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Climate-smart and sustainable production of Cumin (*Cuminum cyminum* L.): Challenges, adaptation strategies, and future prospects

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Abstract

Cumin (*Cuminum cyminum* L.) is a high value seed spice of the Apiaceae family, which is traded globally and is a strategic cash crop to the smallholder farmers of the arid and semi-arid tracts of India, Iran, Syria and Turkey. In India, about 70 percent of world output and over 80 percent of world exports is produced, and 90 percent of national output is produced in Rajasthan and Gujarat. Since cumin is grown on remaining-moist soils during the rabi season, it is highly vulnerable to climate-related disturbances. Increased mean temperatures, reduced winters, occasional drought, uncharacteristic rainfall and an increase in the frequency of *Fusarium oxysporum* f. sp. *cumini* have all contributed to a loss of yields of 20-60 per cent in susceptible seasons. The review critically summarises peer-reviewed articles published in 2015-2025 to provide a cohesive portrait of the challenges, physiological and biochemical responses, and climate-smart adaptation solutions to cumin. Drought to a depth of 20 per cent of field capacity has been reported to cause seed yield to decrease by up to 81 per cent and essential-oil yield by up to 64 per cent, whereas salinity greater than 100 mM NaCl dramatically reduces germination and chlorophyll content. Simultaneously *Fusarium* wilt results in losses of fields of 30-100 percent in highly cultivated areas. Discussed adaptation pathways are the development of synthetic and resistant cultivars (GC-4, RZ-209, MCU-73), molecular and omics-based breeding, shifted sowing windows, drip irrigation and mulching, biocontrol with *Trichoderma* and *Bacillus licheniformis*, integrated nutrient management and plant-growth-promoting rhizobacteria (PGPR). The paper contextualizes these interventions in the Climate-Smart Agriculture (CSA) model of FAO, attributes them to the Sustainable Development Goals (SDG 1, 2, 6, 13, 15), and pinpoints policy and extension and research gaps. This paper concludes that a multi-disciplinary approach that integrates genetics, agronomy, digital tools and institutional support is needed to facilitate resilient cumin production.

Keywords: *Cuminum cyminum*, climate-smart agriculture, abiotic stress, *Fusarium* wilt, essential oil, nanotechnology, precision agriculture, sustainable spice production

1. Introduction

Cumin (*Cuminum cyminum* L.) is the second-most-traded spice in the world after black pepper and the keystone of the global seed-spice economy. It is part of the Apiaceae family and is grown mainly to harvest its aromatic, ridged, fusiform fruits-commercially known as seeds-containing 2.54.5% essential oils composed of cumin aldehyde, 7-terpinene, 2-pinene and p-cymene (Singh *et al.*, 2017; Pruthi, 2017) ^[41, 36]. It has a long history of use in Ayurvedic, Unani and traditional Chinese medicine and is actively researched due to its carminative, antimicrobial, antidiabetic, antioxidant and chemoprotective effects (Mnif & Aifa, 2015; Sowbhagya, 2013) ^[30, 43]. Its utility has given it a long-term demand by the world food, nutraceutical and pharmaceutical industries.

Worldwide, cumin crops are planted on a larger area of more than 1.2 million hectares, of which India alone produces about 70 percent and exports more than 80 percent of the global output. During the 2023-24 trading year, India was the second-largest spice export product after chilli, exporting approximately 1.84 lakh metric tonnes of cumin worth over USD 700 million (Spices Board India, 2024) ^[44]. In India, cumin production is concentrated in Rajasthan and Gujarat, approximately 90 percent of the total domestic production, and Unjha in Gujarat is the largest

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cumin spot market in the world (Spices Board India, 2024; Dharajiya *et al.*, 2023) ^[44, 12]. Other major producers include Iran, Syria, Turkey and, to a lesser degree, China and Afghanistan.

However, the global applicability of cumin is ill-timed in the context of the growing climate change. It needs cool and dry climate (average temperature 15-25 °C in the vegetative stage), low humidity levels in the air, and frost-free flowering and maturity periods (Malhotra, 2020; Meena and Mehta, 2019) ^[26, 29]. These strict specifications render it especially vulnerable to the very changes that climate change entails: increased night temperatures, shortened winter seasons, unseasonal cloudy and humid spells, alterations in rainfall distribution and extreme heat flare-ups during flowering. In the two leading Indian cumin states of Rajasthan and Gujarat, there have been signs of 20-60% yield loss in all seasons of climatic stress, and essential-oil structure and quality have also exhibited changes (Kakani *et al.*, 2024; Dubey *et al.*, 2017) ^[17, 13].

Cumin is experiencing biotic stress in addition to the effects of climate-related abiotic stresses. The most harmful pathogen is Fusarium wilt caused by *Fusarium oxysporum* f. sp. *cumini*, in which the losses in the field reach 30-100% in favourable conditions (Dharajiya *et al.*, 2023; Yadav *et al.*, 2020) ^[12, 46]. The growth of Alternaria blight, powdery mildew and sucking pests like aphids are also increasing in geographic extent and occurrence due to warmer and wetter microclimates (Choudhary *et al.*, 2019) ^[9]. The combination of these stresses has acute effects on rural livelihoods and on the stability of world food supply since cumin is cultivated in large quantities by smallholders with a limited ability to bear risks.

Food and Agriculture Organization of the United Nations defines Climate-Smart Agriculture (CSA) as a sensible framework in responding to such challenges. It has three simultaneous goals: to increase agricultural productivity and incomes in a sustainable manner; to adapt and gain resilience to climate change; to reduce greenhouse-gas emissions where possible (FAO, 2021; Lipper *et al.*, 2018) ^[14, 24]. Applied to cumin, CSA suggests a coordinated bundle of tolerant cultivars, exact agronomy, efficient irrigation, soil-health administration, biological inputs and computer-aided suggestion services to the particular agro-ecologies in which the crop grows prosperously. Economic value of cumin is not limited to export of raw seeds. Premium segment of the world spice industry is now taken up by value-added products, which include powdered cumin, essential oil, oleoresin, and nutraceutical formulations. In 2023/24 India alone was exporting over 1.84 lakh metric tonnes of cumin to over 175 countries and the domestic cumin export industry is earning about USD 616.6 million in revenue in 2023 and is expected to cross USD 700 million in 2025/26 (Spices Board India, 2024) ^[44]. The industry has experienced a compound annual growth rate of approximately 14% in the last seven years due to the increasing number of people worldwide seeking culinary diversification and the rising natural-medicine market. Climate-resilient production is not just a technical issue but a question of export competitiveness in the country due to this commercial trend (Kakani *et al.*, 2024) ^[17].

