



Unlocking the Apiaceae: comprehensive advances in agronomy, biotechnology, phytochemistry, and health applications of major seed spices

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Summary

Seed spices from the Apiaceae family, including cumin, coriander, fennel, dill, ajwain, and others, hold immense significance in global agriculture, cuisine, and health. India leads the world in their production, with Rajasthan and Gujarat as key cultivating states. These spices are not only culinary staples but also rich in essential oils and bioactive compounds with antioxidant, antimicrobial, antidiabetic, and anti-inflammatory properties, contributing to their rising demand in the pharmaceutical, nutraceutical, and cosmetic sectors. This review provides a comprehensive analysis of Apiaceae seed spices, covering their botanical classification, morphology, reproductive biology, and agronomic practices. It also delves into stress physiology, genetic diversity, and modern breeding strategies, including the use of molecular markers. Furthermore, the review highlights their phytochemical profiles and documented health benefits. Despite significant progress, challenges remain, such as the need for improved genomic tools, better stress resilience, and efficient post-harvest handling. Future research must integrate traditional knowledge with biotechnology to unlock the full agricultural and therapeutic potential of these underutilized but economically valuable crops.

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Introduction

Seed spices, primarily belonging to the family *Apiaceae*, play a crucial role in global agriculture, trade, nutrition, and traditional medicine. These spices, including coriander, cumin, fennel, caraway, dill, ajwain, anise, celery, parsley, and angelica, are valued for their aromatic seeds rich in essential oils and bioactive compounds (Geoffriau et al. 2020; Tamokou et al. 2017). Globally, seed spices are vital in the culinary, pharmaceutical, nutraceutical, and cosmetic industries (Asangi et al. 2023). They are indispensable flavouring agents and preservatives in a variety of food products. Countries like India, China, Turkey, Egypt, Morocco, and Iran are the major producers and exporters of seed spices (FAO 2021). The global demand for natural ingredients, plant-based health products, and ethnic cuisines has fuelled their market expansion. Several seed spices are also recognised for their medicinal benefits, such as antioxidant, antimicrobial, digestive, antidiabetic, and anti-inflammatory properties (Tacouri et al. 2013; Shan et al. 2005).

India is the largest producer, consumer, and exporter of seed spices in the world. The country accounts for more than 70% of global seed spice production (NHB 2020). Rajasthan and Gujarat are the leading states, contributing significantly to the

cultivation of cumin, coriander, and fennel. The National Research Centre on Seed Spices (ICAR-NRCSS) in Ajmer has played a pivotal role in research, variety development, and technology dissemination (Singh et al. 2025a; 2025b; 2021a; 2021b; Chaudhary et al. 2023). In India, seed spices are not just commodities but an integral part of the traditional food system and Ayurveda. Their importance extends beyond culinary use to value-added products, essential oil extraction, traditional medicine, and export earnings, contributing to farmers' income and employment generation in arid and semi-arid regions. Given the extensive cultural and linguistic diversity associated with spice nomenclature, Table 1 compiles the major *Apiaceae* seed spices, detailing their botanical names alongside multilingual equivalents to bridge scientific and traditional knowledge systems. The objective of this review is to provide a comprehensive understanding of *Apiaceae* seed spices by detailing their morphological features and diagnostic traits, biology and reproductive physiology, genetic resources and breeding strategies, and the application of molecular markers, while also synthesizing information on agronomy, phytochemistry, and health benefits to guide future research and utilization.

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Table 1. Major seed spices from Apiaceae family: botanical names and multilingual equivalents

Common Name	Botanical Name	Hindi	Sanskrit	Tamil	Telugu	Malayalam	Urdu	Arabic	English Synonyms
Coriander	<i>Coriandrum sativum</i>	Dhaniya	Dhanyaka	Kothamalli	Kothimeera	Malliyila	Dhania	Kuzbara	Cilantro (leaves)
Cumin	<i>Cuminum cyminum</i>	Jeera	Jiraka	Seeragam	Jeelakarra	Jeerakam	Zeera	Kammun	Roman cumin
Fennel	<i>Foeniculum vulgare</i>	Saunf	Madhurika	Perunchiragam	Sompu	Perunjeerakam	Saunf	Shammara	Sweet fennel
Caraway	<i>Carum carvi</i>	Shahi Jeera	Krishna Jiraka	Seeragam	Shahi Jeelakarra	Karuvapatta	Karawiya	Kammun Aswad	Persian cumin
Dill	<i>Anethum graveolens</i>	Soya	Shatpushpa	Sathakuppu	Soya	Sathapushpa	Soya	Shabat	Indian dill
Ajwain	<i>Trachyspermum ammi</i>	Ajwain	Yavani	Omam	Vamu	Ayam	Ajwain	Karawya	Bishop's weed
Anise	<i>Pimpinella anisum</i>	Saufi	Shatapushpa	Seeragam	Anise	Anis	Badiyan Romi	Yansoon	Sweet anise
Celery	<i>Apium graveolens</i>	Ajmoda	Ajmoda	Amodai	Ajmodam	Ajamodam	Ajmod	Karafs	Wild celery
Parsley	<i>Petroselinum crispum</i>	Ajmod	Ajmoda	Parsley	Parsley	Petroselinam	Jafari	Baqdunis	Garden parsley
Angelica	<i>Angelica archangelica</i>	Chorakanda	Chora	Angelica	Angelica	Angelica	Anjelika	Anjelika	Angelica

