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Fennel: A review of its botany, phytochemistry, pharmacology, agronomic practices and post-harvest handling

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Abstract

Fennel (*Foeniculum vulgare* Mill.) is a multi-purpose aromatic medicinal plant with important culinary, pharmaceutical, and industrial applications. This review synthesizes current knowledge on fennel by integrating its botany, phytochemical attributes, therapeutic relevance, and agronomic management practices. The emphasis is placed on crop adaptability across diverse agro-climatic regions, variability in essential oil content and composition, and their dependence on genotype, environment, and management practices. The review consolidates information on morphological characteristics, growth behaviour, climate and soil requirements, and evidence-based cultivation practices including sowing time, nutrient and water management, weed control, and integrated pest and disease management. In addition to this, particular attention is given to sustainable production approaches, especially organic and integrated nutrient management systems, for improving productivity and quality. Unlike earlier reviews that primarily focus on pharmacology or phytochemistry, this article provides an agronomy-oriented synthesis linking crop management with quality outcomes and identifies key research gaps to support diversification and sustainable fennel production.

Keywords: Agronomic practices, essential oil, fennel, insect pest, medicinal properties

Introduction

Nature is full of aromatic plants that have a charisma of their own and are pleasing to our senses. These aromatic plants are culturally, culinarily, and medicinally significant. Among all the aromatic plants, which are available in the wild or nurtured by man, fennel stands out for its mild and unmistakable aroma. With its sweet, anise-like fragrance, fennel has long been appreciated not only for its aromatic qualities but also for its use in cooking and traditional medicine. It has cytoprotective, hepatoprotective, anticancer, chemo-preventive, hypoglycaemic, oestrogenic, and antioxidant properties (Badgujar *et*

al., 2014). Originally native to southern Europe and the Mediterranean region (Rafieian *et al*., 2023), fennel has spread and established itself in the wild across various regions, such as northern Europe, Cyprus, the United States, southern Canada, much of Asia, the far East, and Australia, commonly growing along roadsides, in pastures, and other open habitats. It is believed that fennel has been grown in India since at least 2000 BC. It is recognized by a wide array of names across different languages, such as *Saunf* in Hindi, *Perum Jeerakam* in Malayalam, and *Badishep* in Marathi, and is similarly known internationally as *Hinojo* in Spanish, *Fenouil* in French, and *Hui-Hsiang* in Chinese, reflecting its widespread cultural and linguistic significance. The crop is mainly cultivated in the states of Rajasthan, Maharashtra, Gujarat, and Haryana, with additional cultivation occurring in parts of Punjab, Uttar Pradesh, Madhya Pradesh, and Andhra Pradesh (Khan and Musharaf, 2014).

Classification of fennel

The genus *Foeniculum*, commonly known as fennel, is part of the *Apiaceae* family within the order *Apiales*. The genus name *Foeniculum* originates from the Latin word *foenum*, which means 'hay'. The term *foeniculum*, meaning 'little hay,' refers to the resemblance of the plant's dried leaves to fine, dried hay. There are three primary varieties of fennel: *F. vulgare* Mill. var. *piperitum* (bitter fennel), *F. vulgare* Mill. var. *dulce* (sweet fennel) and *F. vulgare* Mill. var. *azoricum* (Florence fennel or finocchio) (Seidemann, 2005). Fennel is classified as either sweet or bitter based on the concentration of certain secondary metabolites found in its seeds. The compound fenchone is responsible for the bitter taste, while anethole gives fennel its sweetness. Bitter fennel is primarily cultivated for its seeds and essential oil, while Florence fennel is valued not only for its seeds and oil but also for its leaves, which serve culinary purposes, and its swollen leaf base, which is consumed as a vegetable. Sweet fennel is also grown for its bulbous leaf base, seeds, and the essential oil extracted from them. Weiss (2002) characterizes fennel types as either biennial or perennial aromatic herbs, although most of the sources recognise annual forms. Fennel is a cross-pollinating plant with a diploid chromosome number of 2n = 22.

Botany

Fennel is an annual herb characterized by its feathery foliage. It possesses a thickened taproot system, extending upto depths of 1-2 meters. It typically reaches a height of 1.5 to 2.5 meters and has a delicate, slender green and slightly smooth stem with rigid, erect branches and highly divided leaves composed of narrow, linear segments. Lower leaves are borne on stalks, while upper leaves are sessile, directly attached to the stem. The leaves may extend up to 40 cm in length and are intricately dissected, with the terminal segments being form and measuring about 0.5 mm in width. The plant produces small yellow-petaled flowers, and its seeds are small with a pale greenish-blonde hue. The flowers are monoecious *i.e*., both male and hermaphroditic flowers exist on the same plant. In the hermaphroditic flowers, protandry occurs, promoting cross-pollination. These early-maturing pollen grains typically fertilize previously opened flowers that are at the right stage for fertilization through a process known as geitonogamy. That raises the rate of selfing relative to strict outcrossing and can reduce offspring fitness (lower seed set, poorer germination, reduced vigour) when inbreeding depression is present (Layek *et al.,* 2022). As a typical member of the *Apiaceae* (formerly Umbelliferae) family, fennel flowers are organized in an umbel formation. For breeders producing hybrid or open-pollinated seed, geitonogamy reduces the proportion of true cross-progeny. That can reduce heterosis in F1 hybrids and erode genetic distinctness in open-pollinated cultivar seedlots unless strict isolation/protocols are used (Magon *et al.,* 2025).The average diameter of these floral clusters is about 15 cm. The seed measure between 4-10 mm in length and 2-4 mm in width, with a characteristic brownish-green colour. This plant is capable of regenerating from crown or root fragments, but it primarily propagates through seed.

