memory. In the food industry, fennel seeds and their essential oils serve as natural flavoring agents in bakery items, confectionery, beverages, and spice blends. Additionally, fennel demonstrates environmental significance through its insecticidal and larvicidal activities, offering eco-friendly pest control alternatives. Due to its broad pharmacological and industrial applications, fennel remains a promising plant resource for functional foods, natural therapeutics, and agro-based innovations. Updates on F. vulgare, including its nutritional composition, traditional system use, pharmacological attributes, and significant potential as laborious cooking ingredients, were compiled in this chapter.

Keywords: Fennel Seeds, Pharmacological Aspects, Industrial Applications.

Introduction:

From ancient civilizations to the modern era, plants have played a significant role in medical and therapeutic procedures. Many plant parts have been utilized for a long time to treat as well as to prevent a variety of illnesses. Maintaining health and improving human wellbeing through the use of medicinal herbs is still a worthwhile and proven strategy [1]. Medicinal herbs have a few adverse effects, as they possess antioxidant properties as compared to synthetic medications; they reduce the toxicity of other pharmaceuticals [2]. Moreover, the natural components enhance biological balance and prevent drug accumulation. As a result, a variety of illnesses can be treated by using these plants [3]. Globally, more than 5,000 of the approximately 422,000 flowering plant species are known to have therapeutic properties. In the food, pharmaceutical, cosmetics, and healthcare sectors, fennel seeds play a crucial role. Although native to the Mediterranean region, fennel grows well in temperate climates. Due to the abundance of wild fennel, the earliest people on Madeira named this plant "Funchal" which combines the word funcho (fennel) with a suffix. Fennel seeds were also grown in Spanish gardens, and eventually the practice made its way to California, where it started to grow as a wild herb [4].

In England, kitchen gardens or colonies, this herb was brought by English settlers. The Greeks gave the name Marathron to fennel. The Battle of Marathron was named after this plant because it was found in a field of Marathron. The dark green and feathery leaves and grooved stalks of fennel are the characteristics of this perennial herb. It is a flowering plant that has yellow blooms in clusters that resemble oval pearls and are formed like umbrellas. These blooms have regular or irregular shapes and are usually bisexual [5]. The scientific name for fennel is Foeniculum vulgare Mill., which is called "Fennel" in English and "Fenouil" in French. A member of the Apiaceae family, which is widely distributed in Asia and Europe and is renowned for its sweet and fragrant aroma. Fennel seeds are typically around 8mm in length and 3 mm in width. They are elongated, slender, and tubular in shape. Depending on the growth conditions of the plant, they have different sizes [3].

Table 1. Taxonomic Classification [6]

Kingdom	Plantae
Sub-kingdom	Virideplantae
Class	Magnoliopsida
Order	Apiaels
Family	Apiaceae
Genus	Foeniculum Mill
Specie	Foeniculum vulgare Mill

Nutritional Composition of Fennel Seeds:

Fennel is a low-calorie herb that helps in digestion and enhances feelings of fullness due to its high dietary fiber content. Fennel seeds provide a modest contribution to daily protein intake despite their low protein content. Unsaturated fats make up the majority of its low-fat composition. Vitamin C in good amounts is present in fennel seeds, which is essential for a functioning immune system and healthy skin. Vitamin A in small amounts is found in fennel, which is essential for eyesight and strong immune function. Vitamin K is abundant in fennel

seeds, is necessary for healthy blood coagulation, and for maintaining strong bones. Additionally, it has a trace amount of folate, which is essential for DNA synthesis and cell growth [7].

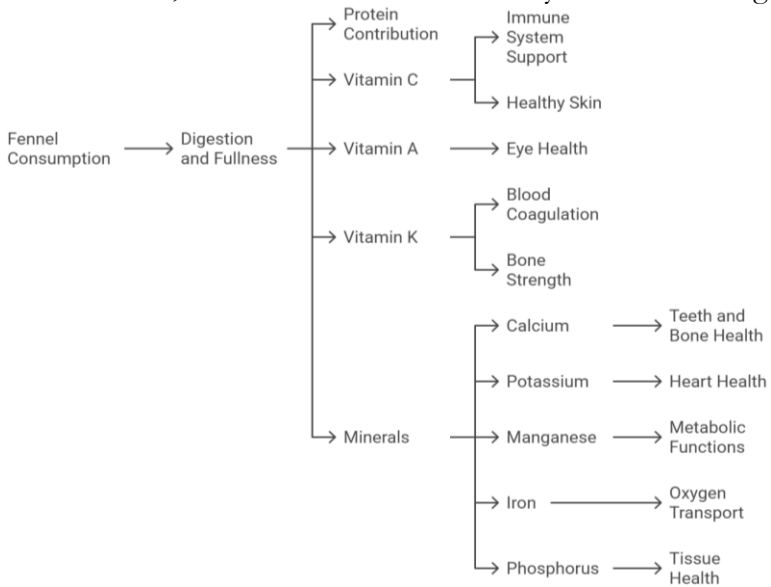

Figure 1. Nutritional profile of fennel seeds (Foeniculum vulgare Mill.) & their functioning [7][8].

Fennel contains calcium, which supports healthy teeth and bones. Fennel is also rich in potassium, a mineral essential for maintaining heart health and fluid balance. Additionally, manganese is also present in fennel seeds, an important trace mineral that supports many physiological processes in the body. Fennel provides a sufficient amount of iron, essential for oxygen transport in the blood. It also contains phosphorus, which supports healthy bones and tissues, along with a small amount of magnesium, which is essential for various metabolic activities in the body [8].