Economic, Culinary, and Pharmaceutical Relevance of Apiaceae Seed Spices

(Coriander, Cumin, Fennel, Caraway, Dill, Ajwain, Anise, Celery, Parsley, Angelica)

a) Economic Relevance

Seed spices such as coriander (*Coriandrum sativum*), cumin (*Cuminum cyminum*), fennel (*Foeniculum vulgare*), caraway (*Carum carvi*), dill (*Anethum graveolens*), ajwain (*Trachyspermum ammi*), anise (*Pimpinella anisum*), celery (*Apium graveolens*), parsley (*Petroselinum crispum*), and angelica (*Angelica archangelica*) are of high economic value due to their extensive use in food, pharmaceutical, and cosmetic industries. These crops are well-suited for cultivation in arid and semi-arid regions, especially in India, where states like Rajasthan and Gujarat dominate their production. Their adaptability to marginal soils, short growth duration, and low input costs make them highly profitable for small and marginal farmers.

India is the world's largest producer and exporter of seed spices, with significant global market shares in cumin, coriander, and fennel. As per Spices Board India (2025), seed spices played a key role in India's total spice exports, which reached USD 3.94 billion in 2021–22. The development of value-added products including essential oils, oleoresins, nutraceuticals, and spice blends has further enhanced their commercial potential and generated employment in agro-processing and export sectors. These crops also contribute significantly to crop diversification and climate-resilient agriculture.

b) Culinary Relevance

Apiaceae seed spices play a pivotal role in both traditional and modern cuisines across Indian, Middle Eastern, Mediterranean, and Asian cultures. Spices such as cumin, coriander, fennel, dill, and ajwain are commonly used in whole, ground, or roasted form to enhance flavor, aroma, and shelf life. Caraway and

anise feature prominently in European breads, liquors, and confections, while celery and parsley are valued for garnishing and flavoring. Angelica, known for its musky aroma, is used in herbal tonics and liqueurs. These spices are key components of regional blends like garam masala, panch phoron, and rasam powder, contributing to both palatability and digestion. In addition to their culinary appeal, they possess antioxidant, antimicrobial, and digestive-enhancing properties. Studies (Calucci et al. 2003, Modak et al. 2007, Singh et al. 2007, Pandey et al. 2012) have demonstrated their potential in managing oxidative stress, inflammation, diabetes, and microbial infections, confirming their importance as both flavoring agents and functional food ingredients. Their bioactive components have demonstrated cytotoxic, antitumor, antidiabetic, anti-inflammatory, hypolipidemic, enzyme-inhibitory, and broad-spectrum antimicrobial properties (Cushnie et al. 2005, Singh et al. 2007, Saleem et al. 2017, Khalil et al. 2018, Pandey et al. 2012; Singh et al. 2026), confirming their dual utility as culinary agents and health protectors.

c) Pharmaceutical Relevance

Seed spices of the Apiaceae family are rich in bioactive compounds such as terpenes (limonene, carvone, anethole), flavonoids, phenolics, and volatile essential oils, which contribute to a wide range of pharmacological properties. These include antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and hepatoprotective effects. Coriander, cumin, and fennel are commonly used in traditional formulations for digestive and metabolic disorders, while ajwain is a well-known remedy in Ayurveda and Unani for treating indigestion, colic, and respiratory issues. Fennel also exhibits estrogenic and galactagogue activity, supporting its use in women's health. Anise and

angelica are often formulated into syrups and tonics for digestive health, whereas caraway and dill are used in pediatric colic and antifatulent preparations. Celery and parsley possess diuretic and anti-inflammatory effects and are used in formulations for renal and joint care. Several of these spices are included in WHO monographs and recognized by the European Medicines Agency (EMA 2006) for their safety and traditional use. Their integration into both culinary practices and modern therapeutics underscores their

value in preventive healthcare, integrative medicine, and the development of nutraceuticals. Beyond their culinary and medicinal applications, they also serve as a novel source for insect pest management, owing to their diverse bioactive compounds with insecticidal, repellent, and antifeedant properties (Ravi et al. 2019). Considering their varied pharmacological roles, Table 3 compiles the therapeutic potential of prominent Apiaceae members, linking traditional uses with scientific evidence