Although there is an increasing amount of work on the biology of abiotic and biotic stress in cumin, there has been a lack of a synthesis that cuts across physiology, genetics, agronomy, socioeconomics and policy within the CSA framework. The existing reviews are inclined either to deal with disease management or with the chemistry of essential oils or a single abiotic stress like drought. It is evident that there is a lack of integrated, multi-disciplinary synthesis to convert the recent

breakthroughs in omics, nanotechnology and digital agriculture into practical climate-smart advice on cumin-growing areas. This gap is filled by the current review on the basis of peer-reviewed literature published between 2015 and 2025 with the following objectives: (i) to record the present state of world cumin production and the effects of climate change; (ii) to critically review the physiological, biochemical and molecular mechanisms of stress responses; (iii) to evaluate adaptation strategies in terms of genetics, agronomy, water

2. Botanical Description and Agro-Ecological Requirements

2.1 Taxonomy and Morphology

Cumin is a small and slender, glabrous yearly herb belonging to the Apiaceae (Umbelliferae) family. The plant is generally 20-50 cm tall, has pinnate leaves that are finely dissected and has a taproot that is shallowly branched laterally. It has small, white to pinkish flowers in compound umbels pollinated entomophilously - a feature which gives it natural out-crossing and thus high levels of population heterogeneity. The fruit is a schizocarp 4-6 mm in length, ridged, brownish-yellow at maturity, and bears the essential oil which is the determining factor of commercial value. It has a base chromosome number of $2n = 14$, is diploid, and has a relatively small cultivated gene pool, historically limiting breeding development (Bisht *et al.*, 2021; Kumar *et al.*, 2022) ^[17, 22].

2.2 Stages of growth and phenology

Cumin takes 100-130 days to complete its life cycle and progressing in a chronological order, germination, vegetative growth, flowering, grain filling and maturation. Flowering usually lasts between 45 and 55 days after sowing and lasts three to four weeks, with individual umbels possibly overlapping. The flowering-to-maturity window (c. 30-40 days long) is the most climatically sensitive phase, as the pollen viability, umbel retention, fertilisation and oil accumulation are negatively impacted by even brief heat, cold or moisture stress (Meena and Mehta, 2019; Bettaieb Rebey *et al.*, 2017) ^[29, 6]. The alignment of sowing date to the current climatic pattern is thus arguably the most important agronomic decision of the cumin farmer every year.

2.3 Soil and Climate Needs

Cumin is best grown in a cool and dry climate with a mean temperature of 15-25 °C in the vegetative stage of growth and 25-30 °C in grain maturity stage. Its crop is susceptible to frost during flowering, damp humidity in the atmosphere and prolonged periods of clouds that predispose the crop to Alternaria blight and fungal diseases. Sandy loamy soils are preferred with well drained soils having pH of between 6.8 and 8.3 and low to moderate electrical conductivity. Waterlogging is the most detrimental and is often associated with root-rot outbreaks and wilt outbreaks (Malhotra, 2020) ^[26]. South Asia typically has its rabi (October-March) season that meets these criteria, although climate-change trends are shrinking and shifting this season.

2.4 Major Growing Regions

India is the largest producer of cumin with over 90% of domestic production being contributed by Rajasthan and Gujarat. The main producing districts in Rajasthan are Jodhpur, Barmer, Nagaur, Jalore, Pali and Jaisalmer; and in Gujarat, they are Banaskantha, Patan, Mehsana and Kachchh (Dharajiya *et al.*, 2023; Spices Board India, 2024) ^[12, 44]. Other important producers are Iran (Khorasan, Yazd, Isfahan and Kerman

provinces), Syria, Turkey, and smaller production regions in China, Afghanistan and some of Central Asia. The cumin trade is channelled through three world centres, Unjha in India, Tehran in Iran, and Mersin in Turkey, with Unjha having the biggest portion (Kafi *et al.*, 2017) ^[15].

3. Current Status of Cumin Production

3.1 Global Trends

The world cumin production has been on a consistent increase over the past 20 years in response to the increase in food processing, retail and nutraceutical industries. Cumin has reached an all-time high of over 8.5 lakh metric tonnes in India alone in the 2023-24 season due to growth in area in Gujarat and good weather during part of the season (Spices Board India, 2024) ^[44]. Nonetheless, the inter-year volatility is also a structural factor: in previous years, the same crop produced a record crop in 2023/24 because of unseasonal rains and wilt outbreaks, forcing international prices to record highs in 2022/23.

Table 1: Global cumin production and major producing countries (approximate figures, 2020–2024 average).

Rank	Country	Share of Global Production (%)	Average Yield (kg ha ⁻¹)	Market Orientation
1	India	~70	450–650	Dominant producer & exporter
2	Syria	~7–9	300–500	Regional trade, Middle East
3	Turkey	~6–8	400–600	Domestic & processed export
4	Iran	~5–7	350–500	Export, traditional medicine
5	China	~3–5	500–700	Spice industry & re-export
6	UAE & others	~4–6	Variable	Re-export, niche markets

Source: Adapted from Spices Board India (2024) ^[44]; Kafi *et al.* (2017) ^[15]; Meena *et al.* (2021) ^[28].

3.3 Yield Gaps and Constraints

National yields in India average between 450 and 650 kg per hectare, and potential yields in experiments and on farmers field are between 900 and 1000 kg per hectare under managed conditions. The stresses of heat and moisture, wilt and blight epidemics, low-quality seed, unequal farmer agronomy and access to extension services explain the yield gap (Meena *et al.*, 2021; Kakani *et al.*, 2024) ^[28, 17]. The same image is true in Iran, where 49 landraces experimented by Kazemi *et al.* (2018) ^[18] experienced a maximum of 60 per cent yield loss in drought, and a genotype × environment interaction has persistently been found to be expensive in multi-location experiments.

3.4 Role in Livelihoods

In spite of these limitations, cumin is a major cash crop to the smallholders in Rajasthan, Gujarat and even some parts of Iran and Syria. It is the main source of working capital in further kharif activities in many of the dryland areas of western Rajasthan. The growth of exports has also contributed to its strategic value: over 2013/14 to 2024/25 the Indian spice exports increased by 88 percent in volume and by 97 percent in value; cumin also gave a growing contribution to this growth (Spices Board India, 2024) ^[44]. However, the volatility of farmer prices, quality limitations and weather-related fluctuations in yields still pose a source of farm income insecurity.

4. Impact of Climate Change on Cumin Production

4.1 Abiotic Stresses

4.1.1 Heat Stress

Cumin is very sensitive to terminal heat and nowadays in many years, it starts showing up as early as late February in arid belt of India. Higher than 32 °C temperature in flowering leads to sterile pollen, decreased photosynthesis, and increased senescence; changes in essential-oil composition with larger proportions of 8-pinene and p-cymene and lower proportions of

The boom-and-bust pattern is a symptom of how vulnerable the world supply is to the climatic shocks within a limited range of producing regions.