Table 2. Nutritional composition of fennel seed [9][10]

Nutrients	Amount (g/100g)
Caloric Energy	31 kcal/100g
Protein	1.24
Lipids	0.2g
Carbohydrate	7.3 g
Fiber	3.1 g
Moisture	71.31-77.46 mg/kg
Sugar	3.93g
Minerals	
Mg	17mg
Na	52mg
P	50mg
Zn	0.2g
Ca	49mg

Fe	mg
Vitamins	
Vitamin C	12mg
Thiamin B-2	10.1mg
Riboflavin B-2	0.032mg
Niacin B-3	0.64mg
Lipids	
Total saturated fatty acids	0.09g
Monounsaturated fatty acids	0.068g
Poly-saturated	0.169g
Essential amino acids	
Leucine	0.63g
Isoleucine	0.73g
Trptophane	0.53g
Non-essential amino acids	
Glycine	0.53g

Phytochemistry and Volatile Compounds:

Phytochemical analysis of fennel seeds has revealed the presence of many kinds of compounds, such as hydrocarbons, phenolic compounds, volatile components, fatty acids, and secondary metabolites. Some of these phytochemicals have also been identified in the essential oil of fennel seeds. Certain parts of fennel have been utilized as anti-aging and coloring agents [11]. The pentane extracts of fennel seeds, stems, and leaves contain varying amounts and compositions of volatile compounds [12]. A total of 28 chemicals were found in the critical CO2 (SCCO2) seed extract of Fennel seeds, with the main ones being methyl chavicol (5.09–9.10%), trans-anethole (68.6–75.0%), and fenchone (8.40–14.7%). From the hydro-distilled oil of Foeniculum vulgare I, only 19 compounds were detected [13].

Flavonoid and Phenolic Compounds:

Flavonoids are generally regarded as potent antioxidants. The hydroalcoholic extract has been found to contain a total flavonoid content of 12.3 ± .18 mg/g in fennel seeds. Foeniculum vulgare contains flavonoids that have been discovered and isolated, including quercetin-3-rutinoside, Rosmarinus acid, and eriodictyol-7-rutinoside [14]. Isoquercetin, quercetin-3-glucuronide, kaempferol-3-glucuronide, quercetin-3-arabinoside, kaempferol-3-arabinoside, and isorhamnetin glucoside are the most common flavonoids found in Foeniculum vulgare [14]. The phenolic chemicals found in Foeniculum vulgare are utilized to prevent oxidative stress-related illnesses like cancer, inflammation, and cardiovascular ailments. These consist of flavonoid aglycones and glycosides [15]. The methanolic extract of fennel contained more total phenolic components than flavonoid compounds. Phenolic acids such as 3 O-caffeoylquinic acid, 1,3-O-di-caffeoylquinic acid, 1,4-O-dicaffeoylquinic acid, 4-O- 4-O-caffeoylquinic acid, 5-O-caffeoylquinic acid, and 1,5-O-di-caffeoylquinic acid have been found in Foeniculum vulgare [16].

Production and Cultivation Area:

Fennel seeds are cultivated worldwide under a wide range of ecological and climate conditions. The Mediterranean region, where fennel is native, remains one of the leading production areas. Other major producers include Italy, India, Greece, and Spain, with Indian cultivation concentrated primarily in the states of Gujarat and Rajasthan [17]. Indian fennel is highly valued for its distinct aroma and flavor, while Egyptian fennel is renowned for its superior quality. The Fayoum region is known for producing high-quality fennel. In the United States, California is a prominent fennel-growing state due to its ideal climate, and its produce is distributed both domestically and internationally [18].

Climate and Soil:

Fennel grows best in a cool and dry climate, which also improves both the yield as well as quality of the crop. Fennel seeds can be cultivated in any soil that is rich in organic matter; however, they do not thrive in sandy or shallow soils [19]. The best soil to grow fennel is black cotton soil and loamy soil with lime (such as Gujarati soils and United Provinces). Another essential requirement is proper drainage for the purpose of growing fennel commercially. Fennel is inappropriate in areas that are impacted by salt and water [20]. The optimal temperature for growing fennel seeds is around 15- 20°C, as higher temperatures can cause premature flowering and reduced seed production. Fennel can thrive in a wide range of soils with a pH of 5.5 to 7.5 and tolerate annual precipitation between 0.3 and 2.6mm [5].

Role of Microbes:

Bacteria play a crucial role in influencing the growth, development, and overall ecological interactions of plants. Fennel roots have symbiotic associations with microbes, particularly mycorrhizal fungi and beneficial soil bacteria, which improve nutrient uptake and encourage the health of plants. These microorganisms are vital for nitrogen fixation, as they help to convert atmospheric nitrogen into a form that plants can readily utilize [21]. Moreover, mycorrhizal relationships improve stress tolerance and water absorption. The interaction between the roots and soil, known as the rhizosphere, creates a dynamic microbial population that affects the physiology and disease resistance of the plant [22]. Additionally, microbial interactions in the soil surrounding fennel may influence the plant's aromatic compounds and therapeutic qualities by assisting in the generation of essential oil. Overall, the intricate interaction between fennel and bacteria underscores the vital role these microorganisms play in shaping the plant's functional traits and ecological resilience [23].

