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EDITORIAL

A Beginning with a Purpose

Dear Readers,

It gives me immense pleasure to welcome you to the first issue of Agrisphere. The launch of this magazine marks the beginning of an endeavour to create a meaningful platform for sharing agricultural knowledge, innovations, experiences and perspectives relevant to the changing needs of farming and rural society.

The theme of our inaugural issue—Climate Change and Climate-Smart Agriculture—has been chosen deliberately. Climate change is increasingly influencing every dimension of agriculture, from crop productivity and pest and disease dynamics to livestock health, biodiversity, natural resources and rural livelihoods. Building resilient agricultural systems therefore requires not only technological innovation but also effective extension, community participation, traditional knowledge and new approaches to agricultural entrepreneurship.

This issue brings together 14 articles addressing diverse dimensions of this challenge. The contributions examine climate-induced crop diseases, precision agronomy, changes in tea biochemistry and quality, climate-smart agriculture and extension strategies, emerging livestock diseases, climate impacts on Darjeeling tea, integrated pest management and climate-smart villages. The issue also explores nature-based solutions, climate-smart agripreneurship, orchid biodiversity, traditional knowledge, sustainable tea production and climate impacts on cut flowers.

We envision Agrisphere as a confluence of agricultural science, innovation and sustainability—a platform that connects research with practice and encourages dialogue among scientists, extension professionals, students, entrepreneurs, policymakers and farmers.

I sincerely thank all the authors and members of the editorial team whose contributions have made this inaugural issue possible. I invite our readers to engage with the ideas presented here, reflect upon their relevance to contemporary agriculture and contribute to the continuing conversation on the future of farming.

May Agrisphere grow into a vibrant platform for knowledge, innovation and sustainable agricultural development.

Editors

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MESSAGE FROM THE PRESIDENT

It is a matter of great pride and satisfaction to present the first issue of *Agrisphere*. The beginning of a new publication is not merely the launch of a magazine; it is the beginning of a platform for dialogue, knowledge exchange and collective thinking about the future of agriculture.

The inaugural issue focuses on Climate Change and Climate-Smart Agriculture, one of the most important challenges facing agriculture today. Increasing climatic variability is affecting crop production, pest and disease patterns, livestock health, biodiversity, natural resources and farm-based livelihoods. Ensuring food and livelihood security under these changing conditions requires agriculture to become more resilient, adaptive, resource-efficient and sustainable.

The fourteen articles included in this issue offer a broad perspective on these emerging challenges. They cover climate-related crop diseases, tea quality and production, climate-smart agriculture, livestock health, precision agronomy, integrated pest management and climate-smart villages. The issue further highlights nature-based solutions, green agripreneurship, biodiversity conservation, traditional knowledge and climate-resilient horticultural production.

These contributions remind us that the pathway towards climate resilience lies in bringing science, innovation, local knowledge and farming communities together. Modern technologies such as sensors, artificial intelligence and decision-support systems can provide new opportunities, while traditional knowledge and nature-based approaches offer valuable locally adapted solutions. *Agrisphere* seeks to provide a platform where such ideas can be communicated beyond conventional academic boundaries. We hope the magazine will encourage interdisciplinary thinking, promote exchange of knowledge and inspire practical solutions for emerging agricultural challenges.

I congratulate the editorial team and all the contributing authors for their valuable efforts in bringing this inaugural issue to readers. I am confident that *Agrisphere* will grow into a respected platform for agricultural science, innovation and sustainability, connecting knowledge with action for the benefit of farming communities.

I wish *Agrisphere* a successful and meaningful journey ahead.

(Dr. Sujit Sarkar)

President, SAARESU

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INDEX

01
Anthracnose disease of chilli (Capsicum annuum) under climate change: Pathogen complexities, environmental determinants, and Climate-Smart management
Sanjog Chhetri, Arindam Ghosh, Sujit Sarkar, Rakesh Yonzone
pp. 1–8

02
Climate-Induced Changes in Tea Biochemistry: Implications for Quality Tea Production
Arindam Ghosh, Sanjog Chettri, Sujit Sarkar, Soumya Majumder
pp. 9–15

03
Accelerating Adoption of Climate-Smart Agriculture: Challenges and Extension Strategies
Litan Das, Prakriti Modak, Sayantan Dey, Saumyadip Chakraborty, Subhrajyoti Panda
pp. 16–24

04
Climate Change and Emerging Livestock Diseases: Strengthening Advisory Systems for Climate-Resilient Animal Health
Shruti, Madan Singh, Harideep Verma
pp. 25–33

05
Impacts of Climate Stressors on Tea Cultivation: Consequences and Adaptive Strategies with Special Reference to Darjeeling Tea Clones
Soumya Majumder, Dipa Kundu, Urmi Saha, Arindam Ghosh, Sujit Sarkar, Plabita Saikia
pp. 34–41

06
Carbon Management in Soil for Sustainable Agriculture
Amrit Tamang, Koushik Ghosh, Mandira Saha, Sagar Tamang and Tarik Mitran
pp. 42–54

