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CLIMATE CHANGE IMPACTS AND MITIGATION ON CHILLI PRODUCTION: ADAPTIVE AGRONOMIC AND GENETIC STRATEGIES

Jaspreet Singh* and Sahil Kumar
Department of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India -151302.
*Corresponding author E-mail: singhjaspreetmgc@gmail.com

ABSTRACT

Chilli peppers (*Capsicum* spp.) are vital horticultural crops with great economic and nutritional value, particularly in India where they are extensively cultivated and consumed. This article reviews how climate change notably rising temperatures, erratic rainfall, drought and increased pest pressures affects chilli cultivation in India and worldwide. It examines the diversity of chilli species and their key traits, outlines historical aspects of their domestication and breeding and highlights pioneering scientists and institutions that have improved chilli over time. The main focus is on adaptation and mitigation strategies. Agronomic approaches (such as improved irrigation, mulching, crop management and season adjustments) and genetic approaches (such as breeding stress-tolerant varieties, molecular techniques and modern biotechnologies) are discussed in depth. The review article also surveys recent technological advances for example, climate-smart irrigation systems, high-throughput phenotyping and gene-editing tools and describes newly developed chilli varieties bred for drought, heat or disease resilience. A selection of climate-resilient cultivars is summarized. The review emphasizes integrated solutions combining traditional knowledge and cutting-edge science to sustain chilli yield and quality under global climate challenges.

***Keywords* :** Climate change, chilli production, *Capsicum* species, drought tolerance, heat stress, agronomic adaptation, genetic improvement, CRISPR, climate-smart agriculture, India.

Introduction

Chilli peppers (*Capsicum* spp.) originated in Central and South America, where they were domesticated by indigenous peoples over 9000 years ago. Widely traded by European explorers, chili reached India in the 16th–17th centuries (via Portuguese traders) and became a staple spice. In botany, the genus *Capsicum* was first described by Carl Linnaeus in 1753 (Cunningham, 2018). Scientific interest in chilies grew over the 19th and 20th centuries: researchers isolated capsaicin (the compound responsible for pungency) in the early 1800s and developed the Scoville scale (1912) to measure heat. In the mid-20th century, agronomists and plant breeders across India and the world began systematically improving peppers for higher yield and disease resistance (Dang, 2012). Institutions such as the Indian Council of Agricultural Research (ICAR) and international centers like AVRDC (The World Vegetable Center) have released dozens of improved cultivars (Du Y-T, 2018). These efforts were shaped by pioneering scientists (for instance, early horticulturists in the 1900s and crop physiologists) who documented the importance of temperature and water stress on pepper growth. Today, chilli cultivation has a rich history of experimentation and breeding, but faces new challenges as the climate changes. Understanding these historical advances and the legacy of past research helps inform current strategies for climate adaptation (Hussain, 2018, Liu, 2018).

Chilli Production in India Current Status and Climate Challenges

India is the world's largest producer, consumer and exporter of chillies. In 2023, India grew chillies on roughly 0.9–1.0 million hectares, yielding about 2.7–2.9 million tonnes (around half of global output) (Lowder, 2018). Production is concentrated in states like Andhra Pradesh, Telangana, Madhya Pradesh and

Karnataka. Andhra Pradesh alone accounts for over 30% of India's chili output, followed by Telangana (approx. 25%), Madhya Pradesh (approx. 12%) and Karnataka (approx. 11%). Average yields in India are relatively modest (around 3 t/ha nationwide, compared to 4–6 t/ha in some countries) (Mahto, 2020). Many Indian chilli crops are grown under rainfed or semi-arid conditions, making them vulnerable to water stress. Indeed, India's chili-growing regions often face erratic monsoon rains and recurring droughts (Naito, 2021). Climate studies indicate that northern and central India key chili areas have seen increasing heat waves and declining winter rainfall in recent decades. High daytime temperatures (often above 35–40°C during flowering) and warm nights are now common, especially in summer seasons (Nizampatnam, 2024). Farmers report heat-related flower drop and poor fruit set during heat spells. Moreover, unpredictable rainfall patterns cause some seasons of waterlogging or flooding (damaging plants) followed by dry spells (causing drought stress). In sum, India's chilli belt is experiencing greater climate variability, which threatens both yield and fruit quality (Oh SangKeun, 2008). At the same time, agricultural research and government programs are responding. Irrigation projects, water harvesting schemes and improved infrastructure have slightly increased irrigation coverage (Park S-i, 2021). Research centers have characterized local landraces that perform better under heat or with limited water. For example, in rainfed plateau regions some farmers successfully grow hardy chilli types by shifting planting dates to avoid peak summer heat. Yet many areas remain highly climate-vulnerable (Quemada, 2022). Climate model projections suggest that without adaptation, chilli yields could decline sharply if temperatures rise approx. 1–2°C above current averages or if droughts become more common. Thus, understanding both traditional practices (like drought-resilient cropping calendars) and modern innovations (drought-tolerant hybrids, sensor-based irrigation) is critical in India's scenario (Ricart, 2023).