Types:

Cultivated fennel is classified into two main types: sweet fennel and bitter fennel. Sweet fennel, also known as French or Roman fennel, grows well in countries such as Czechoslovakia, France, Germany, Italy, Russia, Hungary, India, and Argentina. However, it does not thrive in regions like France, Bulgaria, and Macedonia. Candied fennel seeds, another name for fennel seeds coated in sugar, are a delightful treat that is popular among people from many different nations. The outer layer of these fennel seeds is coated with sugar or sugar syrup, giving them a crisp texture and a sweet flavor [24].

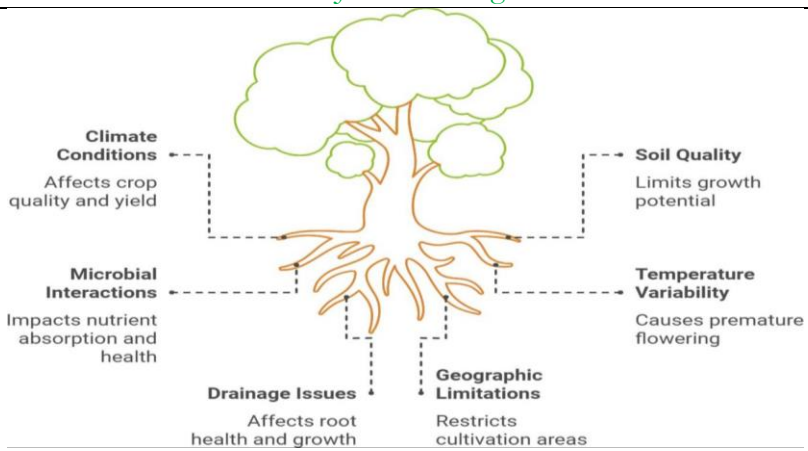

Figure 2. Inconsistent of fennel seed production [17][20][23]

Processing Techniques:

Harvesting:

Fennel seeds are usually harvested 80 to 100 days after planting, once the plants have fully matured. Proper timing of harvest is crucial to ensure that the seeds retain their maximum flavor and quality. It is essential to harvest fennel flower heads before they start releasing seeds, but after they have nearly matured. Early morning is the ideal time for collection, as the plants experience less stress and retain higher moisture levels. Use secateurs or scissors to carefully cut the entire fennel umbels at this stage [25].

Post-Harvest Processing:

Florence fennel is a bulb-less kind of common fennel that is grown from green leaf stems. Fennel comes in a plastic bag that keeps for up to five days and is quite cool. Harvesting under favorable conditions, primarily for the green fennel. Before winnowing, the dried umbels are cleaned to eliminate dust, debris, and chaff. The moisture content of the seeds should be maintained at 9%. Standard-sized packets are used to pack the cleaned, dried, and graded seeds [25].

Drying and Cleaning:

Fennel seeds need to be dehydrated properly to maintain their quality. Different drying techniques may affect the chemical composition and the seed's flavor [25]. Different methods are used, like air drying, sun drying, dehydration, and other drying methods. These procedures may impact the moisture level, flavor, aroma, and shelf life. After drying and being separated from the flower heads, fennel seeds need to be thoroughly cleaned to remove any remaining plant material or contaminants. The cleaning procedure may include manual hand-picking, sieving, or winnowing. Vibrating screens and air classifiers are mostly used for cleaning seeds. For consistency in the final product, fennel seeds are graded based on size, keeping smaller seeds separate from larger ones. Any residual dust or dirt is then removed by cleaning and rinsing the seeds with either air or water [26].

Packaging of Fennel:

Due to their hygroscopic nature and extreme sensitivity to moisture, spices and spice-derived goods can absorb moisture and cause caking, hydrolytic rancidity, mold growth,

discoloration, and insect attack [27]. Additionally, they contain volatile aromatic compounds, and ineffective packaging can cause these principles to be lost and external odor to be absorbed, which can cause major issues, particularly with ground spices. Spices packaging is customized to meet particular requirements and may employ a variety of shapes and materials. These consist of cloth bags, poly pouches, gunny bags, polywoven bags, or jute bags, glass bottles in various shapes and sizes with labels and plastic or metal caps, and flexible pouches such as pillow pouches, gusseted pouches, and stand-up pouches. Based on specific packaging requirements, flexible pouches for fennel seeds are produced in various laminated structures, including polyester/metalized, polyester/LDPE, BOPP/metalized, polyester/ Al, foil/LDPE, BOPP/LDPE, and aluminum foil laminates [25].

Storage:

It is essential to keep fennel seeds correctly to prevent spoilage. Storage conditions may affect seed quality both seed quality and shelf life. Fennel seeds should be stored in an airtight container, by maintaining the right environmental conditions to extend their shelf life while retaining their flavor and therapeutic attributes [28].

Figure 3. Fennel seed harvesting and processing [24][25][26]

Quality Assessment of Final Product:

According to the Food Products Standard & Food Additives Regulations, 2011, set by the FSSAI, specific guidelines must be followed during the processing of fennel (Saunf). The product should possess a characteristic aroma and flavor, free from rancidity, mustiness, or any foreign odors. The product should be completely free from contamination, mold, live or dead insects, and insect fragments. It must not contain any harmful substances or artificial coloring agents. Additionally, it should comply with the following quality standards [29].