3.2 Major Producers

The world leader is India, which produces approximately 70 percent of the world output. In India, the output of Gujarat was around 3.50 lakh metric tonnes during financial year 2023, whereas Rajasthan has an annual production of between 2.3 and 3.4 lakh metric tonnes (Spices Board India, 2024) ^[44]. Iran, Syria and Turkey are the next most important producers. Iranian cumin, especially Khorasani and Yazdi, is regarded as having a good aroma and a high content of cuminaldehyde, and Syrian and Turkish cumin serve the domestic Middle East markets (Kafi *et al.*, 2017; Bettaieb Rebey *et al.*, 2017) ^[15, 6]. Modest quantities are also produced in China which is a growing re-exporter. A comparative overview is provided in Table 1.

cumin aldehyde (Dubey *et al.*, 2017; Bettaieb Rebey *et al.*, 2017) ^[13, 6]. Evidence in the field in Rajasthan and Gujarat has shown that a 1 °C increase above the optimum may result in losses of seed-yield of 8–12 percent with respect to the period of exposure (Kakani *et al.*, 2024) ^[17].

4.1.2 Drought Stress

The most investigated abiotic stressor in cumin and the most harmful is drought. Controlled experiments indicate that extreme water deficit (20 percent of field capacity) decreases seed yield by up to 81 percent and essential-oil yield by up to 64 percent, and increases malondialdehyde (a product of oxidative damage) and peroxidase activity 3.7- and 5.5-fold, respectively (Ameri Bafqi *et al.*, 2025) ^[2]. Intermediate levels of water stress, ironically, may boost the concentration of essential-oil per unit-mass of seed but decrease overall oil-per-hectare, indicating plant investment in defensive secondary metabolites (Bettaieb *et al.*, 2015; Rebey *et al.*, 2017) ^[5, 1]. The Iranian landraces exhibit significant genotypic variation of drought tolerance, and STI, MP and GMC indices are used to determine the superior accessions including UD-705, UD-529 and UD-769 (Kazemi *et al.*, 2018) ^[18].

4.1.3. Cold and Frost Stress

Cumin can withstand cool weather, but when it is too cold (below 4 °C) at flowering time, the umbels are killed overnight, and low temperatures during the vegetative stage slow maturity and reduce the period of grain filling. Oil composition is also altered due to cold injury, and the crop becomes susceptible to secondary pathogens. Exceptionally intense cold waves in the month of December and January have become common in the last ten years in the western Rajasthan and northern Gujarat belt and were reported as a developing risk (Aishwath & Lal, 2016) ^[1].

4.1.4 Salinity

Saline soils, especially in irrigated areas in Rajasthan, Gujarat and Iran, are increasingly becoming a challenge. The addition of NaCl (50125 mM) drastically lowers seed yield, biomass and chlorophyll of the plant, and alters the essential-oil chemotype of the controls (1-phenyl-1,2-ethanediol) to that of stressed plant (1-phenyl-1,2-ethanediol) (Bettaieb Rebey *et al.*, 201). Salinity also provokes antioxidant reactions: The genes of Fe-SOD and catalase are activated, and proline is accumulated to osmoprotect cells (Abolghasemi *et al.*, 2017; Pandey *et al.*, 2015) ^[47, 34].

4.1.5 Waterlogging

Waterlogging, especially brought about by untimely rainfalls or lack of drainage, is especially harmful. It causes hypoxia, root rot and ethylene accumulation and dramatically enhances Fusarium wilt susceptibility. The effects of heavy, untimely rains during the months of December-January have been reported to cause yield losses of 40-100% in the low-lying fields (Choudhary *et al.*, 2019) ^[9].

4.2 Biotic Stresses

4.2.1 Fusarium Wilt

The most devastating disease of cumin in the world is caused by *Fusarium oxysporum* f. sp. *cumini* (Foc), which was identified as the cause of fusarium wilt. It brings about chlorosis of leaves, browning of vascular, wilting and eventual death of plants; in serious cases, 60-100 percent of harvest is lost. The pathogen is soilborne, and it remains years in the soil and is preferable in a temperature range of 1129 C and relative humidity of 7882 (Khaleqsefat *et al.*, 2022; Dharajiya *et al.*, 2023) ^[19, 12]. Field surveys have reported extensive incidence in Rajasthan and Gujarat, especially in those fields that are constantly planted

with cumin, lasting 4-5 years, and the incidence of the disease is more than 30% (Yadav *et al.*, 2020) ^[46].

4.2.2 Alternaria Blight and other diseases

The second major disease is Alternaria blight, which is caused by *Alternaria burnsii*. Unseasonal rain and cloudy, humid weather during flowering are preferred due to outbreaks; 30-80 percent yield losses have been experienced in severely infected fields. Secondary yet important are powdery mildew (*Erysiphe polygoni*), and aphids whose populations grow when there are warmer winters (Choudhary *et al.*, 2019) ^[9]. Cumin yellowing is a new viral disease that has also been reported in Rajasthan (Meena *et al.*, 2014) ^[27].

4.2.3 Weeds

The competition between weeds at the initial vegetative stage is one of the significant factors of yield loss. The prevalent weeds are *Chenopodium album*, *Phalaris minor*, *Convolvulus arvensis* and the parasitic *Plantago pumila* (locally known as zeeri); the parasitic *Orobanche* has become an increasing constraint in Nagaur and Jodhpur districts (Dharajiya *et al.*, 2023) ^[12].

4.2.4 Climate–Biotic Interactions

Climate change makes the management of biotic stress more difficult in that warmer winters increase the duration of pest and pathogen activity, shorten pathogen latency, and increase the population of vectors. The humid conditions that result in concurrent wilt and blight epidemics are caused by unseasonal rains during flowering. Such changed microclimates are, therefore, questioning integrated disease-management practices that were once effective as ten years ago (Aishwath and Lal, 2016; Choudhary *et al.*, 2019) ^[1, 9].

Table 2: Climate stress factors, plant responses, and yield impact in cumin

Climate Stress	Physiological / Biochemical Response	Agronomic Impact	Reported Yield Loss (%)
Heat stress (>32°C at flowering)	Pollen sterility, chlorophyll degradation, HSP accumulation, ROS surge	Poor seed set, forced maturity, shrivelled seeds, altered oil profile	25–50
Terminal drought (20–40% FC)	Stomatal closure, ABA accumulation, proline & MDA rise, APX/POD up-regulation	Reduced biomass, poor grain filling, up to 81% seed yield loss at 20% FC	30–81
Cold / frost (<4 °C)	Membrane injury, photoinhibition, pollen damage	Stunted growth, flower abortion, delayed maturity	20–40
Salinity (NaCl 50–125 mM)	Na ⁺ toxicity, K ⁺ imbalance, SOD/CAT induction, altered fatty-acid profile	Poor germination (≈40% drop), chlorosis, reduced seed yield	15–45
Waterlogging & humid spells	Hypoxia, Fusarium predisposition, ethylene build-up	Wilt outbreaks, root rot, seedling death	40–100
Erratic rainfall at flowering	Pollen washout, blight outbreaks	Alternaria epidemics, shattering, quality loss	30–70

Compiled from Ameri Bafqi *et al.* (2025) ^[2]; Bettaieb Rebey *et al.* (2017) ^[6]; Pandey *et al.* (2015) ^[34]; Dharajiya *et al.* (2023) ^[12]; Choudhary *et al.* (2019) ^[9].