07
Next-Generation IPM Strategies for Climate-Resilient Agriculture
M. Soniya Devi, Rakesh Yonzone, Y. Rupert Anand, S. Bandyopadhyay
pp. 55–59

08
Climate Smart Villages: Bridging Science and Farming Communities
Namitha Rajendran, Shubhadeep Roy
pp. 60–66

09
Nature-Based Solutions for Sustainable Agriculture in Climate-Vulnerable Coastal Regions
Abhishek Ghosh, Niloy Biswas, Shraddha Bhattacharjee
pp. 67-71

10
Climate-Smart Agripreneurship: Creating Green Livelihood Opportunities for Rural Youth
Aditya Lama, Sonam Wangdi Bhutia
pp. 72-77

11
Future of Orchid Diversity under Changing Climate in the Eastern Himalayas: Challenges, Opportunities and Conservation Strategies
Dipika Sarmah
pp. 78-84

12
Climate-Smart and Sustainable Agriculture for a Resilient Future: Relevance toDarjeeling Tea Plantations Climate-Smart and Sustainable Agriculture for a Resilient Future: Relevance toDarjeeling Tea Plantations
Dipa Kundu, Urmi Saha, Soumya Majumder, Plabita Saikia
pp. 85-89

13
Precision Agronomy: Integrating Sensors, AI and Decision Support Systems for Climate Adaptation
Partha Sarathi Patra, Jitendra Majji
pp. 90–98

14
Traditional Knowledge for Sustainable Climate Justice and Adaptation
Arindam Nag
pp. 99-102

15
Impact of Climate Change on Flowering and Production of Cut Flowers
D. Barman
pp. 103-107

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Popular Article

Anthracnose disease of chilli (*Capsicum annuum*) under climate change: Pathogen complexities, environmental determinants, and Climate-Smart management

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Abstract

Anthracnose, caused by Colletotrichum species complexes, is a major constraint to chilli (Capsicum annuum L.) production in India, with yield losses of 10–80%. The disease is predominantly incited by C. truncatum (55–65%) and gloeosporioides complex species (30–40%), with significant regional variation in species dominance. Climate change is reshaping disease epidemiology through rising temperatures favoring thermotolerant C. truncatum (optimal 28–30°C), altered monsoon patterns, and extended leaf wetness periods critical for infection. Anthracnose follows a distinct phenology: primary infections establish during flowering (30–45 DAT), epidemics peak during fruit maturation (60–90 DAT) under monsoon conditions, and natural suppression occurs post-monsoon when humidity drops below 70%. Sustainable, climate-smart management integrates biological control agents (Trichoderma harzianum, Pseudomonas fluorescens), botanical extracts (neem seed kernel extract 5%, garlic extract 5%), and cultural practices (raised beds, optimized spacing, morning drip irrigation, pruning) to reduce canopy humidity and pathogen spread. Future research must prioritize species-resolved epidemiological models and breeding for combined anthracnose and climate resilience.

Keywords: Colletotrichum, Capsicum annuum, climate resilience, biological control, integrated disease management

KEY HIGHLIGHT

- Yield Loss: Anthracnose causes 10–80% chilli yield losses.
- Primary Pathogens: Driven by *C. truncatum* (55–65%) and *C. gloeosporioides* (30–40%).
- Climate Drivers: Thrives at 28–30°C with high humidity and rain.
- Peak Epidemic: Peaks during monsoon fruit maturation.
- Smart Control: Combines biocontrols, botanicals, and raised beds.
- Breeding: Requires stacking *CaAnTH*-1resistance with climate resilience.

1. Introduction

Chilli (*Capsicum annuum* L.) ranks among the most economically significant spice and vegetable crops globally, serving as a cornerstone of agricultural income, exports, and rural livelihoods in India. However, the sustainability of commercial chilli cultivation is perennially threatened by anthracnose disease, a highly destructive complex caused by hemibiotrophic fungi belonging to the genus *Colletotrichum*. While the pathogen can attack foliar tissues, stems, and branches, causing dieback symptoms, the most economically crippling phase is the fruit

rot stage (Figure 1). This manifestation leads to premature fruit drop, severe blemishes on mature pods, compromised market values, and extensive post-harvest decay during storage and transport (Saxena et al., 2016)

The disease represents a complex pathological puzzle because it is governed by several distinct *Colletotrichum* species complexes rather than a single monomorphic agent (de Silva et al., 2019). In India, geographic distribution surveys confirm that the prevalence and field severity of these specific pathogens are highly variable, with regional microclimates directly dictating species dominance and epidemic potential (Mishra et al., 2024).

Climate change is rapidly altering these microclimatic balances. Rising ambient temperatures, shifting rainfall thresholds, and extended canopy wetness durations are expanding the geographical range and changing the seasonal phenology of the disease (Saxena et al., 2016). Unraveling the precise environmental kinetics of the *C. annuum–Colletotrichum* interaction is vital for establishing robust warning systems and deploying targeted biological and cultural interventions (Darvin et al., 2012; Kamble et al., 2015).