Global Chilli Production and Challenges

Globally, chillies are cultivated on about 1.8–2.0 million hectares with annual production around 5.5–6.0 million tonnes. Major producing countries include Bangladesh (approx. 0.6–0.7 Mt), Thailand (approx. 0.3 Mt), China (approx. 0.3 Mt), Ethiopia (approx. 0.3 Mt) and Myanmar (approx. 0.15 Mt). Mexico, long a historical leader, has both sweet and hot pepper cultivation that often appears in statistics for *all peppers* (Shivanna, 2022). India leads specifically in "hot chili" production due to the domestic demand for spicy varieties. Many of the world's chili-producing regions lie in tropical or subtropical climates, which are themselves warming rapidly. For example, in Mexico and Africa, rising night time temperatures can cause flowering failure. In Southeast Asia, increased monsoonal variability brings episodes of extreme rainfall or drought. Even comparatively temperate areas (like parts of Europe and China's highlands) see hotter summers and occasional heat stress. The impacts of climate change on global chilli output are already observed: warmer average temperatures have shortened growing cycles but also reduced yields per plant, as heat stress impairs fruit set (Sun, 2019). Pest and disease dynamics are also shifting: pests like whiteflies, thrips and mites are expanding their range into regions previously too cool for them, increasing viral and fungal problems in chilli fields. Furthermore, elevated atmospheric carbon dioxide (CO_2) can increase plant biomass but tends to dilute nutrient content and reduce capsaicin levels, affecting fruit quality (pungency and nutrition) (Vijay, 2023). Nevertheless, global efforts in major producing countries are underway. Breeding programs in China and the USA, for example, are focusing on heat-tolerant and disease-resistant varieties (Xiong, 2021). Climate-smart agriculture is promoted in parts of Africa, combining drought-tolerant cultivars with water harvesting. International research networks are characterizing wild *Capsicum* species (from Central and South America) that thrive in marginal climates, seeking genes for stress tolerance (Zhang, 2022). Global trade also influences adaptation: countries that export chilies (India, Thailand, China) are sensitive to quality (capitaicin content, colour), providing economic incentive to invest in resilient cultivation methods (Zhang, 2020).

Capsicum Species Diversity and Key Traits

The genus *Capsicum* comprises 20–27 species of peppers, with five domesticated species widely cultivated for their edible fruits. The principal species are *C. annuum*, *C. chinense*, *C. frutescens*, *C. baccatum* and *C. pubescens*. Each species has unique traits relevant to climate adaptation (Table 1) (Abbass, 2022).

- *C. annuum* (including bell peppers, jalapeños, cayenne) is the most globally prevalent originally domesticated in Mexico. It includes both sweet and hot types, with fruit pungency ranging from zero (bell peppers) to approx. 50,000 Scoville Heat Units (SHU) in some chilis. Annumm cultivars prefer warm conditions (day approx. 25–30°C), moderate rainfall and well-drained loamy soils. They have moderate heat tolerance but are sensitive to frost and extreme heat above 35°C, which reduces flowering and fruiting (Ahmad N, 2021).