Phytochemical composition and nutritional contents of fennel

Fennel is a versatile plant, where all parts, including seeds, roots, leaves, and umbels, are utilised for various purposes (Mutlu-ingok *et al*., 2021). The seeds contain about 6.3% moisture, 9.5% protein, 10% fat, 13.4% minerals, 18.5% fibre, and 42.3%

carbohydrates. It has valuable sources of essential minerals and vitamins in its leaves, such as calcium, potassium, sodium, iron, phosphorus, thiamine, riboflavin, niacin, and vitamin C, among others as presented in Table 1 (Farid *et al*., 2020).

The seed of the fennel has about 10-12 per cent of oil, which is mainly deposited in the cotyledons of the seeds. The composition of the seed oils has approximately 22 per cent of oleic acid, 14 per cent of linoleic acid and 4 per centpalmitic acid. The essential oil content is 4-6 per cent, and its composition depends on the growing conditions of the plant (Castaldo *et al*., 2021). The essential oil of fennel contains over 30 terpene compounds, with the most important being trans-anethole (50-80%) and limonene (5%). The wide range in fennel essential oil content reflects strong genotype × environment interaction, as oil accumulation is a stress-responsive trait regulated by temperature, water status, radiation, and harvest maturity rather than a stable yield parameter. (Telci *et al.,* 2009). fennel also has a number of other compounds like tannins, coumarins, hydroxyl cinnamic acids and flavonoids (Mehra *et al*., 2022).

Another major category of phytochemicals that can be found in fennel are phenolic compounds and phenolic glycosides. The plant has different phenolic acids,

Table 1. Nutrients present in dried fennel seeds

Composition	Amount (Per 100 g)
Proximates	
Moisture	90.21 g
Energy	31 Kcal
Protein	1.24 g
Total lipid (fat)	0.2 g
Carbohydrates	7.3 g
Fibres	3.1 g
Sugars	3.93 g
Minerals	
Calcium	49 mg
Iron	0.73 mg
Magnesium	17 mg
Phosphorus	50 mg
Potassium	414 mg
Sodium	52 mg
Zinc	0.2 mg
Vitamins	
Vitamin C	12 mg
Vitamin B1	0.01 mg
Vitamin B2	0.032 mg
Vitamin B3	0.64 mg
Vitamin B6	0.047 mg
Lipids	
Total saturated fatty acids	0.09 g
Total monounsaturated fatty acids	0.068 g
Total polyunsaturated fatty acids	0.169 g

namely, 3-O-caffeoylquinic acid, 4-O-caffeoylquinic acid, 5-O-caffeoylquinic acid, and di-caffeoylquinic acid derivatives (1,3-,1,4-,and 1,5-O-di-caffeoylquinic acids) (Mehra *et al*., 2022). Such phenolic compounds are thought to help in the prevention of a range of oxidative stress-related diseases, such as cardiovascular diseases, cancer and inflammatory diseases. These compounds have become a major interest to the combined fields of nutrition, food science, and medicine due to their possible health-promoting abilities.

Uses of Fennel

Culinary Uses

Fennel is highly valued in the kitchen due to its edible roots, leaves and seeds. These components are used in several preparations, such as stuffing savoury food and flavouring desserts and confectionery. The fresh fennel roots are often served in salads to provide flavour and nutrition, while fennel leaves used for garnishing add freshness. The fennel bulb is a modified root vegetable, which can either be eaten uncooked or cooked by sauteing, stewing, braising or grilling. It is also composed of dietary fibre, which helps in reducing the level of cholesterol in the body. The fennel herb is usually used in preparing herbal teas or mixed juices along with other herbs. Fennel seeds have an anise-like flavour as well as a sweet, aromatic taste. One often eats these seeds following a meal, either bare or with betel leaves or covered with a sugar bite, particularly in Indian and Pakistani culture, as a *mukhwas*. The fennel seeds are also used in some of the spice mixes like *panchphoran* of Bengal and five-spice powder of China. They are used to season egg, fish and vegetable dishes along with sausages and rye breads, particularly in the West. Pollen of fennel has a unique, delicate and sophisticated flavour and is expensive as well. It also goes particularly well in the cooking and is normally added last after the cooking process and before serving the meal.