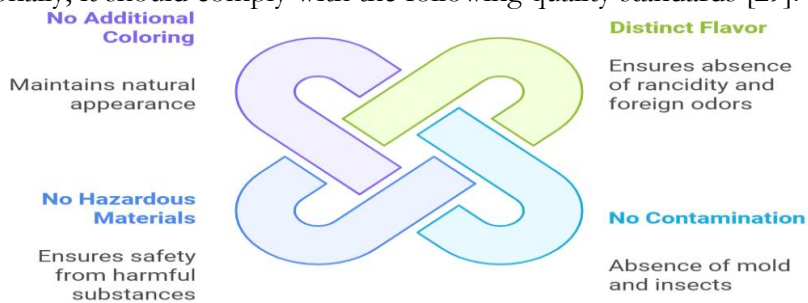

Figure 4. Quality assessment of fennel seed [28]

Culinary Uses:

Fennel is a flavorful and aromatic herb that can be used both in cooking and therapeutically [30]. Fennel seeds are typically used as flavorings in meat and fish recipes, alcoholic beverages, ice cream, and herb mixtures, because of their anise-like aroma. The fennel plant's bulb, seeds, and leaves are widely used in a variety of international culinary traditions. It

is primarily utilized in Mediterranean cooking, where leaves and bulbs are used in both fresh and cooked meals, in salads, pasta meals, and vegetable and side dishes [31]. There are numerous civilizations in India where fennel seeds are used in cooking throughout the Middle East and the subcontinent. Fennel is a member of the most important spices in Gujarati and Kashmiri cuisine.

Therapeutic Aspects of Fennel Seeds:

Many health issues have been treated with fennel for thousands of years in traditional medicine, which has a long history of human use. In the fifth century, fennel was believed to have comforting properties, and from the ninth to the fourteenth centuries, it was attributed with many health benefits. The Romans believed that fennel seed might improve sight. The herb was believed by the English to assist in digestion and console a bloated stomach. Fennel has been used therapeutically since the 18th century, and numerous studies have been done on the subject. In modern medicine and traditional remedies, different parts of the fennel plant are employed to address numerous health issues, particularly digestive ailments. It is also known for its therapeutic benefits in treating diabetes, kidney stones, pneumonia, and other chronic conditions. Moreover, fennel seeds are often used as an ingredient in cream-based preparations. The plant's diuretic properties make it useful for treating kidney and bladder issues. It is also utilized to lessen nausea and vomiting. The herbs can be used to treat gastrointestinal, urinary, respiratory, and hepatic tract blockages in addition to chronic fever. Fennel seeds are also used to treat disorders of the respiratory, endocrine, reproductive, and digestive systems, as well as illnesses affecting the eyes and the stomach, such as chronic diarrhea. Moreover, it is also employed in the use of a galactagogue agent for nursing mothers [32].

Antimicrobial Action:

Due to the presence of compounds like linoleic acid, oleic acid, 1,3-benzenediol, 2,4 2,4-undecaprenyl, and 5-hydroxyfuranocoumarin, which are crucial components of the plant's antibacterial qualities, fennel is used to treat a variety of infectious bacterial, viral, fungal, and mycobacterial conditions. The aqueous extract of fennel has been shown to have bactericidal effects on Salmonella typhi, Shigella flexneri, Enterococcus faecalis, Pseudomonas aeruginosa, Escherichia coli, and aureus [33]. According to one study, this plant extract significantly inhibits the growth of most bacteria, with the exception of Klebsiella pneumoniae and one strain of Pseudomonas aeruginosa. Additionally, this study determined the alcoholic and fennel seed aqueous extracts' minimum inhibitory concentrations (MIC), which ranged from 20 to 80 mg/ml and 5 to 15 mg/ml, respectively [34].

Antioxidant's Activity:

Natural antioxidants are abundant in fennel seeds. This plant's abundance of flavonoids and polyphenols can help prevent the formation of free radicals. This plant's phenolic components, including "eriodyol-7- orutinoside, caffeoylquinic acid, rosmarinic acid, quercetin 3-O-galactoside, and kaempferol-3-O-glucoside," revealed antioxidant properties. Moreover, volatile oil from fennel exhibits potent antioxidant qualities. In contrast to their essence, plant aqueous and ethanolic extracts exhibit antioxidant activity [35]. Marinov et al. revealed the total antioxidant content (TAC) and total phenolic content of fennel seed components. The Folin-Ciocalteu, DPPH, H_2O_2, and FRAP reagents were used to measure TAC for phenolic compounds. This study showed that fennel extracts may act as the primary antioxidant and can

inhibit free radicals. Many antioxidant techniques were used, such as hydrogen peroxide scavenging, total antioxidant metal, free radical scavenging, superoxide anion radical scavenging, and chelating activity, to assess the antioxidant activity of the fennel seed extracts both in aqueous and ethanolic forms. These antioxidants were contrasted with well-known antioxidants such as butylated hydroxyanisole, butylated hydroxytoluene, and α-tocopherol. According to the study's findings, fennel seeds may contain a lot of natural antioxidants. Furthermore, alpha-tocopherol and antioxidant activity were 99.1% and 77.5%, respectively, in 100 mg of the ethanol and watery extracts [33].