5. Physiological and Biochemical Responses to Stress

5.1 Photosynthesis and Stomatal Behaviour

Stomata of cumin plants quickly close under stresses of heat and drought conditions, which restricts the uptake of CO₂ and decreases net photosynthesis. Severe drought (20 percent field capacity) decreases total chlorophyll by up to 49 percent and photosystem II efficiency (Fv/Fm) by 2030 percent of irrigated controls (Ameri Bafqi *et al.*, 2025) ^[2]. Degradation of chlorophyll is enhanced by heat and salinity, whereas the duration of the photosynthetic window (leaf area) that is essential in grain filling is shortened by photoinhibition. Genotypes with preserved chlorophyll levels and stomatal homeostasis during stresses always perform better than vulnerable genotypes in trials across multi-locations (Kazemi *et*

al., 2018; Timachi *et al.*, 2020) ^[18, 45].

5.2 Antioxidant Defence Systems

Reactive oxygen species (ROS) accumulation- superoxide, hydrogen peroxide and hydroxyl radicals- are triggered by abiotic stress in cumin. The plant also reacts by up-regulating enzymatic antioxidants, such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), peroxidase (POD) and glutathione reductase (GR) and non-enzymatic antioxidants, including ascorbate, glutathione, flavonoids and Phen In one variety of cumin that was synthetic as tested by Khatibi *et al.* (2025) ^[21] the catalase, peroxidase and APX activities were 131.8, 122.1 and 264.8 times higher respectively compared to parental genotypes when it was in drought. The power of this

antioxidant device is one of the most important predictors of genotypic tolerance.

5.3 Osmotic Adjustment

In response to salinity and water deficit, cumin plants build up compatible osmolytes, such as proline, glycine-betaine, soluble sugars and polyols. It contained 52.9 percent more proline in the synthetic type than parental genotypes during drought (Khatibi *et al.*, 2025) ^[21]. Comparative studies showed a 2.7-fold rise in proline at 100 mM NaCl (Pandey *et al.*, 2015) ^[34]. These osmolytes stabilize proteins and membranes, scavenge ROS, ensure turgor and permit further metabolic activity during stress. Determination of proline content has become a convenient screening measure in multi-genotype assessments.

5.4 Hormonal Responses

Phytohormones orchestrate cumin's response to environmental stress. In response to drought and salinity, abscisic acid (ABA) increases and mediates the stomatal closure as well as the activation of stress-responsive genes; ethylene and jasmonic acid are induced during biotic stress and play a role in defence signalling; salicylic acid is recognized as a part of systemic acquired resistance to wilt and blight (Dharajiya *et al.*, 2023) ^[12]. Plant bio-regulators such as brassinosteroids, salicylic acid, thiourea, glycine-betaine and sodium nitroprusside application has been reported to reduce the effect of stress, and brassinosteroid foliar sprays have been shown to increase grain yield by 74.5 percent in rain-fed environments (Timachi *et al.*, 2020) ^[45].

5.5 Changes in Essential Oil Profile

Cumin has an essential-oil profile that is climatic sensitive. Moderate stress of water tends to enhance the concentration of oil per unit mass of seed but lowers the overall agate oil production per hectare; extreme stress interferes with the production of cuminaldehyde, γ -terpinene and p-cymene (Bettaieb *et al.*, 2015) ^[5]. The oil yield of agro-ecological sub-regions of India varies between 28.4 and 35.9 g kg⁻¹ of seed; the areas that experienced favourable minimum and maximum temperature give oil that is rich in cuminaldehyde and has a pleasant smell, whereas the stressed areas give oil rich in terpenes and pungent flavour (Dubey *et al.*, 2017) ^[13]. Salinity also alters the chemotype, changing the ratios between γ -terpinene, 2-pinene and petroselinic acid (Bettaieb Rebey *et al.*, 2017) ^[6].

5.6 Gene Expression during Stress

Transcriptomic studies have already commenced to reveal the molecular stress tolerance framework in cumin. The Ardakan genotype of limonene synthase was 2.2 times more expressed in flower tissue in Iranian landraces and flavone synthase was expressed most in leaves during moderate stress (Rebey *et al.*, 2017). Comparative transcriptomics of GC-2, GC-3, GC-4 and GC-5 revealed 2,048, 1,576, 1,987 and 1,174 differentially expressed genes (DEGs) upon Foc infection, with the resistant cultivar GC-4 showing up-regulation of steroid biosynthesis, limonene and pinene degradation, and butanoate metabolism pathways—alongside induction of receptors, transcription factors, R-proteins and PR-proteins (Dharajiya *et al.*, 2023) ^[12].

5.7 Integrated Stress Response Model

Combination of physiological, biochemical and transcriptomic data lends credence to a two-stage stress-response hypothesis in cumin. During the initial, short-term period (hours to days) the

plant perceives stress by osmotic, ionic and ROS signals; triggers MAPK cascades and Ca²⁺ signalling; stomata closure via ABA mediated signals; and antioxidant enzyme transcription. The second, longer-term phase (days to weeks) involves the plant accumulating compatible osmolytes, remodelling membrane-lipid composition, altering fatty-acid unsaturation (through desaturase regulation), changing the secondary-metabolite flux to terpene and phenolic biosynthesis, and in resistant genotypes, the deployment of the phenylpropanoid-pathway products to cell- The combined outlook is essential to formulate specific breeding and agronomic interventions to strengthen certain nodes of the response network.

5.8 Cross-Stress Tolerance

A new field of study is the cross-stress tolerance in cumin, the finding that genotypes that are tolerant to a particular stress tend to be more successful in another stress due to the overlap of elements of the central antioxidant and Osmo protective system. The polycross breeding Iranian synthetic variety, e.g., is drought-tolerant, with greater seed-weight stability and fatty-acid composition, with 31.77 percent more polyunsaturated fatty acids under drought stress, and the highest cuminaldehyde content under normal (64.58%) and drought (71.03%) conditions (Khatibi *et al.* This cross-stress resilience is particularly important in climate change where there is a growing incidence of multiple simultaneous stresses not an exception.