Table 3. Comparative morphological of major seed spices

Feature	Coriander	Cumin	Fennel	Caraway	Dill	Ajwain	Anise	Celery	Parsley	Angelica
Plant Type	Annual herb	Annual herb	Biennial/perennial	Biennial herb	Annual herb	Annual herb	Annual herb	Biennial	Biennial/Annual	Biennial/perennial
Leaf Type	Broad, lobed	Thread-like	Finely feathery	Pinnate	Delicate, thread-like	Feather-like	Delicate pinnate	Compound	Flat/crinkled compound	Large, compound
Stem	Branching, hollow	Slender, erect	Tall, ribbed	Slender	Slender	Erect, striated	Erect, branching	Grooved	Erect, grooved	Tall, hollow
Flower Color	White to pinkish	White	Yellow	White	Yellow	White	White	Greenish-white	White	Green-white
Inflorescence	Compound umbel	Compound umbel	Compound umbel	Umbel	Umbel	Umbel	Umbel	Umbel	Umbel	Large umbels
Seed Shape	Spherical	Slender, ridged	Long, curved	Crescent-shaped	Flat, ridged	Oval, ridged	Small, oval	Oval	Oval	Flat, ridged
Aroma	Citrusy, mild	Warm, pungent	Sweet, anise-like	Spicy, nutty	Pungent, herbal	Strong, thymol	Sweet licorice	Mild earthy	Fresh, grassy	Musky, sweet
Use	Leaf & seed	Seed	Seed & leaf	Seed	Leaf & seed	Seed	Seed	Leaf, stalk & seed	Leaf, stalk & seed	Root & seed
Key Distinctive Traits	Rounded fruits, deeply lobed leaves; both leaves and seeds are aromatic	Slender stems, linear leaves; elongated, ridged seeds with strong aroma	Feathery foliage, sweet licorice-like aroma; elongated greenish seeds	Finely dissected leaves; crescent-shaped, dark brown seeds	Bright yellow flowers; fine feathery leaves, pungent aroma	Oval ridged seeds; strong thymol-like aroma; bushy plant habit	Aromatic plant with white flowers; small oval seeds with sweet anise flavor	Leafy stalks, aromatic leaves; seeds small, crescent-shaped	Crinkled or flat leaves; mostly grown for foliage, seeds used in spice blends	Tall perennial; large divided leaves, sweet musky aroma; seeds and roots used medicinally

Overview of the Apiaceae Family and Its Botanical, Economic, and Functional Diversity

The Apiaceae (formerly Umbelliferae) is among the largest and most economically significant families of flowering plants, encompassing approximately 445 genera and over 3,800 species worldwide. Widely distributed across temperate and subtropical regions, members of this family are easily recognized by their

distinctive compound umbel inflorescences, aromatic compounds, and a rich repository of secondary metabolites with culinary and medicinal value.

Seed spices form a critical subgroup within the Apiaceae family, playing a pivotal role in the global spice economy, ethnic culinary traditions, and the phytopharmaceutical industry. Characteristic morphological features of this family include hollow,

furrowed stems, sheathing compound leaves, and dry schizocarpic fruits that split at maturity into two aromatic mericarp units, which serve as the primary spice component in various cuisines and traditional medicines.

The versatility of Apiaceous crops is remarkable. Species like celery and parsley are consumed as leafy vegetables. Key seed spices such as cumin, coriander, fennel, dill, caraway, anise, and ajwain serve as aromatic condiments and therapeutic agents, rich in bioactive essential oils and phytochemicals.

This family's morphological diversity, phytochemical richness, and ecological plasticity make it particularly valuable for sustainable agriculture, especially in semi-arid and arid agro-ecosystems where resource efficiency is critical. The wide adaptability (Murali et al. 2025), short cropping cycles of many species, and high market demand position Apiaceae crops as integral components in climate-smart farming systems (Singh et al. 2015; Harisha et al. 2019), biodiversity conservation, and bioeconomy enhancement.

Botanical Classification and Morphology of Major Seed Spices

a) Botanical Classification and Taxonomic Placement of Seed Spices

All major seed spices coriander, cumin, fennel, caraway, dill, ajwain, anise, celery, parsley, and angelica are taxonomically classified under the family Apiaceae, formerly known as Umbelliferae. This family is globally

recognized for its high degree of aromaticity, medicinal value, and the presence of a compound umbel inflorescence, which is a defining morphological trait.

Apiaceae is a large and economically significant family within the order *Apiales*, comprising more than 3,700 species across 450 genera. Its members are predominantly herbaceous and are valued not only as culinary spices and condiments but also for their pharmacologically active compounds and essential oils (Saleem et al. 2011, Ferrie et al. 2011; Haldhar et al. 2018). The taxonomic coherence of this group is supported by shared structural features such as hollow stems, sheathing leaf bases, and schizocarpic fruits, which provide both botanical and practical frameworks for identification, breeding, and utilization of these seed spice crops.

b) Morphological Features and Diagnostic Traits of Apiaceae Seed Spices

The Apiaceae family, encompassing a diverse group of seed spices, is morphologically distinguished by its characteristic compound umbel inflorescence, hollow aromatic stems, compound leaves, and dry schizocarpic fruits that split into two mericarps at maturity. While these crops share a conserved structural blueprint, species-specific variations in leaf architecture, fruit morphology, and surface ornamentation serve as critical diagnostic features for accurate identification and classification (Table 2).