Traditional medicinal uses

The history of fennel being particularly used in traditional medicine to treat a variety of ailments by humans spans several thousand years. It has been used in several medical procedures in history, along with Ayurveda, Unani and the Siddha and in Indian and Iranian medicine systems (Rahimi *et al*., 2013). Ancient civilizations had numerous health advantages associated with this plant, as the Romans thought that fennel seeds might assist in vision, whereas the English were fond of this herb because of its digestive qualities and the ability to eliminate bloating. Fennel is a carminative that acts as a reliever against flatulence and improves digestion. The seeds are often found in all-natural mouth-care products, such as in herbal toothpastes, which provide them with antibacterial activity and help to conceal unpleasant oral odours. Moreover, fennel is perceived as a very effective treatment for many diseases, such as kidney stones, diabetes, bronchitis, and persistent cough (Camejo-Rodrigues *et al*., 2003, Novais *et al*., 2004, Dheebisha and Vishwanath, 2020). Though most spices have heating effects, fennel has the opposite cooling effect, which helps one have a calmed mind and clarity. Table 2 displays the role played by the fennel plant in various human health systems.

Antibacterial activity

The study on the antibacterial properties of fennel has found extensive recognition due to the existence of various bioactive chemicals, such as linoleic acid, oleic acid, 1,3-benzenediol and 2,4-undecaprenyl. These constituents have led to its activity against a wide range of pathogenic microorganisms like bacteria, fungi, viruses, and mycobacteria. Among the different bioactive compounds fennel contains 5-hydroxyfuranocoumarin (a linear furanocoumarin), which contributes to its antibacterial activity by interacting with microbial cells and interfering with their growth and quorum sensing pathways. The effects partly through modulation of microbial membrane integrity and inhibition of key cellular processes such as DNA and enzyme function (Noreen *et al*., 2023). (Kwiatkowski *et al*., 2015). Previous studies have reported that aqueous extracts of fennel exhibit strong bactericidal effects against clinically important pathogens, including *Escherichia coli*, *Shigella flexneri*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Enterococcus faecalis* (Ahmed *et al*., 2019).

Symbolic and protective uses

Fennel has been culturally classified to be a protective

Table 2. Role of fennel in different human health systems

Human health	Roles of fennel	References
Cardiovascular Health	Fennel seeds have a high concentration of dietary fibre , which helps the heart. The fibre combines with the bile salts, and decreases the absorption and reabsorption of cholesterol in the body that consequently prevents heart related diseases.	Ningsih *et al* ., 2021; Zahi *et al*., 2025
Brain Health	Fennel juice is said to encourage endorphins to be released, which causes one to get rid of depression and have a feeling of well-being. Its potassium level improves the thinking ability and brain activity. In addition, fennel juice is a natural vasodilator that enhances the blood flow to the brain , hence enhancing mental health, and may slow the development of dementia.	Maheshwari *et al*., 2022
Skin health	The fennel seeds can be used as a significant benefit to the skin because of their antiseptic and antioxidant characteristics. They are used to prevent acne, slow the ageing of skin, dark spots, and wrinkles and achieve a well-radiating complexion . The use of fennel or fennel tea also relieves skin irritation and enhances skin texture. Fennel has a rich layer of minerals such as iron, zinc, selenium and calcium, which, on the other hand, help balance oxygen and keep the skin young	Park and Seong, 2010; Thakur *et al*., 2013
Eye health	Fennel is rich in essential nutrients that support eye health and improve vision. Its antioxidants and amino acids help rejuvenate ocular tissues and prevent macular degeneration. Additionally, applying fennel juice to the eyes can help relieve irritation and reduce fatigue.	Singh *et al*., 2022
Women reproductive health	Fennel juice contains phytoestrogens structurally similar to estrogen, which help alleviate menopausal and premenstrual symptoms. It is also rich in folate, aiding in the prevention of birth defects during pregnancy. By regulating hormonal activity, fennel juice helps ease menstrual discomfort, and its galactagogue properties make it beneficial for lactating mothers to enhance milk production.	Bettaieb Rebey *et al* ., 2019; Erarslan and Kultur, 2024
Renal health	The diuretic properties of fennel help in treating kidney and bladder disorders. It alsorelieves *Pitta* by calming burning sensations in the urinary tract and supporting blood detoxification.	Maheshwari *et al*., 2022
Respiratory health	In respiratory conditions, fennel plays a therapeutic role in relieving coughs and colds, primarily due to the presence of α-pinene, which acts as a natural expectorant by facilitating the expulsion of mucus from the respiratory tract.	Badguzar*et al* . 2014; Singh *et al*., 2022

herb. Fennel, in several cultural traditions, is considered a plant with spiritual power that allows people to develop their intuitive power and connect with spirits. It is also regarded as a symbol of prosperity and good luck, believed to bring good fortune and positive energy. Fennel is also associated with clean physical and spiritual surroundings. It is said historically that fennel has a protective effect against negative energies and witchcraft, as well as evil spirits. It has been put in place as a charm that could help in keeping away the bad spirits and provide spiritual defense (Gori *et al*., 2012).