Anti-Fungal Activity:

Fennel exhibits strong fungicidal properties, effectively inhibiting various fungi, including Candida albicans and Aspergillus species. Research indicates that fennel extracts show limited inhibitory effects against food spoilage molds, with recorded values of 750 µg/ml for Fusarium oxysporum and 250 µg/ml for Aspergillus nigar [36]. Additionally, derivatives from fennel stems possess anti-fungal activity against molds such as Bacillus subtilis, Cladosporium cladosporioides, and Aspergillus niger. Anethole is a more potent anti-fungal compound compared to other fennel derivatives such as scopoletin. In one clinical study, fennel seed extract was shown to generate free radicals and enhance macrophage nitric oxide production, demonstrating significant anti-Canidida activity. Overall, fennel compounds and extracts exhibit strong anti-fungal potential [37].

Anti-Inflammatory Activity:

Fennel seeds contain flavonoids and polyphenols that have anti-inflammatory effects. Fennel fruit extract has inhibitory effects on type 4 allergy reactions. Moreover, it reduces the activity of superoxide dismutase (SOD) and catalase (CAT). Research studies (Mostafa et al.) revealed that provide insight into the benefits of using fennel seeds in managing conditions like IBS, as well as gastritis [38]. It has been demonstrated that the fennel seeds possess anti-inflammatory properties and help to inhibit the growth of bacteria responsible for causing acne.

Memory Preservation Activity:

Fennel plants have been found to enhance cognitive function, including intelligence and memory. Foeniculum vulgare exhibits strong antioxidant activity, which has been associated with improved learning and memory, particularly when used in combination with Origanum vulgare [39]. In vivo animal studies have shown that the aqueous extract of Origanum vulagre can significantly improve memory performance in male rats. Fennel extract has been reported to alter amnesic mice by acting as a neurotrophic factor and an anti-acetylcholinesterase. The effect indicated that the activity of the enzyme acetylcholinesterase was restrained. Hence, fennel may be utilized in the treatment of disorders associated with psychological symptoms, including Alzheimer's disease and schizophrenia [40].

Anti-Mutagenic and Anti-Cancer Activity:

Numerous studies have revealed fennel's possible anti-mutagenic and cancer chemo preventive properties. For instance, it has been shown that fennel seed extracts, both crude and fractionated, showed strong cytotoxic effects on breast cancer cell lines. Moreover, d- d-limonene and α-pinene demonstrated strong binding energies (each representing −6 and −5.9 kcal/mol) to the target breast cancer cell in silico analysis [41]. It is essential to remember that the effect appears to be dependent on the cancer cell lines, as the crude extract of fennel did not

exhibit significant inhibition [39]. In addition, the ethanol extract of fennel seed has shown potential anti-hepatocellular carcinoma by interacting with the inhibition of hepatocellular cancer and oncoprotein survivin [42].

Anti-Anxiety and Anti-Depressant Effects:

Anxiety is often experienced as an overwhelming sense of fear or panic, sometimes accompanied by symptoms such as acute paranoia. It represents a psychological condition marked by intense emotional distress and internal mental disturbances that can significantly affect daily functioning. Fennel has been used as a traditional therapy to reduce anxiety and other psychiatric problems [42]. In addition, 21–27 mg of fennel comprises anethole in fennel seeds, which was found to improve depressive symptoms among depressed postmenopausal women. Essential oil obtained from fennel seeds, which mostly contains trans-anethole, has the best anxiolytic activity than antidepressants. Whereas the fennel extract possessed less anxiolytic effect in comparison to the test drug [43].

Regulate Blood Pressure & Reduce Retention of Water:

According to research in the Journal of Food Science, eating fennel seeds raised the amount of nitrite in saliva, which makes it a superior natural method of controlling blood pressure. In addition, fennel seeds are an excellent source of potassium, which is necessary for cells and bodily fluids and helps in blood pressure and heart rate regulation. Drinking fennel tea every day aids in flushing out extra fluids because it is a diuretic. Additionally, fennel seed reduces the likelihood of urinary tract issues and aids in the removal of pollutants. Fennel possesses diaphoretic attributes that make you sweat more [44].

Fennel Tea for Bloating, IBS, Indigestion, and Constipation:

Due to the essential oils present in fennel seeds, fennel tea is considered highly effective in alleviating bloating, indigestion, and constipation. Estragole, anethole, and fenchone are found in fennel seeds, which help explicate the plant's antispasmodic and anti-inflammatory qualities. By encouraging the synthesis of gastrointestinal enzymes, the volatile oils in fennel seeds can help people with IBS start their digestion. With its numerous gastrointestinal benefits, fennel tea is known to promote a healthy and well-functioning digestive system.

Reduce Asthma & Purification of blood:

Fennel seeds contain phytonutrients that help in clearing sinus congestion. Sinusitis, an inflammatory condition affecting the cavities around the nasal passage, can be alleviated with the aid of these beneficial compounds. Because of their strong expectorant properties, fennel seeds are highly effective when used in tea to ease coughing, bronchitis, and respiratory congestion. It is believed that the fiber and essential oils in fennel seeds aid in blood cleaning by removing sludge and toxic substances from our bodies. Foods that help in blood cleansing should be a part of your diet to guarantee that nutrients are absorbed smoothly.

Fennel Seeds and PCOS:

Traditional medicine uses fennel, an estrogenic component, to treat a different of endocrine, menstrual, reproductive, and digestive issues. Fennel seeds possess antibacterial, anti-fungal, antioxidant, anti-diabetic, and anti-cancer properties. Trans anethole, a chemical that has been introduced as an estrogenic active agent, is the most important and prevalent component found in fennel. Fennel contains several aromatic compounds, including estragole,

photoanethole, fenchone, dianethole, and p-anisaldehyde, which act as biologically active substances with estrogenic properties [45].