Table 2. Therapeutic potential of select Apiaceae crops

Plant	Main compounds	Therapeutic Applications and Health Benefits	References
Coriander	β -Carotene, β -cryptoxanthin epoxide, lutein-5,6-epoxide, violaxanthin, neoxanthin	Traditionally used for skin conditions like acne and pimples. Scientific studies support its role in breast cancer prevention, hepatoprotection, and managing gastric ulcers.	Guerra et al. 2005, Malik et al. 2019, Sathishkumar et al. 2016, Tang et al. 2013, Sahib et al. 2013
Cumin	p-Cymene, thymoquinone, α -thujene, gallic and vanillic acids, luteolin, catechin, coumarin, eugenol	Possesses broad-spectrum pharmacological activities, including antimicrobial, antidiabetic, antiulcer, anticarcinogenic, antistress, and neuroprotective properties particularly beneficial in managing Parkinson's disease.	Hassanien et al. 2015, Mnif et al. 2015, Kim et al. 2016
Fennel	Trans-anethole, estragole, fenchone, limonene, rosmarinic acid	Known for its highly effective bronchitis, diabetes, kidney stones and persistent cough persistent diarrhea, endocrine, reproductive. Effective in alleviating menstrual discomfort, digestive disorders, and supports lactation.	Dheebisha et al. 2020, Noreen et al. 2023
Caraway	Limonene, carvacrol, carvone, carvenone, linalool, p-hydroxybenzoic acid, kaempferol, naringenin	Demonstrates hypolipidemic, antidiabetic, and antioxidant activity. Protects against sepsis-related organ damage and is effective in treating hypertension, eczema, and stress-related conditions	Agrahari et al. 2014, Vallverdú-Queralt et al. 2015, Mollazadeh et al. 2019, Johri et al. 2011, Erjaee et al. 2015, Dadkhah et al. 2011, Sachan et al. 2016
Dill	Carvone, trans-dihydrocarvone, dill ether, α -phellandrene, limonene	Used in traditional medicine for managing blood sugar and lipid levels.	Sharopov et al. 2013, Saleem et al. 2017,

		It's hypoglycemic and hypolipidemic actions make it suitable for diabetes and heart disease management.	Mollazadeh et al. 2019
Ajwain	Thymol, cumene, terpene, α -phellandrene, β -pinene, Cis-myrtanol, γ -terpinene, o-carene, 3, 5-Dihydroxytoluene 3-O- β -D Galactopyranoside	Rich in thymol, it offers antimicrobial, antifungal, and digestive benefits. Commonly used in treating indigestion, flatulence, respiratory ailments, migraines and delirium, headaches and microbial infections.	Rajeshwari et al. 2011, Naaz et al. 2024, Razzak et al. 2020, Mohapatra et al. 2023, Moein et al. 2015
Anise	Trans-anethole, p-anisaldehyde, estragole, farnesol, limonene, 4-methoxypropylphenone	Known for its neuroprotective and hormonal regulation effects. Used in traditional medicine for dementia, depression, Alzheimer's disease, and diabetes control.	Shahrajabian et al. 2019, Shobha et al. 2018, Faried et al. 2020, Shahamat et al. 2016
Celery	Apigenin, luteolin, kaempferol, caffeic and ferulic acids	Helps regulate lipid profiles by reducing hyperlipidemia and triglyceride levels. Shows anti-acne activity and has potential anticancer effects by inhibiting angiogenesis and proliferation.	Shin et al. 2019, Mollazadeh et al. 2019, Kooti et al. 2017, Malik et al. 2019, Danciu et al. 2013
Parsley	Apigenin, phenylpropanoids apiol, oleanolic acid, furanocoumarins, isoimperatorin, oxypeucedanin	Exhibits diuretic, antioxidant, hepatoprotective, and anti-inflammatory properties. Traditionally used for urinary tract infections and kidney stone management.	Meyer et al. 2006, Sbair et al. 2016, Mahmood et al. 2014, Farzaei et al. 2013
Angelica	Ferulic acid, Z-ligustilide, Z-butylidenephthalide, N-butylidenephthalide, E-ligustilide, p-hydroxybenzoic acid	Valued for its antispasmodic, digestive, and calming effects. Used in herbal preparations for gastrointestinal disorders, anxiety, infantile atrophy, and respiratory conditions.	Yao et al. 2011, Lao et al. 2004, Li et al. 2006, Wang et al. 2016

Leaf shape and degree of dissection are among the most visually distinctive traits: fennel exhibits finely divided, feathery leaves; coriander has broadly lobed, parsley-like foliage; and dill is recognized by its delicate, thread-like leaf structure. Equally important are fruit characteristics, particularly surface ornamentation such as longitudinal ridges, glandular oil ducts, or bristles, which serve as key taxonomic markers in differentiating closely related species (Calvino et al. 2008, Plunkett et al. 1999).

Moreover, essential oil composition and aromatic profile provide powerful biochemical signatures. Each species synthesizes a unique blend of volatile compounds such as anethole in anise, carvone in caraway, and thymol in ajwain, which not only influence flavor and fragrance but also contribute to their therapeutic and allelopathic properties. These morphological and phytochemical traits, collectively, offer a robust framework for field identification, taxonomic classification, and quality assessment of Apiaceae seed spices.

c) Field Identification of Apiaceae Seed Spices: A Dichotomous Approach

The Apiaceae family comprises economically important plants used as spices, vegetables, and medicinal herbs (Kozhanova et al. 2025). Accurate identification of Apiaceae species is crucial due to their similar morphology and the potential toxicity of some members. DNA barcoding using family-specific oligonucleotides has been developed to identify Apiaceae species, even in mixtures or damaged

samples (Parveen et al. 2018). Comparative morphological and microscopic studies of commercially traded Apiaceae fruits have revealed distinguishing features in their macroscopic structures, vittae, and sclereids, enabling the development of a dichotomous key for precise identification (Devika et al. 2024). This research supports the potential of Apiaceae plants for various industrial applications, including pharmaceuticals and cosmetics, while emphasizing the importance of accurate species identification for safety and efficacy (Kozhanova et al. 2025).