Fennel as a natural insect repellent

With the growing worries about the safety of the synthetic repellents, such as DEET, the essential oil of fennel has appeared as a strong botanical repellent. It has shown anti-pest properties, and is believed to be environmentally friendly and safe to people. In larvicidal bioassays, fennel essential oil showed substantial toxicity against mosquito larvae, with reported LC_{50} values indicating the concentration at which 50% of larvae are killed: studies with Foeniculum vulgare essential oil have demonstrated effectiveness against mosquito vectors in control assays, suggesting its potential in integrated mosquito management strategies (Rocha *et al.,* 2015). Fennel oil is commonly used with natural repellent oils such as citronella and eucalyptus oils. The skin and patch tests have verified that the use of the methanol extract of the fennel seed has mosquito-repelling activity, especially against the female *Aedes aegypti* mosquitoes (Passara *et al*., 2024).

Insecticidal properties

Fennel essential oil has been scientifically proven to be an insecticide. As an example, it has worked against *Tribolium confusum,* with mortality rate proportional to higher concentration of fennel oil (Cicek *et al*., 2024). The major extracts of fennel seeds, like (E)-anethole, estragole, and (+) fenchone, have also been found to exhibit high bioactivity against insect pests such as *Lasioderma serricorne*, *Callosobruchus chinensis*, and *Sitophilus oryzae* (Badguzar *et al*., 2014).

Fennel in animal husbandry

The research on plant-based phytobiotics like fennel to enhance animal performance and health has been examined by multiple studies on this topic (Abd Elwahab *et al*., 2021; Al-Harthi *et al*., 2022). It is shown that the addition of fennel supplement to broilers has increased weight gain and feed intake (probably because of its palatability, aroma, and antimicrobial effects), which subsequently increased digestibility (Khan *et al*., 2022; Saleh *et al*., 2018). Increased feed consumption and weight gain were also seen in Holstein calves (Safaei-Cherehh *et al*., 2018; Kargar *et al*., 2021) and lambs. Fennel was also found to enhance reproductive performance of poultry, leading to the production of eggs, oviduct growth, albumin synthesis, and yolk formation (Hajalizadeh *et al*., 2019).

Varieties

Fennel is primarily a cross-pollinated crop because it is self-incompatible, resulting in a high level of genetic variation within its populations. The genetic diversity gives breeders a chance to conduct screening and selection to improve the population into particular desired characteristics. Improvement of fennel has been mostly done to produce varieties which are able to be grown in a wide geographical area, having high yield potential with specific quality improvements, such as increased aroma, taste, colour and homogeneity in seed weight and shape. Other aims of breeding are higher essential oil content and pest and disease resistant traits, especially against powdery mildew. The All India Coordinated Research Project (AICRP) on Seed Spices has also developed many improved fennel varieties under commercial cultivation in different parts of the nation. Table 3 provides a summary of these varieties.

Climate

Fennel is a cool-season crop that is mainly grown in winter periods in northern India. It fails to thrive well in southern areas except when it is planted at a higher altitude. Fennel grows best in temperatures between 15°C and 25°C and the optimum rainfall levels are between 50 and 75mm. A temperature of 18-25°C is considered best for harvesting. The prolonged high temperatures (over 25°C) at early growth stages may impair development, resulting in early flowering as well as lower seed yields. Root and shoot biomass and essential oil content of fennel may be reduced due to heat stress that arises with the increasing

Table 3: Different varieties of fennel suitable for cultivation under AICRP

Variety	Release year	Yield	Salient features	Area
Gujarat Fennel-2	1997	19.40 q ha^{-1}	Bushy plants, bold grains Higher essential oil content (2.4%)	North Gujarat and Sourashtra region
Gujarat Fennel-11	2004	24.87 q ha^{-1}	Medium bold seeds and 1.80% essential oil	Gujarat
JF 444-1	2010	25.88 q ha^{-1}	Densely arranged seeds within the umbel, rigid and flattened stem, uniform maturity with smaller central umbellates within the main umbel	All fennel growing areas
RF 101	1999	15.50 q ha^{-1}	Erect with medium height, medium duration; matures in approximately 150–160 days, long and bold grains, best suited for loamy and black cotton soils	Rajasthan
RF 143	2004	12 q ha^{-1}	Moderate in height and recommended for cultivation in loamy and black cotton soils	Rajasthan
RF 178	2006	16 q ha^{-1}	Long and bold seeds	All fennel growing areas of Rajasthan
RF 205	2009	10-12 q ha^{-1}	High-yielding and better-quality seeds	All fennel growing areas
RF 281	2012	18.25 q ha^{-1}	Bold seeded with a 130-140 day duration	Rajasthan
RF 157	2015	21.67 q ha^{-1}	Long and bold seeds	Haryana, Rajasthan and Gujarat
RF 290	2019	20.65 q ha^{-1}	High-yielding variety with elongated, bold seeds, and a greater number of umbellets and seeds per umbel	Rajasthan, Haryana, Bihar, Gujarat and Uttar Pradesh
Pant Madhurika	2001	12-15 q ha^{-1}	Tall, vigorous, and upright with large umbels, bold, sweet-flavored seeds with fine green ridges and medium duration	Uttarakhand
HisarSwarup	2004	16 q ha^{-1}	Erect and spreading, with a bushy growth habit, late maturity period (175–185 days), and produces elongated, bold grains, resistance to lodging and shattering with 1.6% essential oil content.	Haryana under irrigated conditions
Ajmer Fennel-2	2015	17.9 q ha^{-1}	Possesses a fair degree of resistance to Ramularia blight	All fennel growing areas
Ajmer Fennel-3	2018	21.43 q ha^{-1}	High yielding, high oil content (1.9%), resistant to Ramularia blight	All fennel growing areas