The effects of fennel and metformin on uterine tissue and serum levels of progesterone and estrogen were investigated in rats with PCOS. A total of forty female rats were randomly assigned to one of five groups: (1) a control group that accepted normal food and water; (2) a PCOS group that was inducted by intramuscular injection of 4 mg/kg body weight of estradiol valrite; (3) a PCOS group that received 150 mg/kg body weight of fennel after polycystic ovary syndrome was induced; (4) a PCOS group that received 100 mg/kg body weight after induction of PCOS; and (5) a PCOS group that received 111 mg/kg body weight of metformin. All rats received therapy for 63 days, after which their blood samples were taken for biochemical analysis, and their uterine tissue was removed for histological investigation. The study showed that fennel increased uterine endometrial thickness and progesterone while lowering uterine epithelial thickness and estrogen in PCOS rats. Consequently, fennel's protective actions on uterine tissue may help rats with PCOS [46].

Fennel Seeds and Breastfeeding:

Pharmacological research has confirmed the galactagogue effect of fennel. In a randomized trial involving 78 exclusively breastfed infants, nursing mothers were administered a herbal tea three times daily for four weeks. The intervention group received a tea containing 3 g of black tea and 7.5 g of fennel seed powder, while the control group received a tea with only 3 g of black tea. The intervention group showed noticeably higher newborn weight, breastfeeding frequency, and head size, as well as significantly higher lactation for nursing mothers. When the nipples are stimulated, the anterior pituitary gland releases prolactin, a hormone responsible for milk production. This process is regulated by the hypothalamus, which exerts inhibitory control through dopamine. As a result, dopamine acts to suppress prolactin secretion. The primary component of fennel, anethole, has structural similarities with dopamine. Thus, at the receptor sites by competing with dopamine and preventing dopamine's anti-secretory effect on prolactin, anethole may affect milk secretion [47].

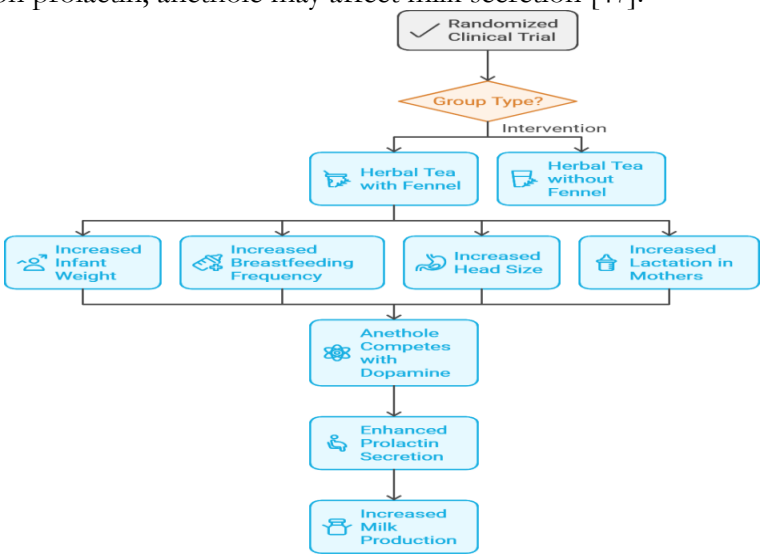

Figure 5. Fennel seeds and breastfeeding (randomized clinical trial) [47]

Anti-Diabetic and Anti-Obesity Activity:

Through antioxidant actions and redox equilibrium restoration, fennel essential oil protects patients from pathological abnormalities and hyperglycemia in diabetic mice. Fennel essential oil has strong anti-hyperglycemia attributes, according to in vivo tests conducted on rats with hyperglycemia [48]. An increase in the activity of glutathione peroxidase, as an antioxidant, may be related to the corrected hyperglycemia state. Moreover, Fennel seeds (2.5 g each) administered in the diet of female patients affect BMI significantly and cholesterol level in female patients [49].

Table 3. Therapeutic applications of fennel seeds

Therapeutic Application	Description	References
Anti-Inflammatory Properties	Fennel contains anethole, which helps to reduce inflammation and alleviate conditions.	[24]
Anti-oxidant effects	Protect cells from oxidative damage and support the immune system.	[33]
Digestive health support	It relieves bloating, indigestion, and nausea, aiding in the digestive process.	[43]
Improvement in respiratory health	Fennel helps to clear respiratory pathways and helps to reduce asthma and cough.	[42]
Hormonal balance support	Fennel aids in regulating estrogen levels, menopausal symptoms, and benefits women with PMS.	[45]
Relief from menstrual discomfort	It helps to relieve cramps and bloating during menstruation. Fennel is also known for its antispasmodic properties.	[46]
Detoxification	Fennel aids in detoxifying the body by promoting the elimination of waste and toxins.	[43]
Boosting metabolism	Fennel helps to boost metabolism and burn body fat more efficiently.	[47]
Anti-bacterial properties	Fennel can help fight against infections	[18]
Reducing blood sugar level	Fennel helps to reduce blood sugar levels and is beneficial for diabetic patients.	[43]
Heart health support	Fennel contains potassium and fiber, content support heart health by regulating cholesterol and blood sugar levels.	[43]
Enhancing lactation in breastfeeding mothers	Fennel helps to enhance milk Production in breastfeeding mothers.	[46]
Improving skin health	The antioxidants and vitamins in fennel seeds promote skin health, support wound healing, and prevent aging.	[33]