d) General Morphological Structure of Apiaceae Seed Spices

The Apiaceae family comprises economically important seed spices with distinctive morphological features. Plants typically have hollow, ribbed stems and pinnate or bi-pinnate leaves with basal sheaths. The inflorescence is a compound umbel with small, actinomorphic flowers, usually white or yellow (Reduron et al. 2020). The fruit is a dry schizocarp that splits into two mericarps, commonly referred to as "seeds". These seeds exhibit diverse shapes, surface patterns, and epicuticular projections, which are useful for taxonomic classification (Kalsoom et al. 2019). Recent research has focused on advanced breeding approaches, including molecular markers, genomics, and gene editing techniques, to enhance the quality of both food and medicinal crops within the Apiaceae family (Kalia et al. 2024).

e) Key Morphological Features for Field Identification of Apiaceae Seed Spices

The Apiaceae family is characterized by distinctive compound umbel inflorescences, hollow stems, and aromatic fruits that split into two mericarps. Key morphological features for field identification include diverse leaf forms, ranging from finely dissected to lobed, and varying root systems (Reduron et al. 2020). Schizocarp morphology, including shape, surface patterns, and epicuticular projections, serves as an important taxonomic tool (Kalsoom et al. 2019). DNA barcoding has emerged as a powerful method for species identification, with ITS and ITS2 markers showing high discrimination abilities (Liu et al. 2014). The combination of ITS/ITS2+psbA-trnH outperforms the rbcL+matK core barcode for Apiaceae identification (Liu et al., 2014). These morphological and molecular approaches are crucial for accurate identification, especially when dealing with dried roots or preserved specimens lacking diagnostic features (Ellis & Hardman 1992; Liu et al. 2014).

Biology and Reproductive Physiology of Seed Spices

a) Life Cycle Dynamics and Growth Stages of Apiaceae Seed Spices

Apiaceae seed spices exhibit diverse life cycle dynamics and growth stages, ranging from annual to perennial habits. Their development progresses through distinct phases, including germination, vegetative growth, flowering, and seed maturation (Spurr & Lucas 2020). Environmental factors significantly influence these stages, affecting yield and essential oil composition. For instance, fennel reaches maximum fruit yield and quality at full maturity of the primary umbel, while essential oil percentage is higher in early harvesting stages (El-Gamal & Ahmed 2017). Similarly, coriander varieties show optimal seed yield and essential oil quality when harvested at the brown-fruit stage, approximately 40-45 days after flowering (Telci et al. 2006). Understanding these growth dynamics is crucial for optimizing cultivation practices and maximizing crop productivity. Ongoing research continues to address challenges in seed spice cultivation, focusing on developing high-yielding, disease-resistant varieties and efficient production technologies.

b) Pollination Biology and Reproductive Strategies in Apiaceae Seed Spices

Apiaceae seed spices exhibit diverse pollination biology and reproductive strategies. Their small, hermaphroditic flowers arranged in compound umbels attract a wide range of insect pollinators, including bees, flies, and butterflies (Meena et al. 2022). Cross-pollination is prevalent, often facilitated by protandry and self-incompatibility mechanisms (Spurr & Lucas, 2020). While considered generalists, some Apiaceae species may be effectively pollinated by a narrower group of insects. Pollinator assemblages can vary across populations, but this doesn't necessarily lead to local specialization or distinct pollination ecotypes (Zych et al. 2018). Insect pollination significantly enhances seed yield and quality in crops like ajwain, with honeybees being particularly important pollinators. The family's floral architecture and uniform displays

contribute to their success in attracting a diverse range of pollinators, making specialisation unlikely except under specific circumstances (Zych et al. 2018).

c) Seed Development, Dormancy, and Germination in Seed Spices

Seed dormancy and germination are complex processes influenced by various factors. Dormancy allows seeds to survive unfavourable conditions, but can also pose challenges for crop production (Bentsink & Koornneef, 2008). Seed spices often exhibit dormancy due to mechanical and chemical barriers, including hard pericarps and essential oils in the seed coat. To overcome dormancy, techniques like gibberellic acid treatment, mechanical scarification, and warm stratification are employed (Nonogaki et al. 2007). In coriander, a comprehensive approach involving leaching, priming with hydrogen peroxide, and coating with *Azospirillum* significantly improved germination rates (Suriyaprakash Palani-Vasantha et al. 2024). Environmental factors such as light, temperature, and soil conditions, along with phytohormones like abscisic acid and gibberellic acid, play crucial roles in regulating dormancy and germination. Understanding these mechanisms is vital for optimizing crop yield and agricultural production (Shu et al. 2015).

d) Abiotic Stress Tolerance and Adaptive Mechanisms in Seed Spices

Seed spices exhibit various adaptive mechanisms to cope with abiotic stresses. Cumin demonstrates moderate drought tolerance, with ecotypes from specific regions showing superior performance under water stress conditions (Mortazavian et al. 2018). Fennel, ajwain, and anise display increased antioxidant enzyme activity, including catalase, ascorbate peroxidase, and peroxidase, when exposed to salinity stress (Nouripour-Sisakht et al. 2022). These species also accumulate osmolytes like proline and soluble carbohydrates to maintain cellular homeostasis under salt stress (Nouripour-Sisakht et al. 2025). Fennel exhibits greater salt tolerance compared to ajwain and anise, maintaining better growth, essential oil yield, and physiological parameters under saline conditions. Salt stress negatively impacts germination, seedling growth, and mature plant performance across these species, but to varying degrees (Nouripour-Sisakht et al. 2022). These adaptive traits contribute to the survival and productivity of seed spices under challenging environmental conditions.