temperatures (El-Sayed and El-Kersh, 2014). The crop is exposed to frost attacks, especially at flowering. The ideal temperature for seed germination varies between 25°C to 29°C. Moreover, high winds at maturity can cause shattering of the seeds, whereas excessively hot winds during flowering can impede seed set.

Soil

Fennel can be planted in any type of soil having plenty of organic matter. The soils should, however, be well-drained. The best types of soil for fennel cultivation are the sandy topsoil and loamy soils. Fennel can also be grown on shallow soils. The optimal pH of soil must lie between 6.5 and 8. Fennel can also be grown on contaminated and polluted soils due to its low heavy metal uptake capacity (Irfan *et al.,* 2025). However, the saline and waterlogged soils are unfit for its cultivation.

Field preparation

The main field should be prepared well by tillage, resulting in a fine seedbed. Firstly, it should be ploughed with a soil-turning plough, and then 2-3 rounds with a cultivator or harrow. In medium-textured soils, two deep ploughings and planking are sufficient to obtain a uniform seedbed, while this number rises to four to five in the case of heavy soils (Lal *et al .,* 2014). The tilled soil is then levelled by planker to achieve uniformity. Along with the last ploughing, 10-15 tonnes per hectare of farmyard manure should be applied, according to the availability (Fogawat *et al.,* 2024). In order to manage infestation of termites, apply Quinalphos 1.50 or 25 kg Methyl Parathion 2% dust per hectare to the soil before planting. Form properly shaped beds and channels for irrigation purposes and crop management.

Sowing time

Ideally, sowing is done between mid-September and mid-October, and any delay in sowing may result in low yields. A number of studies found that late sowing subjects the reproductive stage of the crop to cold stress, resulting in lower yields (El-Badawy *et al*., 2017). A reduction of 10-15% both in seed and essential oil yield occurs when sowing is delayed past mid-November due to shorter growth period and less optimal environmental conditions (Verma and Saxena, 2024). In Punjab, the optimal time for sowing fennel is the last week of October (Anonymous, 2025), while in Rajasthan, the first week of October is considered ideal.

Seed rate

Fennel is typically propagated by seeds, which can either be sown directly into the field or first raised in nursery beds and later transplanted. Generally, a seed rate of 9-12 kg per hectare for direct sowing, while for transplanting, 2.5 to 3.0 kg of seed per hectare for dwarf varieties, and 3 to 4 kg per hectare for other varieties is required. All yield-contributing parameters, including plant population per square meter, number of branches and umbels per plant, number of umbellets per umbel, seeds per umbellet, and seed yield, exhibited significantly improved performance when seeds were sown at a rate of 10 kg per ha using the line sowing method (Sarker *et al*., 2023). Sowing should be done at an appropriate depth of 1.5-2 cm in rows spaced 45–60 cm apart and plant spacing of 20-30 cm. In direct-sown crops, thin out the seedlings at 4 to 5 weeks of age to maintain a spacing of 25 to 30 cm between plants. The field should be irrigated immediately after sowing to ensure proper germination.

Seed treatment

Treatment of seeds in fennel is an important agronomic activity since it is important towards the promotion of crop establishment, growth and final yield output, as well as in the protection of plants. The main benefit of seed treatment is that it prevents pest and disease infestation. The fennel seeds have high susceptibility to a wide range of pathogenic fungal and bacterial infections that may negatively impact the quality and production of crops. Fungicides and insecticides sprayed on the seeds before planting act as an insurance mechanism to protect the crop against the harmful microorganisms. In addition to disease prevention, seed treatment in fennel can also entail the use of growth regulators and micronutrients. These treatments help in improved root growth, robust stem growth and sound foliage development. The provision of seeds with vital nutrients and hormones enhances ideal plant growth and production capabilities. In order to prevent disease incidences, the seeds can be treated using Bavistin, Captan, or *Trichoderma* in proportions of 4 grams per kilogram of seed.