- *C. chinense* (habaneros, Scotch bonnets) was domesticated in the Amazon region. Its tiny fruits can reach very high pungency (100,000–2,000,000 SHU). Chinense types thrive in humid tropical heat, they have high heat tolerance (flowering at higher temperatures than annuum) but very low cold tolerance (no fruiting below approx. 18°C). These plants are perennial in warm climates but behave as annuals in temperate zones. They favour rich organic soil (Bibi, 2023).
- *C. frutescens* (tabasco pepper, bird's eye chili) is native to tropical Americas. It is an evergreen shrub often bearing fruits year-round in the right climate. Pungency is moderate to high (30,000–100,000 SHU). Frutescens peppers tolerate heat and humidity well and set fruit in warm, rainy seasons, but they do poorly in cool or dry climates (Dang, 2014).
- *C. baccatum* (ají peppers) originated in the Andes. It has upright white to yellow flowers and peppers of diverse colours. Baccatum types have moderate heat (20,000–50,000 SHU) and are adapted to cooler highland conditions, they can tolerate cooler night temperatures better than chinense or frutescens. Many grow well under moderate rainfall and have some resistance to certain pests (Habib-Ur-Rahman, 2021).
- *C. pubescens* (rocoto, manzano pepper) is also Andean, unique for its dense hair (pubescence) and striking black seeds. It is a perennial shrub tolerant of altitude and cool weather, capable of fruiting at elevations up to 3000m. Pubescens cultivars have mild heat (approx. 10,000–30,000 SHU) and are sensitive to high heat, they prefer daytime approx. 18–24°C and night temperatures above 10°C. Remarkably, rocoto peppers can endure light frosts that kill other peppers (Lee, 2006).

Table 1: Attributes of major *Capsicum* species and their climatic adaptations (Mondal, 2021, Natayu, 2021).

Species	Habit & Growth	Optimal Temp (°C)	Heat Tolerance	Drought Tolerance	Cold Tolerance	Soil Requirement
C. annuum	Annual, bushy (sometimes vining)	20–30 (day)	Moderate	Low–Moderate	Low (very sensitive)	Well-drained loam, pH 6–7
C. chinense	Perennial shrub (in tropics)	24–30	High	Moderate	Very low (tropical)	Rich organic, well-drained
C. frutescens	Perennial shrub (often treated as annual)	20–30	High	Moderate	Low	Fertile, well-drained loam
C. baccatum	Upright perennial bush	18–26	Moderate	Moderate	Moderate (tolerates cool)	Well-drained fertile loam
C. pubescens	Woody perennial	15–25	Low	Moderate	High (frost-tolerant)	Rich loam, slightly acidic
C. chacoense	Compact perennial shrub (approx. 0.8–1m)	20–28	High	High	Very low (sensitive)	Sandy loam, well-drained
C. cardenasii	Perennial woody shrub (0.5–1m)	18–22	Moderate	Moderate	Moderate (cool climate)	Rich, well-drained hillside soil
C. praetermissum	Tall perennial bush	18–25	Moderate	Moderate	Moderate–High	Well-drained loam
C. eximium	Perennial shrub (woody)	18–22	Moderate	Moderate	Moderate	Rich organic soil
C. rhomboideum	Tall perennial (approx. 2.5m)	20–28	Moderate	Moderate	Moderate	Well-drained soil
C. lanceolatum	Bushy upright shrub (1–5m)	18–22	Moderate	Moderate	Moderate	Moist, rich soil
C. flexuosum	Perennial (subshrub)	18–22	Moderate	Moderate	Moderate	Rich, humid soil
C. tovarii	Woody perennial shrub (approx. 1.2□m)	20–25	Moderate	Moderate	Moderate	Well-drained loam

Impacts of Climate Change on Chilli

Chillies are sensitive to weather extremes at various growth stages. The most critical period is flowering and fruit set: high day or night temperatures can disrupt pollination. Experiments show that exposures of 35–40°C during flowering cause flower abortion and few fruits setting. In field conditions, unmitigated heat waves often lead chilli plants to drop buds and young fruits, slashing yield. Repeated heat stress also shrinks fruit size and delays maturation. Conversely, mild chilling (below approx. 12°C) can injure pepper seedlings and stall fruit ripening in sensitive varieties, although some high-altitude types (e.g. *C. pubescens*) tolerate light frost (Park and Kim, 2023).