Agronomy and Cultivation Practices of Seed Spices

a) Climate and Soil Requirements

Seed spices from the Apiaceae family exhibit specific climate and soil requirements for optimal growth and essential oil production. These crops generally thrive in cool, dry environments with well-drained soils (Loncar et al. 2024). Coriander, cumin, and fennel perform best in cool winters with minimal rainfall and slightly alkaline soils (Choudhary et al. 2021, Choudhary et al. 2025), while dill, ajwain, and anise are moderately frost-tolerant but sensitive to excessive humidity (Chaurasia et al. 2020). Climate conditions significantly influence

the quality of essential oils in Apiaceae fruits, with yearly weather patterns having a more substantial impact than geographical location (Lončar et al. 2024). Fertilization practices also affect yield, with biofertilizers showing promise for caraway and chemical fertilizers proving most effective for anise and coriander in organic agriculture (Aćimović et al. 2013). Understanding these climate-soil interactions is critical for site-specific cultivation, yield maximization, and quality enhancement of Apiaceous seed spices, especially under changing climate scenarios.

b) Soil Preferences

Apiaceae seed spices exhibit diverse soil preferences and stress tolerances. Cumin and fennel show moderate salinity and alkalinity tolerance, making them suitable for marginal lands (Kumar et al. 2020). Conversely, celery is highly sensitive to salinity stress compared to other Apiaceae species (Solima & El-Shaieny 2014). Well-drained loamy to sandy loam soils with neutral to slightly acidic pH (6.0-7.5) are generally ideal for these crops. Salinity stress primarily affects germination and early growth through osmotic stress rather than ion toxicity (Solima & El-Shaieny 2014). Proper soil selection and management are crucial for maximizing crop potential and commercial value. Factors such as sowing date, seed rate, and harvest maturity significantly influence yield and quality.

c) Land Preparation and Sowing

Proper land preparation and seed treatment are crucial for the successful cultivation of Apiaceae seed spices. Deep ploughing and harrowing create a fine tilth for optimal germination and root development. In saline or poorly drained soils, raised beds or ridges can improve drainage and reduce salt accumulation, particularly beneficial for sensitive crops like cumin (Piri et al. 2020). Seed biopriming with beneficial microorganisms such as *Trichoderma* spp. and *Pseudomonas fluorescens* enhances seedling vigor, root colonization, and resistance to soil-borne pathogens (Talaviya & Jadeja 2015). These bioagents act as biological shields, promoting plant health under stress conditions. *P. fluorescens* inoculation has shown particular efficacy in improving cumin seed germination and seedling indices under salinity stress (Piri et al. 2020). Integrated nutrient management, combining organic and inorganic fertilizers, can further enhance crop yields, quality, and farmer profits while minimizing environmental nutrient losses.

d) Sowing Time and Method for Apiaceae Seed Spices

Optimal sowing time and spacing are crucial for maximizing yield in Apiaceae seed spices. For dill, sowing on October 15th with 40 cm x 10 cm spacing resulted in the highest seed yield and economic returns (Meena & Singh, 2013). Coriander performed best when sown in December in semiarid Mediterranean environments, with earlier sowing dates leading to higher yields (Carrubba et al. 2006). For fennel, November 1st sowing with 45 cm row spacing produced the highest seed yield, with the Ajmer Fennel-2 variety outperforming others (Kumar & Pal, 2024). Cumin sown on November 5th with 30 cm spacing demonstrated superior growth, yield, and economic

performance compared to other treatments. These studies highlight the importance of precise sowing times and spatial arrangements for each Apiaceae crop, considering local environmental conditions to optimize seed spice production and profitability.

e) Irrigation and Water Management in Apiaceae Seed Spices

Effective irrigation management is crucial for optimizing growth, yield, and quality of Apiaceae seed spices in arid and semi-arid regions. Cumin is sensitive to over-irrigation, requiring only 3-4 light irrigations during its lifecycle (Mehriya et al. 2020). In contrast, fennel and coriander are more water-demanding, benefiting from 6-8 irrigations at critical growth stages (Harisha et al. 2019). Drip irrigation coupled with fertigation has proven highly effective in improving Water Use Efficiency (WUE) for crops like fennel and coriander. Irrigation at 0.8 evapotranspiration (ET) was found optimal for coriander production, while 0.6 cumulative pan evaporation (CPE) was ideal for cumin. Proper irrigation management, combined with appropriate fertilizer application, can significantly enhance crop growth, yield, and water use efficiency in seed spices (Singh et al. 2015; Harisha et al. 2017; Harisha et al. 2019; Mehriya et al. 2020).