6. Climate-Smart Adaptation Strategies

6.1 Genetic Improvement

Traditional breeding has provided a line of better breeds of cumin in the last thirty years. Indian varieties are GC-1 to GC-5 (Gujarat), RZ-19, RZ-209, RZ-223 and RZ-345 (Rajasthan), and MCU-73, MCU-105 and MCU-25 (ICAR-NRCSS, Ajmer)—many of which offer moderate wilt tolerance and location stability (Ramesh *et al.* Synthetic varieties made by polycross breeding have reached a seed-yield increase of up to 84 percent over parental genotypes in drought, in Iran (Khatibi *et al.*, 2024, 2025) ^[20, 21]. Such breeding achievements are, however, limited by the small genetic base of cumin, out-crossing behaviour and low investment as compared to cereals. The use of wild relatives and landraces to pre-breed is becoming more popular in order to expand the genetic pool.

6.2 Molecular and Omics Approaches

Conventional breeding is starting to be complemented with molecular tools. The molecular markers of SCoT have been used on polycross cumin populations to ensure homogeneity and determine intra- and inter-population diversity with molecular variance revealing 71 percent between-population variance among Iranian breeding lines (Khatibi *et al.*, 2024) ^[20]. Transcriptomic analysis has also revealed the differentially expressed genes linked to the wilt resistance in GC-4 encompassing the phenylpropanoid biosynthesis, steroid biosynthesis, and ROS scavenging genes (Dharajiya *et al.*, 2023) ^[12]. Genome-wide association studies (GWAS), wilt and drought tolerance QTL mapping, and CRISPR/Cas9-based editing are still in the exploration phase in cumin but can have a considerable potential (Pandey *et al.*, 2015) ^[34]. Nevertheless, there is still a gap in genomic resources relative to cereals and legumes that the research policy must fill.

6.3 Agronomic Practices

The quickest and least expensive mode of adaptation is

frequently agronomic adjustment. Spacing the planting day by 10 - 15 days will enable the crop to evade terminal heat and the onset of pest pressure; in split-plot experiments in Iran, late November planting with two critical irrigations gave the highest yield (Sharifi-Noori *et al.*, 2017, cited in Rebey *et al.*, 2017). The raised-bed planting enhances the drainage of heavy soils and decreases the rate of wilt by 25-50% (Yadav *et al.*, 2020) ^[46]. The intercrops of fenugreek, coriander or mustard and rotation with pearl millet or mung bean, disrupt the pathogen cycles and enhances soil biology (Meena *et al.*, 2021) ^[28]. There is a general recommendation of 1215 kg of seed per hectare and a row spacing of 30 cm.

6.3.1 Summer Ploughing and Soil Solarisation

Summer ploughing with subsequent (where possible) soil solarisation with transparent polyethylene mulch decreases the density of *Foc* propagules in the upper soil layer. This low-cost, easy-to-implement practice has been demonstrated to produce optimum reduction of viable *Fusarium* propagules at 5 cm depth, and is especially successful in conjunction with biocontrol agents like *Trichoderma harzianum* or *Aspergillus versicolor* in hot-arid climates (Champawat & Pathak, 1990; Yadav *et al.*, 2020) ^[46]. It is a practice that has gained more and more popularity among farmers in Nagaur, Barmer and Banaskantha in recent years.

6.3.2. Crop rotation and Crop diversification.

Cumin cultivated on a single piece of land in over three seasons is highly associated with wilt and low yield. Spinning cumin and pearl millet, mung bean, cluster bean (guar) or fenugreek at least once a season enables pathogen populations to reduce and enhances the balance of organic-matter in the soil. The incidence of disease in fields constantly cultivated to cumin over 45 years in Rajasthan has been documented using field surveys that reported disease incidences of over 30 to 10 on rotated fields (Damodaran *et al.*, 2023) ^[10]. Diversification also diversifies market risk because farmers will be less susceptible to fluctuating cumin prices.

6.4 Water Management

The key aspect of climate-smart cumin production is efficient water use. Drip irrigation technologies provide water savings of 30-50 percent over surface irrigation and canopy humidity and

blight pressure (Yadav *et al.*, 2020) ^[46]. Phenological scheduling of irrigation - especially during flowering and grain filling - maximizes the productivity of water: Iranian studies have shown a genotype-specific sensitivity of accessions to 70, 150 and 200 mm of water, indicating that plasticity to water (Bahreininejad *et al.*, 2014) ^[4]. Crop residue and plastic film mulching save soil moisture, stabilize soil temperature and weed suppress. Deficit irrigation that is timed to less sensitive phenological phases provides a pragmatic tradeoff in presence of water shortage.

6.5 Soil and Nutrient Management

Integrated nutrient management (INM)- a combination of farmyard manure, compost, chemical fertilizers and biofertilizers- enhances nutrient availability, soil structure and microbial diversity, and increases drought tolerance. It is usually treated with 15 kg N, 20 kg P and 20 kg K 2 O per hectare as a basal application and 30 kg N as top-dressing 60 days post planting (Malhotra, 2020) ^[26]. Zinc, iron and boron foliar applications have been demonstrated to enhance umbel formation and seed set under stress. Agronomic biofortification of micronutrients is gaining a new focus as a climate-smart approach (Sharma *et al.*, 2020; Dhage and Vidyashree, 2025) ^[39, 11].

6.6 Biological Approaches

Biological strategies have been particularly useful in the management of wilt and development of stress tolerance. In the field, the results indicate that seed and soil treatment with *Trichoderma viride* and *T. harzianum* could yield 90.5 -90.5% disease control and only 6.0 -6.0% wilt incidence and 420 kg per hectare seed yield (Pipaliya *et al.*, 2021) ^[35]. *Trichoderma asperellum* isolates reduced the growth of *Foc* mycelia by up to 84.3 *in vitro* (Yadav *et al.*, 2020) ^[46]. *Foc* was inhibited by *Bacillus licheniformis* (CSR-D4) by 79.85% and disease incidence was decreased to 15-90 percent in pot trials, and at the same time, *Bacillus licheniformis* (CSR-D4) increased chlorophyll, carotenoid, peroxidase and proline levels in treated plants (Damodaran et *Pseudomonas fluorescens* strains enhanced seedling growth and antioxidant enzyme during salinity stress (Moradi *et al.*, 2018; Moradi *et al.*, 2020) ^[31, 32]. These biocontrol agents have been used together with soil solarisation and Brassica amendments to offer an integrated low-cost climate-smart disease-management package.