Figure 1: Typical sunken lesions of anthracnose fruit rot

2. The Pathogen complex: Cryptic diversity in Asia

Anthracnose of *Capsicum annuum* is driven by a highly diverse, polyphyletic assemblage of species. Modern multi-locus phylogenetic studies utilizing genetic markers such as ITS, *TUB2*, *CHS-1*, *GAPDH*, *ACT*, and *CAL* have redefined the taxonomic profile of Asian isolates (de Silva et al., 2019; Mishra et al., 2024).

Table 1. Taxonomic profiles, spore morphologies, and regional climate niches of major *Colletotrichum* species complexes in Asia (de Silva et al., 2019)

Fungal Species	Species Complex	Typical Spore Morphology	Regional Climate Niche
***Colletotrichum truncatum* (syn. *C. capsici*)**	*truncatum*	Falcate (curved, sickle-shaped) with acute ends	Dominates hot, humid, lowland growing tracts
Colletotrichum gloeosporioides s.s.	*gloeosporioides*	Cylindrical with rounded ends	Widespread across subtropical and temperate belts
Colletotrichum scovillei	*acutatum*	Fusiform (pointed at both ends)	Prefers moderate highland zones; high virulence on fruit

3. Environmental drivers: Direct evidence from Chilli Patho system

C. truncatum, the dominant species in warmer, lowland chilli-growing belts, exhibits a higher temperature optimum (28–30°C) than *C. gloeosporioides* complex species (25–27°C) (Sharma & Kulshrestha, 2022). Under projected warming scenarios (2.5–3.5°C increase in mean summer temperature by 2050), a species shift toward *C. truncatum* dominance is expected, which may alter disease phenology, fungicide sensitivity, and resistance-breaking potential (de Silva et al., 2019; Saxena et al., 2016).

3.1 Temperature: Species-specific responses

Controlled-environment studies on chilli anthracnose pathogens provide clear species-specific thermal response curves(Darvin et al., 2012; Saxena et al., 2016; de Silva et al., 2019):

- *C. truncatum*: Mycelial growth rate is maximal at 30°C (8.2 mm/day), with conidial germination greater than 90% between 25–32°C. At 35°C, growth declines by 60%, and at 38°C, complete inhibition occurs. The optimal temperature for lesion development on detached fruits is 28°C, with a minimum wetness duration of 8 hours required for infection at this temperature.
- *C. gloeosporioides* sensu lato: Optimal growth occurs at 25–27°C; at 30°C, the growth rate decreases by 30%. However, this complex shows greater low-temperature adaptability, with 40% germination even at 15°C, making it more prevalent in cooler, higher-altitude regions.

Phenological shift: Rising night temperatures reduce the diurnal temperature range, which accelerates the incubation period (from 5–7 days down to 3–4 days) and increases the rate of lesion expansion (from 2.1 mm/day to 4.3 mm/day at 28°C constant temperature compared to 25°C with a 10°C night dip). This means multiple repeating infection cycles can occur within a single cropping season, drastically amplifying regional disease pressure.

3.2 Moisture: Rainfall, Humidity, and Leaf Wetness Duration

Moisture availability is the single most critical constraint for anthracnose infection. Experimental field data from major chilli-producing tracts demonstrate (Darvin et al., 2012; Mishra et al., 2024):

Rainfall threshold: Disease severity indices (PDI) increase sharply when cumulative weekly rainfall exceeds 40 mm, with greater than 60 mm/week leading to rapid epidemic proportions (PDI greater than 70%) in susceptible cultivars.

- **Relative humidity (RH):** Infection efficiency approaches 85–90% when canopy RH is greater than 90% for 12 or more hours post-inoculation. At RH less than 70%, infection drops below 20%, even with free moisture present on the fruit surface.
- **Leaf wetness duration (LWD):** The minimum LWD required for visible lesion development is 6 hours at 28°C for *C. truncatum*, extending to 10 hours at 25°C for *C. gloeosporioides*. Climate models project a 20–30% increase in the number of days with LWD greater than 8 hours during the monsoon season across central India, directly expanding the seasonal infection window.

Post-harvest implications: Latent infectionswhere spores infect green tissue but remain dormant until ripening or storage, are exacerbated by high pre-harvest humidity. Fruits harvested from fields experiencing greater than 85% RH during the preceding week show 40–60% higher post-harvest rot incidence, even if they appeared perfectly healthy at harvest.

3.3 Elevated CO_2: Minimal direct effect, Indirect host-mediated impacts

Unlike many biotrophic rusts and mildews, hemibiotrophs like *Colletotrichum* show negligible direct growth stimulation under elevated atmospheric CO_2 conditions (550–750 ppm) (Saxena et al., 2016). However, CO_2 enrichment alters host physiology in ways that indirectly influence susceptibility:

- **Cuticular thickness:** Elevated CO_2 increases leaf and fruit cuticular wax deposition by 15–20% in some *Capsicum* genotypes, potentially acting as a improved physical barrier against appressorium penetration.
- **Stomatal density and conductance:** Reduced stomatal conductance under high CO_2 lowers transpiration, which may increase leaf surface microclimate temperature and prolong surface wetnesscreating localized microclimates highly conducive to spore germination.
- **Defense priming and molecular responses:** Elevated atmospheric CO_2 has been reported to induce the expression of key defense-associated genes such as PR-1 (Pathogenesis-Related Protein 1), commonly used as a molecular marker of salicylic acid-dependent systemic acquired resistance, and PDF1.2 (Plant Defensin 1.2), which reflects activation of jasmonic acid and ethylene-mediated defense pathways. Upregulation of these genes indicates enhanced preparedness of the plant immune system, a phenomenon often referred to as "defense priming." Nevertheless, this response varies considerably among chilli genotypes and may be substantially weakened under concurrent heat stress, highlighting the complex interaction between elevated CO_2, temperature, and host defense mechanisms.