Water availability is equally crucial. Drought during fruit development causes fruit drop and stunted pepper growth. Many chilli varieties have shallow roots and high transpiration, so moisture stress rapidly reduces yield (Saleh, 2018). On the other hand, excessive rainfall or waterlogging (more frequent under erratic monsoons) causes root oxygen deficit, fungal rot and nutrient leaching. Soil salinity often a problem when irrigation water is scarce further hampers chilli by creating osmotic stress. Nutrient imbalances (from acid rain or depleted soils) also degrade plant vigour (Song, 2020). Overall, projections suggest more frequent drought spells and intense rain events in Asian and African chilli regions, exacerbating current fluctuations (Wang, 2021).

Elevated CO_2 levels have mixed effects: they can stimulate foliage growth, but many studies find that capsaicin and vitamin C concentrations in fruits decrease under prolonged CO_2 enrichment. The net effect on yield is uncertain, if heat or drought limit plant growth, the CO_2 "fertilization" benefit may not materialize (Zhang, 2022).

Adaptive Agronomic Practices

Farmers and agronomists use many on-farm strategies to mitigate climate impacts on chilli. These adaptive agronomic practices are often low-tech yet effective. Key measures include:

- **Efficient Irrigation:** Drip and sprinkler systems deliver water precisely to chilli roots. By using drip irrigation, farmers can reduce water use by approx. 30–50% compared to flood irrigation, maintaining yield during drought. Water harvesting (check dams, contour bunds) and farm ponds store monsoon water for irrigation in dry spells. Micro-irrigation scheduling based on soil moisture sensors further optimizes use (Youngstrom, 2025).
- **Mulching:** Applying organic (straw) or plastic mulch conserves soil moisture and moderates' temperature at the soil surface. Mulches reduce evaporation, suppress weeds and keep root zones cooler in summer. In drought-prone areas, farmers report up to 20% yield improvement with mulching (Sun X, 2024).
- **Shade and Protected Cultivation:** Installing shade nets, pergolas or high tunnels can lower midday temperatures by 5–7°C, reducing heat stress on pepper plants. Similarly, glass or poly greenhouses allow controlling temperature and humidity. In hill regions, transparent tunnels help peppers escape rain and cold. These structures require investment but can stabilize yields (Selma, 2019).
- **Season and Planting Adjustments:** Altering sowing dates and using short-duration varieties avoids the hottest or driest months. For example, some growers plant chilli early in spring to fruit before peak summer, then follow with other crops. Strip planting (staggered sowing) spreads the risk of a heat wave over time. Also, adjusting plant spacing can improve airflow and reduce fungal disease under humid conditions (Varshney, 2021).
- **Crop Rotation and Intercropping:** Rotating chilli with non-host crops breaks pest/disease cycles. Intercropping with legumes (e.g. groundnut, bean) adds nitrogen and conserves soil moisture via ground cover. Certain agroforestry systems (e.g. light shade from scattered trees) protect peppers from afternoon sun and wind. Windbreaks of hedges or trees around fields can reduce plant desiccation during dry, hot winds (Wang, 2019).
- **Soil and Nutrient Management:** Conservation tillage (minimal ploughing) and cover crops improve soil organic matter, enhancing moisture retention. Raised beds improve drainage under heavy rains. Adding gypsum or organic compost can mitigate salinity and improve soil structure. Balanced fertilization (with potassium and micronutrients) boosts plant stress tolerance. For instance, potassium-rich fertilizers help chillies maintain cell turgor during drought (Papikian, 2019).
- **Integrated Pest Management (IPM):** Monitoring and controlling pests in a timely way helps stressed plants. Biopesticides and pheromone traps reduce damage without chemical residue, an important consideration as warmer climate increases pest outbreak. Maintaining plant health through foliar nutrition sprays (e.g. seaweed extracts, micronutrients) can also strengthen stress resilience (Oh, 2022).

Table 2: Agronomic strategies for climate resilience in chilli cultivation (Salaria, 2023, Song, 2018, Yan, 2024).