Applications in the Food Industry:

Use of Fennel Seeds as a Food Ingredient:

Fennel is used in cuisines all over the world. It adds flavor to salty meals, including olives in Italy. Tender fennel leaves and stems are used in soups and sauces in Spain, and the seeds add taste to olives and dried figs. All components of the fennel plant—shoots, stems, blossoms, leaves, and seeds—are used in Portugal to flavor teas, hazelnuts, cake, and other foods. In India, fennel is fed to cattle as a remedy for diarrhea. It is also used as traditional medicine to treat a wide range of ailments, from common colds and coughs to more severe conditions such as cancer [50].

Whole Seeds:

Whole fennel seeds are used as a condiment in numerous nations, like India, Egypt, and China. Fennel seeds are utilized in various dishes and traditional curries. A modest amount of fennel adds a pleasant flavor to curries and is typically used to make flavor soups, Pastries, buns, sauces, meat dishes, and candies [50]. Fennel is used in Polish borscht, spaghetti, German breads, sweet pickles, salads, and English-style soups. Fennel is used in different liquors to flavor them. Fennel seed vinegar is utilized to sharpen herb sauces and make salad dressings. After that, vinegar should be added and it should be strained out of the sunlight into clean bottles, and placed at room temperature.

Essential oil & Fennel Powders:

Essential oils that contain significant levels of bioactive compounds, such as bioactive essential oils, are derived from fennel seeds. It is a flavoring agent in licorice candy, pickles, and other foods. Due to its antibacterial and antioxidant attributes, fennel has been recognized as a natural flavoring agent in the culinary industry, commonly in baked goods, beverages, and other food preparations. The essential oil from fennel seeds, which is used in aromatherapy due to its calming and soothing attributes, is found in fennel powder. Fennel powder is a fantastic source of various nutrients, including minerals, vitamins, and dietary fiber. Among the compounds, it contains anethole, which may have anti-inflammatory and antioxidant properties. In culinary applications, fennel powder complements a variety of herbs and spices, including cumin, thyme, coriander, and cinnamon. It enhances the flavor of roasted meats, fish, and vegetables. To preserve its aroma and freshness, fennel powder should be stored in an air-tight container, kept in a cool and dark place [51].

Bread and Pastry, and Commercial Blends Made with Fennel:

Bread, pastries, fusion dishes, and a wide range of baked items all contain fennel seeds. It is anticipated that as gourmet diversity grows, fennel seeds will become a necessity in the kitchen. Blends come in a variety of types. Fennel tea is prepared from fresh leaves and dried herbs. Concentrated tea is made from the entire leaves, pure herbs, and the plant oil is of high grade. In addition to fennel seeds and herbs used in mixes, green seed tea is also offered, along with leaves and bulbs.

Value-Added Products:

In culinary applications, fennel powder complements a variety of herbs and spices, including thyme, cumin, cinnamon, and coriander. It enhances the flavor of roasted meats, vegetables, and fish. To preserve its aroma and freshness, fennel powder should be stored in an airtight container kept in a cool, dark place. Sugar-coated fennel is used as a breath refresher and

is known for its delicious flavor. They are often used in particular spice blends, such as Chinese five-spice powder and Indian panch phoron, and are frequently used spices in both Asian and European cooking. The seeds are frequently used in soups, fish and seafood meals, German and Italian bread, and Italian sausages. The most popular value-added fennel products are fennel oil, fennel seed tea, and ground fennel [52]. In culinary applications, fennel powder complements a variety of herbs and spices, including cumin, thyme, coriander, and cinnamon. It enhances the flavor of roasted meats, fish, and vegetables. To preserve its aroma and freshness, fennel powder should be stored in an air-tight container, kept in a cool and dark place. Fennel leaves help to reduce weight, stomach aches, and improve vision. Fennel syrups are also effective in relieving chronic coughs. Research suggests that fennel provides therapeutic effects beyond its flavor and nutritional benefits. These include helping to control blood pressure and decrease asthma symptoms. Additionally, research suggests that fennel may be useful in anti- microbial, antibacterial, anti-fungal, and anti-inflammatory therapies [53]. The other components of the fennel plant can also be used. Additionally, fennel leaves are used as salad dressing and garnishes. A popular vegetable in Italy and in other nations is the fennel bulb. However, it is observed that various types are used for producing bulbs as opposed to seeds. Since fennel pollen doesn't taste like fennel seed or anise, it gives meals a well-defined flavor. It is often hand-collected from wild or planted fennel. According to [54], essential oils can be extracted from fennel seeds, green biomass, and dry biomass. This offers new business opportunities for fennel farmers by enabling value addition after harvesting.

Figure 6. Culinary and medicinal uses of fennel seeds

Environmental Applications:

In addition to its pharmacological properties, Foeniculum vulgare also showed some environmental properties. These actions are essential for controlling insects, worms, mosquitoes, and some dangerous malaria vector larvae. Extracts from Fennel seeds have been tested for their nematicidal, insecticidal, repellent, acaricidal, and larvicidal properties. Fennel exhibits multiple biological activities, like repellent, insecticidal, acaricidal, and larvicidal properties.