4. Disease Onset, Progression, and Decline: A Phenological Framework

Understanding the temporal dynamics of anthracnose development is essential for implementing timely and effective disease management strategies. Field observations conducted in major chilli-growing regions have revealed a distinct seasonal pattern in disease occurrence and severity (Mishra et al., 2024; Saxena et al., 2016).

Table 2. Seasonal progression of chilli anthracnose in relation to crop phenology and environmental conditions

Phase	Timing (Indian Subcontinent)	Environmental Triggers	Epidemiological Significance
Primary Infection	Flowering to early fruit set (30–45 DAT)	First monsoon rains (June–July); RH greater than 80% for 3 consecutive days	Establishment of quiescent infections; initial inoculum build-up.
Epidemic Phase	Fruit maturity and ripening (60–90 DAT)	Peak monsoon (July–September); temperature 26–30°C; weekly rainfall greater than 50 mm; RH greater than 90%	Maximum lesion expansion, rapid conidial splash dispersal, and secondary spread.
Decline Phase	Post-monsoon (October–November)	Cessation of rainfall; RH less than 70%; daytime temperature greater than 32°C	Natural disease suppression; ideal clean harvest window for mature red pods.

**DAT = Days After Transplanting*

Critical insight: The epidemic phase coincides precisely with the period of maximum crop value (market-ready green and red-ripe stages). Therefore, preventive interventions must be deployed during the primary infection phase at early flowering, not when symptoms become blindingly obvious on mature fruits, as curative chemical options are severely limited at that point.

5. Climate-Smart, Eco-Friendly Management: Evidence-Based Strategies

5.1 Biological Control with Species-Specific Efficacy

Not all biocontrol agents perform equally against all *Colletotrichum* species. Recent screening studies in India have identified strain-specific efficacy profiles (Kamble et al., 2015):

- *Trichoderma harzianum* (Strain Th-14): Exhibits 68–72% mycelial inhibition of *C. truncatum* through aggressive mycoparasitism and β-1,3-glucanase enzymatic production; it is notably less effective against *C. gloeosporioides* (52% inhibition).
- *Pseudomonas fluorescens* (Pf-1): Reduces anthracnose severity by 55–60% when applied as a seedling root dip (10^8 CFU/mL) followed by two subsequent foliar sprays at 15-day intervals. Mechanisms include siderophore-mediated iron competition and induction of systemic resistance (ISR) via jasmonic acid pathways.
- *Bacillus subtilis* (BS-3): Produces potent lipopeptides (surfactin, fengycin) that physically disrupt *Colletotrichum* conidial membranes. Field trials show 40–45% disease reduction in *C. truncatum*-dominated regions.

Application window: Biocontrol agents should be applied prior to the onset of monsoon (i.e., at flowering) to establish stable rhizosphere and phyllosphere colonization before environmental conditions favor rapid fungal growth.

5.2 Botanical Extracts: Dose-Response and Practical Constraints

- Neem Seed Kernel Extract (NSKE) 5%: Reduces spore germination by 70–75% *in vitro*, but field efficacy drops to 30–35% due to rapid UV degradation and rainfall wash-off. It requires repeated application at 7-day intervals during the rainy epidemic phase.
- Garlic Extract (5%): Allicin exhibits strong direct fungicidal activity, but phytotoxicity (leaf scorch) is observed in *C. annuum* foliage at concentrations greater than 7%. Best used as an eco-friendly dip treatment for harvested fruits rather than a broad foliar spray.
- Wood Ash (2% Suspension): Raises leaf surface pH to greater than 9.0, directly inhibiting conidial germination. It is effective as a cheap preventive dusting agent during early fruit set but quickly loses efficacy after heavy rain events.

5.3 Cultural Practices with Climate-Adaptive Modifications

Practice	Climate-Adaptive Modification	Mechanism	Reference
Raised Beds (15–20 cm height)	Increase bed height in high-rainfall zones; pair with plastic mulch to reduce soil splash.	Reduces waterlogging stress; minimizes splash dispersal of conidia from soil debris to	Mishra et al., 2024

		lower fruits.	
Plant Spacing	Wider spacing (60 × 45 cm vs. 45 × 30 cm) in high-humidity zones.	Enhances microclimatic air circulation; reduces canopy relative humidity by 8–12%.	Saxena et al., 2016
Drip Irrigation	Schedule irrigation in early morning hours only; avoid evening runs.	Ensures canopy and fruit surface foliage dries before nightfall; reduces LWD by 4–6 hours.	Saxena et al., 2016
Staking and Pruning	Remove lower branches (up to 15 cm from ground level) and senescent leaves.	Prevents initial soil-to-plant splash transmission; improves structural aeration.	Mishra et al., 2024