Strategy / Practice	Yield & Water Impact	Cost / Labour / Scale	Example / Challenges
Drip irrigation	Yield +20–50% under drought, saves 30–50% water	High setup cost, moderate labour, farm-level	India, Israel, needs clean water and maintenance
Mulching (organic/plastic)	+10–20% yield in dry spells, reduces evaporation	Low–moderate cost, low labour, farm-level	Karnataka, Maharashtra, plastic disposal issues
Shade nets / Protected cultivation	Stabilizes yield, minor water effect	Medium cost, low–moderate labour, farm-level	Greenhouse chilli, ventilation required
Adjusted planting schedule	+10–30% yield stability, variable water effect	Low cost, low labour, farm-level	NE India, risk of pest cycle changes
Crop rotation / Intercropping	Sustainable yield, better soil moisture	Low–medium cost, moderate labour, community level	Chilli–groundnut mix, needs planning
Soil amendments	Improves yield and water retention	Low–medium cost, moderate labour, farm-level	Terra preta systems, input availability limits
Rainwater harvesting	Improves yield reliability, boosts water supply	Medium–high cost, moderate labour, farm/community	Rajasthan, needs good storage design
Conservation tillage	+5–15% yield, saves irrigation water	Low–medium cost, low labour, farm-level	May increase weed pressure
Agroforestry buffers	Improves yield stability, enhances infiltration	Medium cost, high labour, community scale	South India, tree-crop competition possible
Fertigation systems	+20–40% yield, efficient fertilizer & water use	High setup cost, moderate labour, farm-level	Gujarat, needs skillful handling

Genetic and Biotechnological Strategies

Breeding and biotechnology offer long-term solutions by creating chilli plants inherently better adapted to stress. Traditional breeding methods have achieved moderate success: selecting parent lines with tolerance traits (e.g. broad leaves to reduce transpiration) and crossing them. Conventional hybridization has produced many improved cultivars with higher yield or some disease resistance. However, conventional breeding is slow (often 8–12 years per new variety) and limited by the narrow gene pool of cultivated *Capsicum (*Qin, 2014).

To accelerate progress, plant scientists use molecular breeding techniques. Marker-assisted selection (MAS) identifies genetic markers linked to traits like drought tolerance, speeding selection. For example, quantitative trait loci (QTLs) for heat tolerance in chilli have been mapped, allowing breeders to screen seedlings via DNA tests rather than waiting for adult plants. Induced mutagenesis (using chemicals or radiation) has created novel genetic variation, some mutant lines show improved salt or heat tolerance (Salman, 2022).

Modern biotechnologies are pushing chili improvement further. Transgenic approaches (genetically modifying peppers) have been demonstrated: for instance, inserting stress-resistance genes (from other plants or extremophile microbes) into pepper cultivars increased survival under heat or drought in trials. While regulatory and public acceptance issues exist (no GMO chillies are yet commercialized broadly), researchers have shown that overexpressing certain genes (like dehydration-response factors) in pepper can boost stress resilience (Sihombing, 2023).

Today the most transformative tools are CRISPR/Cas and genome editing. CRISPR enables precise, targeted changes to the chilli genome without introducing foreign DNA (in some systems the edits are indistinguishable from natural mutations). Scientists have identified key transcription factors and enzymes controlling stress responses in *Capsicum* (e.g. NAC, WRKY, HSF families) (Moradpour, 2020). Using CRISPR, breeders aim to tweak these genes for example, activating a heat shock factor to enhance heat tolerance or knocking out susceptibility genes for viruses. In 2025, Indian researchers engineered a CRISPR-based “gene switch” that activates defence genes only under heat or pathogen stress this system was tested in tomatoes but its developers specifically noted its potential for chilli. Such “smart” gene circuits could greatly boost pepper resilience (Kalita, 2024).

Speed breeding (growing multiple generations per year under controlled lights) and genomic selection (using genome-wide markers to predict performance) are also being tried in chilli, though they are at early stages. Tissue culture techniques (embryo rescue, doubled haploids) can shorten breeding cycles and bring wild genes (from *C. baccatum*, *C. pubescens* and other wild species) into cultivated backgrounds faster. Wild relatives of chilli, with natural adaptations to heat or drought, are being screened as donors. For example, some *C. baccatum* landraces show deep root systems for drought resilience, *C. pubescens* genes could improve cold tolerance. Modern approaches like pan-genome analysis (comparing many chilli genomes) have identified novel alleles for stress tolerance in wild accessions, guiding breeding efforts (Liu, 2021).