Nutrient requirement

To ensure economic sustainability and viability of seed production, a timely and sufficient supply of nutrients is necessary. One of the major nutrients is nitrogen, which promotes vigorous vegetative growth in the field crops. Under normal soil conditions, 90 kg of nitrogen and 40 kg of P_2O_5 per hectare are recommended, but in case of enhanced growth, the required nutrient dose is 120 kg of nitrogen and 50 kg of P_2O_5per hectare. Nitrogen should be applied in two equal split doses at 30 and 60 days after sowing. Other than the inorganic fertilizers, there are organic manures that can be used to increase crop productivity, like farm yard manure and vermi-compost. The most widely utilised organic manure is farmyard manure (FYM) with a composition of around 0.5 per cent nitrogen, 0.2 per cent phosphorus and 0.5 per cent potassium. FYM enables the growth of plants by supplying the necessary micronutrients, improving the soil structure, and increasing nutrient availability. Farmyard manure should be applied in the range of 10-15 tonnes per hectare to the soil 3-4 weeks before sowing according to the nutritional content available in the FYM. The practice of 12-15 tonnes per hectare vermin compost also affected multiple fennel growth and yield characteristics, such as plant height, number of primary and secondary branches, umbels per plant, umbellets per umbel, seed yield, total biomass, harvest index, and content of essential oils, in a significantly positive way (Valiki *et al*., 2015).

Nevertheless, poor quality and low yields of crops are commonly due to improper or unfavourable application of nutrients. Integrated nutrient management (INM) is a wholesome practice that incorporates organic manures like farmyard manure, compost, and green manure with biofertilizers and chemical fertilizers. For instance, using a mixture of inorganic and organic fertilizers like FYM and biofertilizers resulted in enhanced growth and yield parameters of fennel (Kusuma *et al*., 2019a). In order to increase yield, *Azospirillum* and *Azotobacter* should be inoculated while for enhancing oil quality, the crop should be sprayed foliarly with zinc and boron. The micronutrient foliar application has become a potential approach to bio-fortification, which leads to better foliage and bulb yield and improved crop nutrition.

Application of plant growth regulators (PGRs) such as gibberellic acid (GA_3), naphthalene acetic acid (NAA) and indole butyric acid (IBA) is getting increasingly popular to enhance the growth, yield and quality of the spice crops (Kurmi *et al*., 2020). They are very important in enhancing photosynthetic rates and flowering, hence positively affecting the potential production and the overall plant quality (Simkin *et al*., 2019). Indicatively, Bera *et al*., (2024) found that gibberellic acid (GA_3) at 100 ppm has shown great results in improving the growth parameters of plants like height, branching and flowering; naphthalene acetic acid (NAA) at 100 ppm recorded high results in improving the yield parameters of plants such as umbels per plant, seeds per umbel, and yield of umbels; and kinetin at 10 ppm achieved success in enhancing plants total chlorophyll content. Further, Kusuma *et al*., (2019b) found that out of the various vegetative growth regulators, the usage of GA_3 at 50ppm resulted in the highest plant height in fennel.

Irrigation

The quantity of irrigations that fennel usually needs during its growth process is between 6 and 10. In the early stages, an irrigation interval of 5 to 20 days should be there, while for later stages (March-April), a 12-15-dayirrigation interval would be best. Immediately after direct sowing or transplantation of seedlings, the use of light irrigation is recommended. Maintaining ample moisture during the flowering and seed development stages is important so as to maximize the yield potential.Moreover, the fennel seeds are usually grown in areas where the supply of water is low; thus, drip irrigation should be practised to achieve maximum utilization of the water. The drip irrigation system will pump water directly to the root zone of the plants in a closed circuit of plastic pipes as per the crop needs. The use of drip irrigation with an IW/CPE of 0.8 showed great effect on the fennel performance, increasing plant growth, water use and quality parameters, and enhancing an overall economic profitability (Shivran *et al*., 2023).

Weed management

Farmers usually have concerns for the cultivation activities like seedbed preparation, fertilization, and

irrigation management. They, however, tend to overlook the issue of weed control, which is a major limitation to crop production. Fennel is a slow germinating plant with slow initial growth, which usually leads to excessive weed competition. The weeding should be done twice, at 30 and 60 days after sowing. One can apply pre-emergence type of herbicides such as pendimethalin or oxadiargyl followed by manual weeding. The application of pendimethalin at 1.0 kg per ha, or its reduced dose of 0.50 kg per ha integrated with a hand weeding at 40 days after sowing (DAS), has been identified as the most effective approach for minimizing weed infestation and significantly enhancing seed yield in fennel cultivation (Kumar *et al*., 2019).In another study, it was observed that while hand weeding maximized fennel growth and yield traits, a sequential application of pendimethalin 30% EC (pre-emergence) and quizalofop-ethyl 5% EC (post-emergence) offered statistically comparable agronomic performance with enhanced weed suppression and higher economic efficiency (B:C 1.74) (Mamatha *et al*., 2021). Practices such as earthing up and soil solarisation also effectively manage weeds and soil-borne pests.