5.4 Host Resistance: Genomic Resources and Breeding Progress

While commercial highly resistant cultivars are limited, significant progress has been made in identifying resistance quantitative trait loci (QTLs):

- QTL *CaAnTH-1* located on chromosome 5 confers high resistance to *C. truncatum* in wild accessions of *Capsicum*.
- Resistant Sources: Cultivars 'Bhut Jolokia' (highly correlated with elevated capsaicin content) and 'Kashmiri Long' show moderate field resistance (PDI less than 25%) compared to highly susceptible mainstream cultivars like 'Pusa Jwala' (PDI greater than 70%).
- **Marker-Assisted Backcrossing:** Introgression of *CaAnTH-1* into elite commercial *C. annuum* backgrounds is underway, but climate adaptation traits (such as heat and drought tolerance) must be stacked simultaneously for future field relevance.

6. Integrated Climate-Smart Disease Management Calendar

To help progressive farmers and extension specialists plan effectively, this calendar aligns eco-friendly interventions with specific crop growth stages and microclimatic risks:

1. **Nursery to Crop Establishment (0–10 DAT): Prerequisite: Pathogen-free seedbed.**

Perform seed treatment with *T. harzianum* (10 g/kg seed) combined with a 2% NSKE nursery spray. This prevents early seed-borne inoculum transmission and establishes robust biocontrol in the early rhizosphere.

2. **Flowering Initiation (25–30 DAT): Timing: Pre-monsoon window.**

Apply a foliar spray of *P. fluorescens* (10^8 CFU/mL) mixed with a 1% wood ash suspension. This actively blocks primary infection sites on emerging flowers before seasonal monsoons arrive.

3. **Early Fruit Set (35–45 DAT): Timing: Monsoon onset.**

Spray *B. subtilis* (BS-3) alternating with 5% NSKE on alternate weeks. This maintains a high biological population in the phyllosphere and reduces the initial field inoculum load during early pod development.

4. **Monsoon Peak & Secondary Spread (50–65 DAT): Timing: Critical epidemic window.**

Maintain strict weekly surveillance. Continue the bio-botanical rotation. Crucially, avoid copper-based fungicides during periods of prolonged, hyper-high relative humidity, as copper accumulates and induces severe phytotoxicity and fruit spotting under these specific microclimatic conditions.

5. **Fruit Maturation & Harvest (70–90 DAT): Timing: Color break stage.**

Cease all botanical and biological sprays 15 days prior to harvest. Harvest mature pods promptly at the "color break" stage to minimize field exposure to late-season dampness and latent infection triggers.

6. **Post-Harvest Processing: Storage optimization.**

Dip harvested fruits in a 5% garlic extract solution for 2 minutes, dry completely, and store at 13°C with 80% relative humidity. This effectively suppresses latent lesions and extends shelf-life by 8–10 days.

7. Conclusion

Anthracnose of chilli (*Capsicum annuum* L.) in India is a highly climate-sensitive disease complex caused by several species of *Colletotrichum*. Rising temperatures and changing weather patterns are influencing the distribution and prevalence of different pathogen species, with thermotolerant species such as *C. truncatum* becoming increasingly dominant in many lowland tropical regions. However, moisture-related factors, including rainfall, high relative humidity, and prolonged leaf wetness, remain the primary drivers of disease outbreaks. Epidemics are particularly severe during the monsoon season when environmental conditions are highly favorable for pathogen infection and spread, coinciding with the susceptible fruit development and maturation stages of the crop.

Achieving effective, eco-friendly control demands a strictly climate-adaptive approach: deploying species-specific biological strains, matching spray programs to the early primary infection phase, and adopting modified cultural practices that physically lower canopy relative humidity and splash dynamics. Moving forward, breeding programs must focus on stacking anthracnose resistance alleles with climate-resilient traits. Future pathological research must abandon oversimplified, monolithic assumptions and adopt region-specific, species-resolved frameworks to safeguard chilli production against a changing environment.

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Popular Article

Climate-Induced Changes in Tea Biochemistry: Implications for Quality Tea Production

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Abstract

Climate change has emerged as one of the greatest challenges to sustainable tea production worldwide. Tea (*Camellia sinensis*) is highly sensitive to environmental conditions, and variations in temperature, rainfall, humidity, light intensity, atmospheric CO_2 etc. directly influence its growth, yield, and biochemical composition. Important quality-related compounds such as catechins, polyphenols, caffeine, amino acids, and volatile aroma compounds determine the flavour, aroma, colour, and health-promoting properties of tea. Climate-induced changes in these metabolites often result in reduced tea quality, lower productivity, and increased vulnerability to pests and diseases, thereby affecting tea growers' livelihoods. This article discusses how major climatic factors alter tea biochemistry and highlights their implications for tea quality. It also summarizes climate-smart strategies, including shade tree management, mulching, rainwater harvesting, efficient irrigation, soil organic matter management, climate-resilient cultivars, weather-based advisories, and improved harvesting and processing practices, to sustain tea quality and ensure the long-term resilience of the tea sector under changing climatic conditions.