Table 3: Breeding and Biotechnological Approaches for Chilli Resilience (Mahmoud, Dutt, 2024), (Noman, 2019), (Morales-Merida, 2024)

Approach / Technique	Target Traits & Tools	Timeframe / Resources
Conventional hybridization	Targets yield, flavour and disease resistance through cross-breeding of elite lines	approx. 10 years per variety, moderate cost, field-based
Mutation breeding (chemical/radiation)	Induces novel alleles for stress tolerance via mutagenesis and selection	5–8 years, low–moderate cost, greenhouse or field
Marker-assisted selection (MAS)	Uses DNA markers linked to drought/heat or disease QTLs	6–8 years, moderate cost, lab + field stages
Genomic selection	Predicts stress tolerance using genome-wide data	3–4 years, high cost, greenhouse or controlled facilities
Transgenic (GM) approach	Inserts specific stress-tolerance genes (e.g., DREB, HSPs) via Agrobacterium	3–5 years, high cost, strict regulation
Genome editing (CRISPR/Cas9, base editing)	Precisely edits regulatory genes like HSF, NAC, WRKY	2–5 years, moderate cost, lab/greenhouse
Speed breeding	Uses controlled environments and light regimes to shorten generation cycles	2–3 years, high cost, greenhouse-based
Polyploidy induction	Doubles genome content to enhance vigour and tolerance	4–6 years, moderate cost, lab–field transition
Wild species introgression	Transfers tolerance traits from wild Capsicum relatives	6–10 years, moderate resources, field trials
Epigenetic breeding	Exploits methylation or small RNA changes for stress memory	3–5 years, moderate cost, lab stage

Latest Technologies and Climate-Resilient Varieties

Beyond traditional breeding, new technologies are emerging to support chilli resilience. Digital agriculture tools like remote sensing and IoT are gaining attention: drones and satellites can monitor crop health and stress (for example, detecting areas of moisture stress in chilli fields early), while automated sensors measure soil moisture and trigger irrigation only when needed. These precision farming approaches are nascent in chilli but have shown promise in trials (e.g. drip systems linked to soil sensors in Maharashtra farms). Climate modelling and decision-support apps help farmers choose sowing dates or varieties based on forecasted conditions (Lei, 2014).

In biotechnology, recent milestones include the aforementioned CRISPR gene switch for stress, as well as advances in omics. Researchers have sequenced the pepper genome (completed in 2014) and are building pangenomes of multiple varieties. Transcriptomics and metabolomics studies identify pathways that chilies use under stress, potentially revealing natural compounds that could be augmented. Speed phenotyping using image analysis (infrared imaging for water stress, chlorophyll fluorescence) allows screening thousands of peppers for stress tolerance traits quickly (He, 2023).

On the varieties front, numerous new cultivars have been released with specific climate advantages (Table 4). In India, institutes have bred chilli lines with improved heat tolerance and water use efficiency. For example, *Pusa Jwala* (released by IARI) is an early, high-yielding *C. annuum* variety that tolerates the intense heat of late spring better than older lines. *Indamati*, a *C. annuum* cultivar adapted to the cool climate of Kashmir, shows better cold hardiness than common varieties. Some recently released hybrids (e.g. certain *C. frutescens*-based hybrids) perform well under prolonged summer warmth (Li, 2021).

Internationally, breeders have capitalized on exotic germplasm. The notorious "ghost pepper" (*Bhut Jolokia*, *C. chinense*) from Northeast India is extremely heat-tolerant and is being crossed into ornamental hot pepper lines. In African countries, local chili landraces selected for rainfed conditions are being formally registered as varieties. Additionally, biotechnologists have engineered chili plants for virus resistance (important as viruses can thrive under warmer weather). For instance, varieties carrying nematode- and virus-resistance genes (introduced via breeding) are now grown in South India to combat pressure from higher temperatures (Pan, 2022).

Importantly, the first gene-edited chilli cultivars are on the horizon. Experimental lines with edited heat-tolerance genes are undergoing field trials in research farms and if regulatory policies permit, could reach farmers in the next decade. Meanwhile, marker-assisted hybrids with stacked traits (heat + wilt resistance, for example) are emerging from Indian research stations (Qin, 2020).