Adulteration:

The quality of the fennel available on the market differs either careless harvesting and deliberate adulteration. Adulterants are added to expensive substances in order to increase quantities, lower manufacturing costs, or serve other villainous purposes globally. The fennel

seeds may contain sand, weed seeds, and dirt stem tissues. Because of this, adulterants are unsuitable for use in medicine. Manufacturers used chemicals/ dyes to enhance the colors of seeds. Seeds may be adulterated by mixing cumin seeds [55].

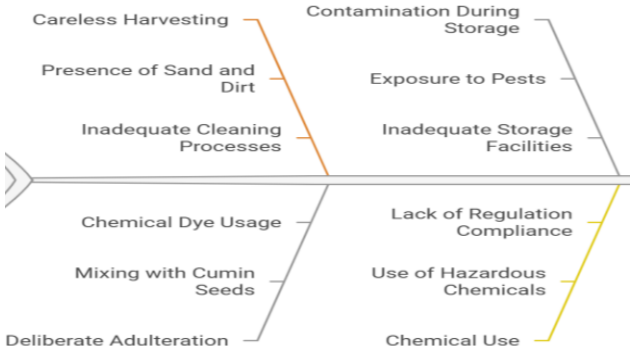

Figure 7. Analyzing adulteration causes of fennel seeds [55]

Tools for Identifying Adulteration:

Organoleptic or Sensory Evaluation & Macroscopic and Microscopical:

Using the organoleptic method, one can find the distinctive color, smell, or taste of the seeds using their senses of sight, smell, or taste. This technique allows for rapid sample viewing and for precision and verification. It is typically used in conjunction with macroscopy, microscopy, and other analytical techniques. By comparing the analyzed plant tissues with the typical histological characteristics of each spice, microscopy has been demonstrated to be an easy and fast method for the initial examination of the identity and purity of spices [56].

DNA Bar-Coding:

DNA bar-coding has become more popular as a method for quality control, botanical verification, and distinguishing between closely related plant species. The foundation of DNA-based techniques is the comparison of a small number of genetic sequences or nucleotides, which are specific to a particular plant species and range in length from 300 to 1000 base pairs, with a standard reference material that has been verified. These methods can differentiate between various species, cultivars, or variations, but they are not tissue specific; therefore, they cannot differentiate between various plant organs or sections [57].

Infrared Spectroscopy & Spectrometry of Mass:

A quick, straightforward, nondestructive, and environmentally friendly method for identification and quantification of adulterants in botanical components, such as spices, is infrared spectroscopy, which includes Fourier transform mid-IR and FT-NIR [58]. According to literature, MS has a 26% utilization rate, making it one of the most popular and dependable methods among those employed for food adulterant detection. MS is regarded as a potent confirmatory technique for quality assurance and offers more sensitivity and selectivity in analysis [58].

Spectroscopy of Nuclear Magnetic Resonance:

One of the main fingerprinting spectroscopic methods for identifying foreign particles is NMR. NMR is a fingerprinting method that, alongside IR spectroscopy, can detect signals from all chemical components in a sample and identify foreign compounds that are present in the verified sample [59].

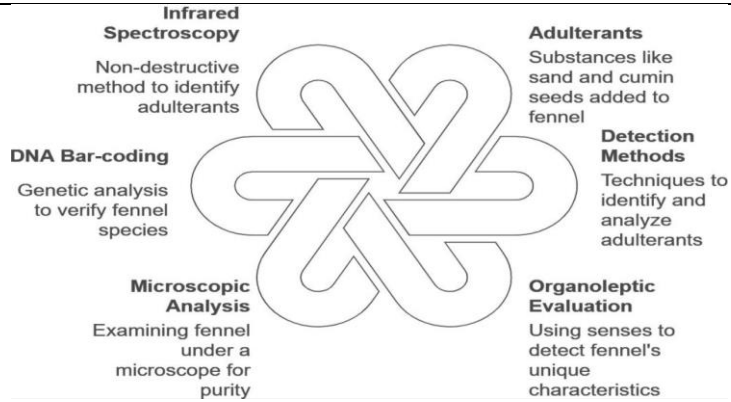

Figure 8. Techniques to identify adulteration of fennel seeds.

Adverse Consequences:

Preparing herbal products with the least degree of toxicity and adverse effects is generally essential. One of the most crucial ingredients in fennel extract is estragole [60]. It is prohibited to use this drug because it can cause cancerous tumors in animals. This ingredient causes tumors in rats but has not been reported to cause cancer in humans. The total content of anethole in fennel is 2,090 mg/kg. Studies report that rats repeatedly administered 695 mg/kg exhibited moderate liver damage. Consequently, anethole may cause mild liver toxicity even at standard therapeutic levels [61].

Conclusion:

Recent studies have shown that fennel extracts contain a variety of pharmacological effects, such as anti-inflammatory, anti-allergic, analgesic, antibacterial, cytotoxicity activity, antioxidant, anti-mutagenic, and anti-stress properties. The therapeutic properties of the plant are derived from its numerous chemical components. There are many components present in fennel seed essence, and phenolic compounds are thought to be the most essential and effective ones. The bioactive substances in fennel are necessary for preserving human health and are utilized in the production of many medications. Fennel's antioxidant, antibacterial, and estrogenic qualities have been the subject of the most well-known and successful studies in a variety of animal models. Future research on the potential medicinal uses of this plant to treat various non-communicable diseases is therefore encouraged.

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