Keywords: Climate change, Tea biochemistry, Tea quality, Climate-smart agriculture, Tea production

KEY HIGHLIGHT

- Climate change alters tea biochemistry, affecting flavour, aroma and quality
- Key compounds such as catechins, amino acids and caffeine shape tea quality
- Heat, drought and erratic rainfall can reduce yield and quality
- Declining tea quality threatens farmer income and export competitiveness
- Climate-smart practices can help sustain tea quality and production

1.Introduction

Camellia sinensis, commonly known as the tea plant, is the source of one of the world's most popular non-alcoholic beverages, prepared from its tender shoots consisting of two leaves and a bud. It serves as an important economic asset for millions across the world, particularly in countries such as China, India, Sri Lanka and Kenya. Tea growing is a vital part of world agriculture, as it contributes billions of dollars to the global economy each year while helping millions of small-scale farmers sustain their livelihoods. In India, it generates employment of about 2 million people. Tea grows best under moderately warm temperatures, high humidity, and well-distributed annual rainfall. It prefers well-drained, acidic soils and partial shade with diffused sunlight. Tea is commonly cultivated at 600–2,400 m altitude, where cooler conditions enhance flavour, aroma, and antioxidant content, contributing to superior tea quality. Therefore,

the crop is highly vulnerable to the effects of climate change, since its development, production, and quality depend heavily on above-mentioned environmental factors. The recent fluctuations in climate, such as inconsistent rainfall, extended drought, and severe heat, have heightened the difficulties in growing tea, threatening both the viability of this important crop and the livelihoods of the tea growers. Over the last twenty years, studies examining how climate change affects tea farming have significantly increased, highlighting the pressing requirement to tackle these effects. Climate change affects not only the growth and yield of tea but also alters the biochemical composition of tea leaves. Compounds such as catechins, caffeine, L-theanine, polyphenols, and volatile organic compounds (VOCs) dictate the sensory and therapeutic qualities of the beverage. Therefore, understanding the responsiveness of these secondary metabolites to climatic variables is critical for stabilizing product quality and ensuring agricultural sustainability.

2. Tea Chemistry: The Foundation of Tea Quality

The quality of tea begins with the biochemical composition of the tea leaf. The superiority of tea is largely determined by the composition and balance of its major biochemical constituents, each of which contributes distinct sensory characteristics to the final beverage. Among the catechins, epigallocatechin gallate **(**EGCG**)** is the predominant polyphenol responsible for the characteristic astringency, bitterness, and puckering mouthfeel of tea. Epigallocatechin (EGC) contributes significantly to the antioxidant capacity of tea, enhancing its health-promoting properties. Epicatechin gallate (ECG) imparts astringency, briskness, puckering dryness, and a slightly bitter taste, while epicatechin (EC) provides a comparatively milder flavour profile with reduced mouth-drying effects. The amino acid L-theanine plays a vital role in enhancing sweetness and imparting the desirable umami taste, thereby improving the overall flavour balance. In contrast, caffeine contributes to the characteristic bitterness of tea while also providing its well-known stimulating effect. During black tea manufacturing, catechins are oxidized into theaflavins and thearubigins, which are essential quality determinants. Theaflavins are primarily responsible for the bright liquor, briskness, and freshness of black tea, whereas thearubigins contribute to the rich reddish-brown colour, body, and mouthfeel of the infusion. Together, these biochemical compounds determine the sensory attributes, quality, and consumer acceptability of tea.

3. Climate Change Alters Tea Biochemistry

1. Rising temperature

Tea grows best within the temperature range of 18-32 ºC. But elevated temperatures can greatly hinder the speed at which fresh leaves emerge. This directly reduces tea yield and affects farmers' income. Extreme heat events are becoming more frequent under rising temperatures. When high temperatures are accompanied by low humidity, tea leaves may develop sunburn, reducing leaf quality and flavour. Excessive heat increases water loss through evaporation, causing dehydration, stunted growth, and leaf damage. In contrast, low temperatures also adversely tea plants. Temperature below 13 ºC induce dormancy and also reduce growth and yield (Baid, 2024).A study by Yu et al., (2024) showed that at higher temperature, anthocyanin rich purple tea plants also change their colour from purple to green. They also found that the anthocyanin synthesis is enhanced in lower temperature (15-20 ºC) due to the expression of anthocyanidin synthase (ANS) gene compared to higher temperature of

25 ºC and 35 ºC. Interestingly, some polyphenols like epicatechin gallate (ECG), epicatechin (EC), gallocatechin (GC), and catechin (C) were found to increase in higher temperature (35 ºC).