Table 4: Examples of Climate-Resilient Chilli Varieties and their Attributes (Gao, 2022, Das, 2022, Singha, 2022)

Variety / Species	Origin & Type	Climate Resilience Traits	Yield / Quality Attributes	Region & Notes
Indamati (*C. annuum*)	IARI India (1986), OP	Moderate heat tolerance, low drought tolerance, resistant to bacterial wilt	8–10 t/ha, 110–120 days, 50,000–80,000 SHU	Cool hills (J&K), mild frost tolerance, thick fruits
Byadgi Malabar (*C. annuum*)	Local landrace, Karnataka	High heat tolerance, moderate drought, mild CMV resistance	4–6 t/ha, 130–140 days, 40,000–60,000 SHU	Semi-arid tropics, valued for deep red color and dry-season performance
Bhut Jolokia (*C. chinense*)	Northeast India landrace (GI tag 2007)	Very high heat tolerance, moderate drought, tolerant to fungal wilt	3–5 t/ha, 150–160 days, >1,000,000 SHU	Humid tropics, world's hottest pepper, thrives in hot, humid climates
Arka Abhir (*C. annuum*)	IIHR India (2018), Hybrid	Moderate heat and drought tolerance, virus (TYLCV) and thrips tolerant	15–18 t/ha, 80–85 days, non-pungent (bell)	Ideal for protected cultivation, orange fruit, high-yield hybrid
Pant C-1 (*C. annuum*)	SKRAU Pantnagar (2012), OP	Moderate tolerance to heat and drought, resistant to mosaic viruses	9–11 t/ha, 120–130 days, 10,000–20,000 SHU	Upland plains (N. India), deep crimson fruits, stable under stress
Kashi Anmol (*C. annuum*)	ICAR-IIVR Varanasi (2015), Hybrid	High heat and drought resilience, tolerant to leaf curl virus	14–16 t/ha, 100 days, 30,000–40,000 SHU	Central and northern plains, dual-purpose, steady performance
Tejaswini (*C. annuum*)	UAS Dharwad, Hybrid	Good drought and pest resilience, tolerates heat spikes	12–14 t/ha, 110 days, 60,000 SHU	Karnataka & Maharashtra, suitable for rainfed farming
Pusa Sadabahar (*C. annuum*)	IARI Delhi, OP	Tolerant to high temperature and mosaic complex	10–12 t/ha, 115 days, medium pungent	Indo-Gangetic plains, performs well under variable weather
LCA 334 (*C. annuum*)	Local selection andhra Pradesh	Moderate heat tolerance, drought adaptable, resistant to leaf curl	11–13 t/ha, 120 days, 50,000 SHU	South India, used in dry chilli trade, strong plant architecture
Kashi Gaurav (*C. annuum*)	ICAR-IIVR (2020), Hybrid	High resilience to heat and drought, resistant to Phytophthora	16–18 t/ha, 95–100 days, 35,000–45,000 SHU	Central India, suitable for both irrigated and rainfed systems

Conclusion

Climate change poses a multi-faceted threat to chilli production: rising heat, water stress and shifting pest pressures together can undermine both yield and quality. India's chilli industry, as the global leader, is especially at risk due to its reliance on rainfed systems and wide geographic range of cultivation. However, a mix of ancient and modern strategies offers a path forward. Traditional agronomic practices efficient irrigation, mulching, adjusted planting, soil conservation remain critically important. At the same time, cutting-edge genetic tools and breeding are rapidly enhancing chilli resilience from within the plant's genome. The integration of both approaches is key: resilient varieties must be matched with climate-smart farm management. This review has surveyed the historical context of chilli cultivation, the diversity of *Capsicum* species, the specific impacts of climate stress and an array of adaptive solutions. We emphasize that collaboration among farmers, breeders and researchers is vital. Farmers' knowledge of local landraces and cropping patterns should guide breeding objectives. Breeders and biotechnologists should target the traits most limiting in the field (e.g. heat tolerance of pollen, root vigour in drought). Policymakers can support adaptation by funding climate-tolerant variety development and promoting sustainable irrigation infrastructure.

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