f) Nutrient and Weed Management in Apiaceae Seed Spices

Integrated nutrient and weed management strategies are crucial for optimizing yield and quality in Apiaceae seed spices. A balanced fertilization approach combining organic and inorganic sources, such as 60 kg N, 30 kg P, 30 kg K, and 30 kg S per hectare, significantly enhances crop performance and nutrient uptake. Incorporating biofertilizers and vermicompost improves soil health and nutrient efficiency. Effective weed control is essential, with manual weeding at 30 and 45 days after sowing (DAS) showing significant benefits (Nagar et al. 2009). Pre-emergence application of pendimethalin at 1.0 kg/ha followed by hand weeding at 45 DAS proves highly effective, offering optimal weed control efficiency and economic returns. In coriander specifically, oxadiazon at 0.5 kg/ha pre-emergence effectively controls weeds and increases seed yield (Patel et al. 2004). These integrated approaches not only suppress weed growth but also enhance crop productivity and economic viability.

g) Pest and Disease Management in Apiaceae Seed Spices

Integrated pest and disease management is crucial for Apiaceae seed spices like coriander and cumin. Major threats include aphids (*Hyadaphis coriandri*), powdery mildew (*Erysiphe polygoni*), and wilt (*Fusarium oxysporum*) (Nair et al. 2021). Effective control strategies combine biocontrol agents, fungicides, and insecticides. For coriander, foliar sprays of *Lecanicillium lecanii* with propiconazole and carbendazim effectively manage aphids and powdery mildew (Nair et al. 2021). In cumin, kresoxim-methyl and thiamethoxam sprays control blight and aphids (Patel et al. 2025). For wilt management in coriander, *Trichoderma harzianum* and *Pseudomonas fluorescens* combined with carbendazim and mancozeb are

effective (Singh et al. 2009). These integrated approaches address various diseases affecting seed spices, which are crucial for India's spice production, contributing 75% globally (Verma et al. 2022).

h) Integrated Disease Management Practices in Seed Spices

Sustainable management of diseases in Apiaceae seed spices requires an integrated approach combining biological and chemical interventions. Seed treatment with *Trichoderma harzianum* or carbendazim (2 g/kg seed) effectively reduces damping-off and wilt incidence in cumin, while improving plant growth parameters (Bardia & Rai, 2007). Soil application of biocontrol agents like *T. harzianum*, *T. viride*, or *Pseudomonas fluorescens* (5 kg/ha) at sowing and one month later significantly decreases Fusarium population and wilt incidence (Talaviya & Jadeja 2015). Foliar sprays with carbendazim or neem leaf extract, combined with seed and soil treatments, further enhance disease management and yield in susceptible crops (Singh et al. 2015). The integration of these methods, along with the use of disease-tolerant varieties, not only reduces disease severity but also increases biochemical defenses like soluble proteins and phenols in plants (Verma et al. 2022). This multi-pronged strategy aligns with sustainable spice production systems.

i) Harvesting and Post-Harvest Handling in Seed Spices

Timely harvesting of Apiaceae seed spices at physiological maturity, indicated by color changes in umbels, is crucial for optimal quality and essential oil content. Post-harvest handling involves rapid drying to reduce moisture content to 8-10%, followed by threshing, winnowing, and grading based on size, color, and purity (Pruthi et al. 2016). Proper drying and storage in moisture-proof bags help preserve aroma and prevent fungal infestation (Hordofa & Tolossa 2020). These practices are essential for maintaining export quality standards and enhancing market value. Apiaceae seeds, including caraway, anise, coriander, dill, fennel, and cumin, are widely used in folk medicine, pharmaceuticals, and as spices due to their rich essential oil content. Their antioxidant, antimicrobial, hypoglycemic, and hypolipidemic properties make them valuable as natural food preservatives and health supplements. These spices find applications in various food products and spice blends, contributing to their functional food status (Acimovic et al. 2015).

Genetic Resources and Breeding of Apiaceae Seed Spices

a) Traditional and Modern Breeding Approaches

Recent advancements in Apiaceae breeding combine traditional and modern approaches to enhance crop quality and yield. Conventional methods like mass selection and pure-line selection have been effective for coriander and cumin improvement (Kalia et al. 2024). Biotechnological tools, including in vitro regeneration and tissue culture, are now complementing these methods for various Apiaceous crops (Wang et al. 2022). Doubled haploid technology shows promise in

accelerating breeding cycles, as demonstrated in dill, caraway, and fennel field trials (Ferrie et al. 2011). Modern techniques like CRISPR/Cas9 gene editing and marker-assisted selection are being applied to coriander for precise trait improvement. Additionally, omics studies are uncovering genetic variations linked to key agronomic traits across the Apiaceae family (Wang et al. 2022). This integration of traditional and modern approaches is crucial for addressing challenges related to climate change, quality, and sustainability in seed spice improvement.

b) Use of Molecular Markers

The application of molecular markers has revolutionized genetic studies (Sunilkumar et al. 2016) and breeding strategies across the Apiaceae family, particularly in economically important seed spice crops such as coriander, cumin, fennel, caraway, dill, ajwain, anise, celery, parsley, and angelica (Choudhary et al. 2019). Modern molecular tools, including simple sequence repeats (SSRs), amplified fragment length polymorphisms (AFLPs), inter-simple sequence repeats (ISSRs), random amplified polymorphic DNA (RAPD), and single-nucleotide polymorphisms (SNPs) have been widely used to analyze genetic diversity, construct linkage maps, and support marker-assisted selection (MAS) in these crops.