2. Erratic rainfall

Rainfall amount and seasonal distribution have a significant influence on the biochemical composition and quality of tea. Excessive rainfall during the monsoon promotes rapid leaf growth, but it dilutes important quality-related compounds such as catechins and methylxanthines, resulting in inferior flavour, aroma, and overall tea quality. Increased leaf moisture, reduced sunshine, and seasonal changes in enzyme activity further contribute to the degradation of these metabolites during processing. Although total phenolic content and antioxidant activity may remain high due to the accumulation of other phenolic compounds, the reduction in catechins negatively affects the sensory characteristics and health-promoting properties of tea. While some compounds, such as certain amino acids, may increase under wet conditions, the overall biochemical changes associated with excessive rainfall generally reduce tea quality (Ahmed et al., 2014). Excessive rainfall also affects the respiration and nutrient absorption efficiency in tea plants (Ran et al., 2023).

3. Drought

Drought plays a crucial role in determining tea quality. Prolonged drought leads to a reduction in the contents of polyphenols and starch (Ran et al., 2023). Moderate water stress can stimulate the accumulation of beneficial phytochemicals, including catechins and methylxanthines, producing tea with superior flavour, aroma, and antioxidant properties. However, prolonged or severe drought adversely affects plant metabolism, reducing growth, yield, and the accumulation of quality-related compounds. Changes in rainfall patterns and frequent drought events have therefore become major concerns for tea cultivation under climate change. These observations agree with farmers' experiences and help explain why spring-harvested tea, produced under relatively drier conditions, generally commands higher market prices than tea harvested during the monsoon season (Ahmed et al., 2014).

4. Humidity

The amount of amino acid content in tea plants increases with higher levels of relative humidity (Jayasinghe & Kumar, 2021). Esterified catechins such as EGCG, GCG, ECG, key compounds that are accountable for astringency, flavour, aroma are enhanced due to the high air humidity, where structural genes and transcription factors including *CsCHS, CsC4H, CsANS, CsLAR1, CsDFR, CsANR2* and *CsTCP* are upregulated (Xiang et al., 2025). In contrast, under high humidity, non-esterified catechins, such as epicatechin decrease. Low relative humidity increases water loss from tea leaves, causing water stress and reducing the accumulation of quality-related amino acids (Xiang et al., 2025).

5. Light intensity

Light intensity and day length play important roles in regulating the growth, dormancy, and biochemical composition of tea plants. When daylight remains below 11 hours and 15 minutes for several weeks, tea bushes enter a dormant phase. In Northeast India, tea plants remain dormant for nearly three months during winter because of shorter days and lower temperatures. Excessive and prolonged exposure to sunlight causes photoinhibition, leading to changes in the chemical composition of tea leaves. Moreover, the amino acid content of tea shoots decreases with increasing sunshine duration but increases under higher humidity conditions (Jayasinghe & Kumar, 2021; Tocklai Tea Research Institute).

6. Elevated CO_2

Elevated atmospheric CO_2 enhances photosynthesis, resulting in greater plant growth and biomass accumulation. It also modifies the

biochemical composition of tea leaves by increasing the levels of carbohydrates and several beneficial metabolites, including soluble sugars, flavonoids, catechins, L-theanine, salicylic acid, proteins, and free fatty acids, while reducing caffeine and jasmonic acid biosynthesis. These changes can improve certain quality-related traits by promoting the accumulation of beneficial secondary metabolites. However, the suppression of caffeine- and jasmonic acid-mediated defence mechanisms weakens the tea plant's resistance to insect pests, such as tea aphids, and diseases like anthracnose, thereby increasing its susceptibility to biotic stresses (Ahammed et al., 2020). Therefore, although elevated CO_2 may enhance some aspects of tea quality, it also poses challenges for sustainable tea production by compromising the plant's natural defence system.

7. Altitude

Altitude is a key environmental factor influencing tea quality by modifying temperature, humidity, and solar radiation, which collectively affect the biochemical composition of tea leaves. Tea cultivated at higher elevations generally contains lower levels of catechins and polyphenols but higher concentrations of amino acids and a more diverse range of aroma compounds, resulting in improved flavour, aroma, and overall quality, although these responses may vary among cultivar and local environmental conditions. However, these changes are not always linear, and superior tea quality depends on an optimum altitude range rather than simply increasing elevation (Wang et al., 2022).

Overall, climate change alters the biochemical composition of tea leaves by influencing the accumulation of key metabolites such as catechins, amino acids, caffeine, polyphenols, and aroma compounds. These changes ultimately affect tea flavour, nutritional value, market quality, and the economic sustainability of tea cultivation, highlighting the need for climate-smart management practices.