Table 3: Climate-smart adaptation strategies for cumin and their documented benefits

Strategy Category	Intervention	Documented Benefits
Genetic improvement	Synthetic varieties via polycross breeding; resistant cultivars (GC-4, RZ-209, RZ-223, MCU-73)	Up to 71.6% higher seed yield and improved proline, chlorophyll and antioxidant activity under drought
Molecular / omics tools	QTL mapping, SCoT markers, transcriptomics, CRISPR/Cas	DEG identification in GC-4 reveals PR-proteins, ROS scavengers, R-genes and signalling
Agronomic adjustment	Shifted sowing window, raised-bed planting, optimum spacing, intercropping	Escape from terminal heat & blight; improved drainage; lower pest load
Water management	Drip irrigation, mulching, deficit-irrigation scheduling	30–50% water savings; higher oil yield; reduced blight
Soil & nutrient management	INM, biofertilizers, micronutrient and nano-silica foliar sprays	Better umbel formation; higher resilience to drought and salinity
Biological agents	<i>Trichoderma viride</i> , <i>T. harzianum</i> , <i>T. asperellum</i> , <i>Pseudomonas fluorescens</i> , <i>Bacillus licheniformis</i> , AMF	Up to 90% disease control and 20–40% yield gain under wilt pressure
Nanotechnology	Nano-silica (4 mM nSi), ZnO/Fe nanoparticles, CMC-naringenin composites	Alleviated drought symptoms; improved essential oil yield and antioxidant capacity
Digital & precision tools	Weather-based advisories, AI disease forecasting, IoT soil sensors	Timely management, reduced input use, better risk management

7. The role of the Climate-Smart Agriculture (CSA) Framework

7.1 CSA Principles

The Climate-Smart Agriculture model, outlined by FAO in 2010

and mainstreamed by the CSA Sourcebook (FAO, 2013, 2021) ^[14], is based on three pillars that are interrelated: sustainably increasing productivity and incomes; adapting and becoming resilient to climate change; and reducing greenhouse-gas

emissions where possible. CSA is context-specific: what is climate-smart in one agro-ecology may not be in another, and the framework does not focus on prescriptive technology packages but on enabling policies, institutional support and innovative finance (Lipper *et al.*, 2018; FAO, 2021) ^[24, 14].

7.2 Application to Cumin

Applied to cumin, CSA involves a system of coherent package: tolerant cultivars, resource-efficient agronomy, drip irrigation, integrated nutrient management, biological inputs and digital advisory services. The climate-smart agenda of cumin is characterized by the productivity and adaptation pillars (as opposed to cereals, where the emission-reduction potential is substantial) (Lal *et al.*, 2019) ^[23]. Field experiments in Rajasthan and Gujarat have shown that a combined package of GC-4 or RZ-209 planting, delayed sowing, drip + mulch and *Trichoderma* seed treatment can increase the yield by 25-40% and decrease the usage of water and agrochemicals by 30-50% (Lal *et al.*, 2019; Yadav *et al.*) ^[23, 46].

7.3 Interconnections with the Sustainable Development Goals

Production of climate-smart cumin is directly aligned with a number of SDGs. Improved productivity and income security will lead to SDG 1 (no poverty) and SDG 2 (zero hunger) among the smallholders. Better use of water helps achieve SDG 6 (clean water and sanitation). Less agrochemical load and soil conservation are associated with SDG 13 (climate action) and SDG 15 (life on land). SDG 8 (decent work and economic growth) is also supported by export-oriented value chains that can be organized in a fair manner, whereas SDG 5 (gender equality) is supported by gender-responsive extension (Chauhan *et al.*, 2023) ^[8].

7.4 Sustainability Dimensions and Carbon

Carbon accounting in cumin production systems is underdeveloped, and initial results show that the per-kilogram carbon footprint can be decreased by 25-40 percent by switching from flood irrigation and heavy urea usage to drip irrigation and biofertilizer-based nutrient management (Chauhan *et al.*, 2023; Lipper *et al.*, 2018) ^[8, 24]. Introduction of carbon-market on a voluntary basis, especially via cooperative producer organisations, is another revenue stream that is yet to be fully exploited.

8. Future Prospects and Technologies

8.1 Precision Agriculture

Technologies of precision agriculture: remote sensing, multi-spectral drone-based imaging, GPS-controlled activities, sensor-controlled irrigation and variable rate input application are being also applied to high-value and low-margin crops like cumin. Multi-spectral imagery is able to identify the early indicators of wilt and nutrient deficiency way before visual symptoms develop, and real-time irrigation control can be achieved with the help of IoT-based soil-moisture sensors and canopy-temperature sensors. The cumin adoption is still low yet on the increase in commercial Gujarat farms (Kakamoukas *et al.*, 2021; Kakani *et al.*, 2024) ^[16, 17].

8.2 Artificial Intelligence and Machine Learning

Machine learning and artificial intelligence (AI) are being used to predict the yields, forecast the disease, and generate advisories. Most recently, wavelet-based, multilayer-perceptron and radial-basis-function neural networks are compared to

explain cumin drying behaviour under varying plasma and ultrasound treatments (Azadbakht *et al.*, 2024) ^[3]. In Rajasthan and Gujarat, mobile advisory services have been providing regional language-specific advice on crops, but uptake is still not even. The intersection of satellite imagery, IoT data streams and AI analytics provide an effective path to risk-based decision-making to smallholder cumin farmers.

8.3 Nanotechnology

Nanotechnology is a promising direction in cumin resilience that is especially promising. When sprayed at 4 mM foliar concentration, nSi nanoparticles of silicon dioxide were found to protect total chlorophyll, maintain peroxidase activity, lower malondialdehyde levels and enhance seed and essential-oil yield under extreme drought (20% FC); however, at higher concentrations of nSi (6mM), drought aggravated the effects, suggesting that the effect is narrow. Nano-silica also transcriptionally reprograms the phenylpropanoid and terpenoid pathways, up-regulating the gene of PAL1 and limonene synthase in stressed cumin (Malayeri *et al.*, 2026) ^[25]. The carboxymethylcellulose-naringenin nanocomposites (CMC-Nar, approximately 65 nm) are also capable of relieving the drought stress in Isfahan and Kashan cumin varieties (Nahrevarian *et al.*, 2024) ^[33]. Zinc and other nano-fertilizers have been shown to have biofortification capabilities in other crops and can be modified to cumin (Dhage & Vidyashree, 2025; Sobhani *et al.*, 2025) ^[11, 42].

8.4 Biotechnology and Omics

Genomics, transcriptomics, proteomics and metabolomics are starting to provide insights into the molecular architecture of cumin stress responses. Salinity stress metabolomics has discovered 45 metabolites with different levels of expression that comprise luteolin, salvianolic acid, kaempferol and quercetin that are the basis of antioxidant defence and the functional-food value of the plant (Pandey *et al.*, 2015) ^[34]. Pathway-level transcriptomic profiling of GC-4 during *Foc* infection can be leveraged to deploy in next-generation breeding (Dharajiya *et al.*, 2023) ^[12]. Combining the data of omic sequencing with speed-breeding methods may significantly reduce the time of cultivar development.