In coriander, extensive molecular characterization using RAPD, ISSR, and SSR markers has helped elucidate the genetic structure of Indian and global germplasm (Choudhary et al. 2019; Choudhary et al. 2017; Alp FM 2017). Transcriptome profiling of coriander accessions for disease resistance genes (Choudhary et al. 2019, 2020, 2021). Cumin has similarly benefited from marker-based studies using molecular markers to distinguish between genotypes and evaluate genetic variability, which are essential for trait improvement and disease resistance breeding (Choudhary et al. 2015). Fennel accessions have been evaluated using SSR and ISSR markers for trait-associated diversity, and high polymorphism rates have enabled genotype differentiation and parent selection for hybridization programs (Choudhary et al. 2015; Sharma et al. 2020; Choudhary et al. 2018).

In celery, molecular markers have revealed considerable intra-specific variability, classifying cultivars into distinct groups based on geography and usage types (Yang X 1993; Choudhary et al. 2016). SSR markers derived from ESTs and transcriptome sequences have further advanced varietal identification and diversity analysis in celery (Fu et al. 2014; Jethra et al. 2017).

In caraway and dill, molecular markers have revealed substantial genetic diversity across regional germplasm collections. These markers have assisted in population structure analysis, aiding in the identification of genetically distinct landraces and breeding lines (Jethra et al. 2018). Ajwain and anise, although less studied, have also shown promising results with RAPD and ISSR markers, enabling preliminary diversity assessments and species discrimination. In parsley, SSR and RAPD markers have

contributed to variety fingerprinting and phylogenetic studies, while in angelica, molecular markers are increasingly being used to understand genetic variation among wild and cultivated populations for conservation and breeding purposes (Tina Jalalifar et al. 2024; Akçali et al. 2020).

Advances in next-generation sequencing have significantly enriched the genomic landscape of Apiaceae crops, enabling deeper insights into their evolution, trait development, and molecular breeding potential. In coriander, a high-quality genome sequence has been published, shedding light on genes associated with flavor, secondary metabolites, and domestication-related traits (Song et al. 2020b). This genomic resource, characterized by high gene density and metabolic complexity, has paved the way for downstream applications in functional genomics. To support broader research access, the Coriander Genomics Database was developed as an integrated platform combining genomic, transcriptomic, and metabolic information (Song et al. 2020). Additionally, a genome-wide study of the Auxin Response Factor (ARF) gene family across coriander and two related species revealed conserved and divergent gene functions relevant to plant development and stress responses (Pei et al. 2021).

In fennel, transcriptomic and organelle genome studies have provided valuable resources for crop improvement. A comprehensive leaf transcriptome revealed key genes involved in the biosynthesis of *l*-anethole, an important aromatic compound, alongside numerous microsatellite and SNP markers, supporting marker-assisted breeding (Palumbo et al. 2018). Further, mitochondrial genome analysis uncovered two distinct *atp6* gene sequences in cytoplasmic male sterile (CMS) lines, offering important insights for hybrid seed production (Palumbo et al. 2020). The chloroplast genome of *Anethum foeniculum* was also sequenced, facilitating phylogenetic analyses and taxonomic classification within Apiaceae (Yu & Min 2022).

Significantly, a chromosome-scale genome of celery has recently been assembled, revealing the evolutionary history of this species, including sequential paleopolyploidization events, karyotype rearrangements, and a noticeable reduction in resistance gene content compared to other members of Apiales (Song et al. 2021). This comprehensive genomic analysis not only provides a reference for celery improvement but also offers comparative insights across the Apiaceae family. Collectively, these genomic and transcriptomic resources for coriander, fennel, celery, and related Apiaceae crops form a robust foundation for trait discovery, evolutionary studies, and genomics-assisted breeding, ultimately facilitating genetic improvement of economically important seed spices. In light of the current advancements and persisting challenges, the following future directions are proposed to enhance the sustainable production and utilization of Apiaceae seed spices. Future research should focus on integrating advanced genomic and metabolomic approaches with traditional breeding to develop climate-resilient, high-

yielding varieties. Additionally, greater emphasis is needed on functional genomics, transcriptomics, and genome editing tools such as CRISPR-Cas to accelerate trait improvement and stress tolerance. Exploring novel applications in nutraceuticals, pharmaceuticals, and eco-friendly pest management will further strengthen the economic and health significance of these crops.

Conclusion

Apiaceae seed spices represent a unique convergence of agronomic value, genetic diversity, and health-promoting potential. Advances in morphological characterization, reproductive biology, and molecular breeding have opened new avenues for crop improvement, while phytochemical research underscores their significance in functional foods and pharmaceuticals. However, challenges such as limited genomic resources, climate resilience, and post-harvest processing persist. Bridging these gaps through integrated approaches combining traditional knowledge with cutting-edge biotechnology will be crucial for harnessing the full potential of these spices in agriculture, health, and industry.

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