Disease management

Ramularia blight: It is caused by *Ramularia foeniculi*. It is a widespread and highly destructive disease affecting fennel. The initial symptoms typically emerge in January, starting on the older, lower leaves as small, angular, brown necrotic lesions. Those lesions grow larger gradually extending to the stems, in the peduncles, on the reproductive parts and eventually all the aerial parts of the plant. When the infection is severe, the whole plant can become brown and dry to death. The resulting seeds of infected plants tend to be deformed and blacken, and have less potential of germinating. Depending on the disease management, healthy disease-free seeds need to be used. Thiram 75 WP or Captan 75 WP @ 3 g per kg of seed should be used for seed treatment. Also, foliar fungicides like Mancozeb 0.2% (25 g per 10 litres of water) and Carbendazim (10 g per 10 litres of water) have been found to reduce disease transmission when used three times at intervals of 10 days post disease outbreaks (Amin *et al*., 2021).

Damping off: Damping-off induced by *Pythium aphanidermatum* is manifested in two stages, pre- and post-emergence phases of the seedling. During the pre-emergence stage, seedlings decay and die before germinating in soil because the radicle and plumule get spoilt. During the post-emergence stage, the area below soil level gets waterlogged, and the soil is soft, hence collapsing the emerged seedling. The disease is severe in the nursery, though it may also manifest in low-lying areas of direct field sowing. The conditions such as moist soil, high humidity, rainy weather and low temperatures are favourable for damping-off. The principles of disease prevention focus on the use of healthy seeds, field sanitation and deep summer ploughing in nurseries. Summer solarization of soils is useful in eliminating soil pathogens. It is advisable to treat the seeds with fungicides like Thiram, Captan or Metalaxyl @ 3 g per kg.

Fusarium Wilt: It occurs due to *Fusarium oxysurum* f.sp. *ricini*. The disease affects the crop at all growth stages, occurring in patches. The early disease symptoms include hypocotyl discolouration, leaf drop, wilting, followed by complete yellowing and drying of leaves at later stages. Affected stems have brown discolouration and prominent white mycelial growth in the pith internally. Favourable conditions include moist, humid (>80%) conditions with light during February-March, and continuing monocropping, which increases the chance of wilt becoming chronic in the field. The disease management strategies involving the use of certified healthy seeds, crop rotation and deep summer ploughing have a major role in reducing the incidence of disease. Inoculum accumulation and the spread of the disease are curtailed with field sanitation and removal of infected plants in a timely manner. Thiram (3 g/kg) and Carbendazim (2 g/kg) are commercially successful from the standpoint of seed treatments as prevention strategies.

Powdery mildew: It is caused by *Leveillula taurica*. The symptoms normally appear during the flowering phase, during cloudy weather in February or March. The initial fungal growth appears on the leaves, followed by the stem, branches and flowers, preventing seed formation and desiccating plants in extreme cases of infection. Cool and damp conditions (20-25°C)

along with humidity greater than 80 per cent are conducive to disease development. Management involves foliar application of wettable sulphur (80WP, 30g/10L) or Hexaconazole (0.005%, 10ml/10L) after 3 months of sowing at every 15-day intervals in dry weather.

Root rot: It is caused by *Rhizoctonia solani*. The disease is characterized by seed decay and reddish-brown lesions on seedling stems and roots below the soil line, which may girdle stems, causing plant death and uneven crop stands. In mature plants, lesions may extend into the stem base, forming dry cankers. Favourable conditions include dry spells after heavy rains, high temperatures (30–35°C), and low humidity (50–60%). Management includes the utilization of healthy and pathogen-free seed, crop rotation, crop residue burning, and maintaining adequate soil moisture through timely irrigation. Organic manure and seed or soil application of *Trichoderma* spp. (1 kg/25 kg FYM or 10 g/kg seed) reduce pathogen load. Seeds treated with Thiram at 3 g/kg or Carbendazim at 2 g/kg and soil drenching with Carbendazim (1 g/L) at 15-day intervals (2–3 times) effectively control the disease.

Insect pest

Insect pests are a significant constraint to fennel productivity. Fennel crop is infested by a variety of insect pests, particularly sap-sucking insects such as jassids (*Empoasca kerri*), thrips (*Thrips tabaci* and *T. flavus*), whitefly (*Bemisia tabaci*), and aphids (*Hyadaphis coriandri* and *Aphis gossypii*), which feed on plant sap and weaken the crop. Other damaging pests include chalcid wasp (*Systole albipennis*), cutworm (*Agrotis* sp.), various lepidopteran caterpillars, and grasshopper (*Acrida* sp.). These pests occur from germination to crop maturity, causing varying degrees of yield and quality loss, particularly under the semi-arid winter conditions of Rajasthan. Among them, the aphid *Hyadaphis coriandri* is consistently reported as a major pest in Rajasthan and other regions. It is the most destructive pest, as both nymphs and adults feed on leaf, stem, and umbel sap, leading to weakened and stunted plants. Honeydew excretion promotes sooty mould development, further inhibiting growth. Severe infestations result in drying of growing points and flower stalks, poor seed formation, and shrivelled, low-quality seeds (Kanjiya *et al*., 2018a). On a severe level, the aphid infestation may reduce the seed yield by 80 per cent due to aborted seed setting (Ramalho *et al*., 2012). Fennel also becomes the target of seed midge (*Systole albipensis*), which is responsible for both the qualitative and quantitative loss in the field and storage (Meena *et al*., 2015). The females lay eggs in the seed embryo, and the growing larvae feed and pupate in the grain. The adults escape from the grain by boring holes, resulting in poor grain quality, viability and germination potential.