8.5 Priming and Biopriming of seeds

The seed priming and biopriming is the low-cost stress-relief pathway. Bio-priming with *Trichoderma* T36 or *Pseudomonas* CHA0 and coating cumin seeds with a vermiculite-kaolin-perlite matrix enhances seedling emergence, antioxidant enzyme activity and soluble protein content significantly in drought (Bahmani *et al.*, 2019) ^[48]. Amla extract priming with NaCl has also demonstrated potential in enhancing cumin germination in salinity (Said & Mohammed, 2023) ^[38]. It has been reported that UV-C priming (25-30 min exposure) enhances the activity of antioxidant enzymes in cumin seed stored (Ameri Bafqi *et al.*, 2025) ^[2].

9. Policy, Extension and Socioeconomic Dimensions.

9.1 Policy and Institutional Support.

Policy support cannot be ignored in transforming technical advances to farm-level change. In India, seed multiplication, market infrastructure and export promotion of cumin are assisted by the Union of the Mission for Integrated Development of Horticulture (MIDH), Spices Board and ICAR-NRCSS (Ajmer). Farmer decisions are significantly influenced by minimum support prices, crop insurance in the Pradhan Mantri Fasal Bima

Yojana and mandi infrastructure. The SPICED scheme introduced by the Spices Board has its specific approach to sustainability and gradual interventions to export development (Spices Board India, 2024) ^[44]. Iran, Syria and Turkey utilize similar yet less powerful policy tools, which frequently are directed at market and credit support and rarely at research.

9.2 Extension Services

Extension services are the intermediaries between research and practice. There is the input of Krishi Vigyan Kendra (KVKs), state agricultural universities, ICAR-NRCSS and even private agri-tech firms. Nonetheless, field surveys regularly find areas of inaccessibility and lateness, especially among women farmers, and among those who farm marginalized holdings in the remote corners of Rajasthan. Digital extension tools are scalable and rely on infrastructure and digital literacy (Singh and Gupta, 2023; Chauhan *et al.*, 2023) ^[40, 8].

9.3. The dynamics of the market and exports will be discussed in section

The export earnings of India have also increased at an estimated USD 616.6 million in 2023 to an estimated USD 700+ million in 202526 and the export has expanded to 175 countries (Spices Board India, 2024) ^[44]. The high-quality standards in the European Union, the United States and the Gulf market (including pesticide residues, aflatoxins and microbial load) provide a good incentive towards good agricultural practices and traceability. On the other hand, unpredictable export prices may deter investment in resilience over the long run. Enhancing value-chain resilience would be beneficial through strengthening contract farming, transparent price discovery, and origin-based quality certification.

9.4 Gender and Equity

The women play a significant role in sowing, weeding, harvesting, cleaning and post-harvest management of cumin, but limited land-ownership, credit access and representation in extension. Empirical evidence suggests that women report climate-change effects and adaptational demands in different ways than men - more frequently acutely, due to their multiple responsibilities in water-carrying, food preparation at home and livestock management (Chauhan *et al.*, 2023) ^[8]. Resilience-building requires gender-responsive CSA programmes that include specific capacity-building, tool ergonomics and input access.

10. Conceptual Framework: From Climate Change to Sustainable Production

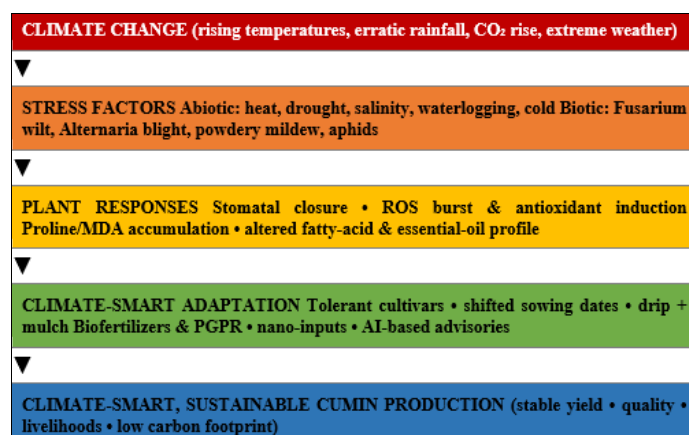


Fig 1: Conceptual flow from Climate Change → Stress Factors → Plant Responses → Adaptation → Sustainable Cumin Production

Figure 1 distils the argument of this review into a five-stage conceptual pathway. Climate-change drivers generate a combination of abiotic and biotic stresses. Plants respond through physiological and biochemical adjustments that, while necessary, are insufficient alone to sustain productivity. Climate-smart adaptation strategies—spanning genetics, agronomy, water and nutrient management, biological inputs and digital tools—transform these stresses into a manageable range, ultimately delivering sustainable cumin systems that maintain yield, quality, livelihoods and environmental integrity.

11. Illustrative Case Studies

11.1 Case Study 1: Wilt Management through Biocontrol in Rajasthan

Damodaran *et al.* (2023) ^[10] investigated the prevalence of Fusarium wilt in field surveys in Rajasthan where cumin had been planted continuously over 45 years, and found the incidence to be over 30 per cent in fields where symptoms were severe, and the plants were completely dead. *Bacillus licheniformis* (strain CSR-D4) treatment of seeds and soil in controlled pot experiments reduced Foc mycelial growth by 79.85 *in vitro*. The disease incidence in treated plants was only 15 percent as opposed to 90 percent in the untreated controls. At the same time, there was higher chlorophyll and carotenoid levels, increased peroxidase activity, and 40 percent increased proline levels in treated plants, which is a sign of induced systemic resistance. The case demonstrates that one biocontrol agent, along with crop rotation and sound sowing, can help change the approach toward wilt management into a reactive, chemical-based strategy into a proactive, eco-friendly strategy.

11.2 Case Study 2: Synthetic Variety Development in Iran

In one of the pioneering breeding programs, Iranian scientists created a synthetic cumin by polycross breeding of the desired parental genotypes (Khatibi *et al.*, 2024, 2025) ^[20, 21]. Compared to parental genotypes under drought, the synthetic variety was found to have a 71.59 percent higher seed yield, 46.53 percent greater chlorophyll-a content, 24.03 percent more total chlorophyll and a 52.90 percent higher proline accumulation with three growing seasons at normal irrigation (field capacity) and severe drought (30 percent of field capacity). The catalase, peroxidase and ascorbate peroxidase antioxidant enzymes were increased by 131.81, 122.05 and 264.78 percent, respectively. The homogeneity and genetic uniqueness of improved populations was confirmed by SCoT molecular markers. The case shows how physiological, biochemical and molecular methods can be used to combine to breed seed and spice and can serve as a model to implement cumin programmes in India and beyond.

11.3 Case Study 3: Nano-Silica for Drought Mitigation in Iranian Cumin

A two-season split-plot experiment in Bafgh, Iran, demonstrated that foliar application of 4 mM silicon dioxide nanoparticles (nSi) significantly alleviated drought stress in cumin grown under 20% field capacity (Ameri Bafqi *et al.*, 2025) ^[2]. In the absence of nSi, there was 5.5 and 3.7-fold enhancement in peroxidase activity and malondialdehyde, respectively, and 49, 81, and 64% decreases in total chlorophyll, seed yield, and essential-oil yield, respectively. The nSi treatment of 4 mM concentration did not affect chlorophyll content, peroxidase activity was maintained at an optimum and MDA accumulation was reduced and seed and oil yield was restored in a significant manner. Interestingly, an increase in the amount of nSi (6 mM) enhanced the impact of drought, indicating that there is a

concentration range. Subsequent transcriptomic studies have demonstrated that nSi is a molecular priming agent, which up-regulates PAL1 and limonene-synthase genes in the phenylpropanoid and terpenoid pathways (Malayeri *et al.*, 2026)^[25]. The case demonstrates the potential of nano-technological interventions in cumin, as well as the necessity to optimise the concentration of the intervention attentively.

11.4 Case Study 4: Eco-Friendly Wilt Management in Gujarat

A field study at Sardarkrushinagar Dantiwada Agricultural University in Gujarat found that soil application of *Trichoderma viride* with seed treatment using *T. harzianum* resulted in 90.52 per cent disease control, reducing the wilt incidence to 6.03 per cent and a seed yield of 420 kg per hectare (Pipaliya *et al.*, 20)^[35]. The second-best treatment combination (soil *T. harzianum* + seed *T. harzianum*) had 83.51% of disease control and 387 kg per hectare of seed yield. Both packages proved to be significantly more economically profitable than the use of chemical fungicides, as the cost of bioagents is lower, and the low-residue cumin is more profitable in the market. The case highlights the economic and ecological argument in support of biological management.

12. Research Gaps and Future Directions

12.1 Genetic and Genomic Resources

Although significant progress has been made, the cumin genome is yet to be assembled to the scale of chromosome-quality reference genome of cereals and legumes. The marker density, QTL resolution, and transformation protocols are all in need of development. Drought and wilt tolerance phenotyping platforms at high-throughput are mostly lacking in countries where cumin is grown. The deployment of modern breeding tools at scale critically depends on investment in the underlying resources (Pandey *et al.*, 2015; Dharajiya *et al.*, 2023)^[34, 12].

12.2 Agronomic Long-Term Trials

There is a paucity of long-term, multi-location agronomic evidence of cumin in real-world climate-change conditions in peer-reviewed literature. Majority of the studies published are site specific and season specific, and it is hard to tell how heat, drought, salinity and disease will interact in future climates. Long-term trials, organized globally by producing countries would significantly reinforce the evidence-based support of climate-smart recommendations (Meena *et al.*, 2021)^[28].

12.3 Physiological and Post-harvest Research

More attention should be paid to climate-quality interactions, such as essential-oil composition, risk of mycotoxin contamination, and shelf-life behaviour under stress. Drying, cleaning and storage losses can be significant post-harvest and can be sensitive to both climatic and handling factors (Ameri Bafqi *et al.*, 2025; Azadbakht *et al.*, 2024)^[2, 3]. There is a dearth of value-chain studies that trace the effects of stress in the field to export container.

12.4 Socioeconomic, Policy and Gender Gaps

The literature on economic research of the returns to drip irrigation, biofertilizers and precision tools in cumin is scattered. Few studies have provided gender-disaggregated evidence on the adoption of CSA, even though women are the main participants in cumin farm labour. There is also a lack of policy studies on the integration of carbon-finance in cumin, certification schemes and resilient contract-farming models in

cumin (Chauhan *et al.*, 2023)^[8].

12.5 Priority Directions

Future-research priorities encompass: (i) creating high-quality cumin reference genome with associated pan-genome resources; (ii) creating coordinated multi-country long-term CSA trials of genotype x environment x management interactions; (iii) creating AI-based wilt and blight early-warning systems coupled with mobile advisory systems; (iv) systematically assessing nano-enabled inputs and biofertilizers under different agro-ecologies.

Abbreviations

ABA – Absciscic acid; AMF – Arbuscular mycorrhizal fungi; APX – Ascorbate peroxidase; CAT – Catalase; CSA – Climate-Smart Agriculture; CRISPR – Clustered Regularly Interspaced Short Palindromic Repeats; DEG – Differentially expressed gene; FAO – Food and Agriculture Organization; FC – Field capacity; Foc – *Fusarium oxysporum* f. sp. *cumini*; GWAS – Genome-wide association study; HSP – Heat-shock protein; ICAR–NRCSS – Indian Council of Agricultural Research – National Research Centre on Seed Spices; INM – Integrated Nutrient Management; MDA – Malondialdehyde; nSi – Silicon dioxide nanoparticles; PAL – Phenylalanine ammonia-lyase; PGPR – Plant-growth-promoting rhizobacteria; POD – Peroxidase; QTL – Quantitative trait locus; ROS – Reactive oxygen species; SCoT – Start Codon Targeted marker; SDG – Sustainable Development Goal; SOD – Superoxide dismutase.

13. Conclusion

Cumin is a premium seed spice whose cultivation is becoming threatened by the climate change. The increasing temperatures, unpredictable rainfall, heightened wilt and blight stresses, and changing pest complexes are all threats to yields, quality and income of farmers in the semi-arid cumin growing areas. Simultaneously, scientific knowledge of the physiological, biochemical and molecular mechanisms of stress responses in cumin has developed at a very rapid rate within the last ten years, providing various approaches to intervention. Since antioxidant biology and proline osmoprotection, the field has shifted away to the descriptive observation to the more mechanistic insight of transcriptomics of resistant cultivars like GC-4.

There will be no one strategy that will be adequate. The resilient cumin industry requires a portfolio to integrate tolerant cultivars and synthetic varieties, molecular-breeding instruments, climate-sensitive agronomy, effective drip irrigation, combined nutrient and biological control, and computer-aided decision-support systems. Nanotechnology, especially silicon dioxide, zinc-based and naringenin-composite nanoparticles, have great potential to alleviate drought and enhance the yield of essential-oil, yet must be critically considered with regard to concentration optima and environmental safety. The ecologically friendly, low-cost use of biocontrol agents like *Trichoderma*, *Pseudomonas fluorescens* and *Bacillus licheniformis* is worthwhile against *Fusarium* wilt and is worthy of mass application.

Technical interventions should be incorporated in supportive policy, fair markets and gender responsive extension otherwise they cannot be implemented at scale. In the future, a combination of omics, artificial intelligence, precision farming and nanotechnology presents a potent suite of tools to future-proof cumin systems. The realisation of this potential will require long-term public investment in research, proper cooperation between the producing countries, and the active

work with smallholder farmers who are the main source of cumin in the world. When done in a consistent manner, climate-sensitive and ecologically-friendly cumin production can not only ensure a prized spice, but also be a model of resilient dryland farming in general.

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