The cultural practices are quite critical in alleviating the problem of insect pests due to the excessive application of insecticides. One of the main techniques to mitigate the adverse effects of insect pests is the adoption of resistant or tolerant fennel varieties. The practice of intercropping, especially with onion and garlic, is useful in driving away pests, as it produces alkaloids and glycosides that interfere with the physiological processes of insects (Debra and Misheck, 2014). Intercropping cereals increases the natural enemy abundance and diversity by providing food and shelter.

The overuse of chemical pesticides has resulted in a number of challenges, such as pesticide residues in marketable products, pest resistance, destruction of non-target organisms, environmental destruction, and increased costs of production. Bio-pesticides that are made by using natural sources like fungi, bacteria, viruses, nematodes and plant extracts are environmentally safer pest control methods (Nawaz *et al*., 2016). Pests need to be controlled using both botanical and microbial biopesticides in order to produce fennel more safely and in a more sustainable manner.

Harvesting

Fennel takes 7-8 months for maturation. Depending on the plant part, fennel is ready to be harvested at different times. Leaves can be collected continuously throughout the growing period, starting from the point when the plant has reached a height of about 6 inches. The harvesting of bulbs will normally be done at the stage when they reach a diameter of 2-3 inches; typically, 80-100 days post sowing. The harvesting of the seeds is done at the end of summer or at the

beginning of autumn when the flower heads are dry and brown. The umbels will be harvested four to five times with intervals of 10 to 15 days, followed by drying for 4 to 5 days in the sun before threshing. Once dried, fennel seeds are cleaned and graded before being stored in jute bags. Being vulnerable to frost attack, a 0.1% solution of sulphuric acid is sprayed on fennel seeds as a preventive measure. The average seed yield ranges between 10-11 quintals of seeds per hectare.

Post-harvest handling

Whole seeds

Following the harvesting process, fennel umbels, particularly those of green fennel, are dried in dark and well-ventilated places to avoid poor quality. One must ensure that the umbels are not piled up because this may lead to seed defects. After the umbels have been sufficiently dried, they are threshed and purified by winnowing to remove dust and rubbish. The moisture content of the seed should be kept to a minimum of 9% in order to avoid fungal contamination. The cleaned seed will be packed in gunny bags, lined with eco-friendly plastic and then stored in well-ventilated areas to maintain the quality (Malhotra and Vashishtha, 2008).

Essential oil extraction

Conventional techniques that are normally used in extracting the fennel essential oil include hydro-distillation and steam distillation, mostly using the Clevenger-type apparatus, which allows the separation of oil and water to occur during the distillation process (Baser and Buchbauer, 2010). The technique is typically applied in large-scale extracts in the laboratory as it is simple and efficient. Among other developments, in the recent past, supercritical carbon dioxide (SC-CO_2) extraction has emerged as one of the most efficient and selective methods. The best SC-CO_2 conditions, such as 100 bar pressure, 40°C temperature and extract time of 120 minutes, have been reported to fetch oil that is rich in trans-anethole and low in methyl chavicol (Damjanovic *et al*., 2004). (Marčac Duraković *et al*., 2024). The yield of the fennel essential oil is based on the type of fennel. Indian fennel normally produces 0.7-2.5 per cent volatile oil, whereas European fennel can produce up to 2-6 per cent. The oil has high antimicrobial and antioxidant properties, and thus it can be used in the formulation of drinks, bakery and other food substances. The essential oil should be kept in air tight aluminium containers in a cool, dry place to keep it safe and avoid degradation.

Fennel powder

Fennel powder is made by crushing dried fennel seeds, and the rate at which it is crushed determines the aromatic retention. In order to reduce the amount of volatile constituents lost, extreme methods like pre-chilling of the seeds or low-temperature grinding are frequently used. The size of particles of the powder is what defines its application; finely ground powder is generally used as a kind of seasoning in food preparation, although coarsely ground types can be used in other flavouring processes.

Conclusion

Fennel is a multidimensional crop of considerable economic and therapeutic importance, owing to its adaptability to diverse agro-climatic conditions and suitability for both conventional and organic farming systems. However, future expansion and productivity enhancement of fennel are constrained by climate variability, lack of stable high-yielding and quality-specific genotypes, and inconsistency in essential oil yield and composition across environments. Future research under Indian systems should prioritize the development of climate-resilient and location-specific varieties, detailed genotype × environment interaction studies, and refinement of optimized agronomic and nutrient management packages. Emphasis is also required on integrated pest and disease management, resource-use efficiency, quality-oriented production, and post-harvest handling and value-addition technologies. A multidisciplinary approach integrating breeding, agronomy, plant protection, and value-chain development will be essential to realize the full potential of fennel for enhancing farmers' income and ensuring sustainable production under changing climatic scenarios.

Conflict of Interest

The authors declare that they have no conflict of interest.

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