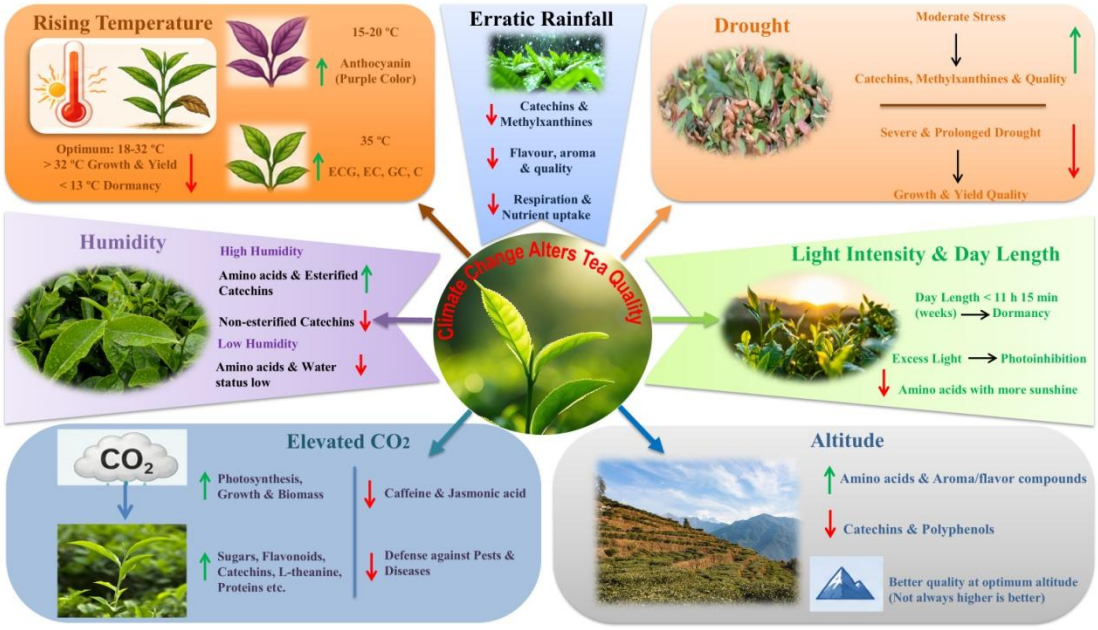


Figure 1: Influence of climate change factors on tea biocomponents and quality. **Green** and **Red** arrows represents Increase and Decrease respectively

4. Implications for Tea Growers and the Tea Industry

Reduced Premium Tea Quality

The market value of tea is directly impacted by climate-induced alteration in the biochemical composition of tea leaves affect the quality attributes of tea. Changes in the leaf biochemical compositions such as catechins, amino acids, caffeine, and volatile aroma compounds can reduce the flavour, aroma, briskness, colour, and antioxidant potential of the made tea product. As a result, it is becoming more difficult to produce premium quality tea in the face of shifting climate patterns, especially during the time of intense heat, unpredictable rains, or long drought.

Lower Farmer Income

The quality of tea is related to the price that tea growers obtain. So, decline in the quality due to adverse climatic conditions often leads to lower auction prize and ultimately harms tea growers' income. As mentioned previously, that due to climate change especially because of rising temperature, size of leaf of tea gets decreased which eventually decrease the production of made tea. This increases production costs for the need of more irrigation, shade management and labour. Small tea growers, who often lack the financial means to adjust to these shifts, face a significant risk of losing income.

Reduced Export Competitiveness

Countries renowned for producing high-quality teas, such as India, China, Sri Lanka, and Kenya, depend heavily on consistent quality to remain competitive in international markets. Climate-induced deterioration in tea quality may reduce consumer confidence and weaken the reputation of premium teas, particularly geographically distinctive products such as Darjeeling tea. Failure to maintain international quality standards could result in reduced export demand and lower foreign exchange earnings.

Changing Consumer Preferences

Modern buyers are gradually looking for teas that offer better taste, scent, visual appeal, and health benefits. Changes in climate that affect the biochemical composition or the concentration of these compounds in tea could change these sought-after traits, resulting in lower satisfaction for consumers and changes in their buying habits. Consumers might show a growing preference for teas that are made using climate-adaptive farming practices or those that have certifications for sustainable growing methods and reliable quality.

Economic Consequences

The simultaneous effects of declining tea quality, lower yields, and rising production expenses have considerable economic consequences for the tea industry. Lower productivity and reduced export revenues can adversely affect tea estates, processing sectors, traders, and rural populations relying on tea farming for their livelihood. It is crucial to invest in sustainable agricultural methods, resilient tea varieties, effective water management, and enhanced processing technologies to maintain the profitability and long-term sustainability of the tea sector amidst changing climatic circumstances.

5. Climate-Smart strategies for maintaining tea quality

A few climate-smart strategies can be adopted to maintain tea quality. These are listed below-

Shade Tree Management

Shade trees help regulate the microclimate within tea plantations by reducing excessive heat, lowering leaf temperature, and maintaining humidity. They also minimize sunburn, reduce water loss through evaporation, and improve soil fertility through its leaf litter. Proper shade

management therefore helps preserve tea quality and enhances the resilience of tea plants to climate stress. Leguminous deciduous shade trees like *Albizia* spp., *Leucaena leucocephala*, *Dalbergia sissoo* etc. should be planted throughout the tea field with proper gaps in between tea bushes.

Mulching

Mulching with organic materials such as pruned tea branches, fallen shade tree litters, grasses, or crop residues helps conserve soil moisture, regulate soil temperature, and suppress weed growth. It also reduces soil erosion and gradually adds organic matter to the soil as it decomposes. These benefits improve root health and enable tea plants to better withstand drought and erratic weather conditions.

Rainwater Harvesting

Harvesting and storing rainwater during the rainy season provides an alternative water source during dry periods. Farm ponds, reservoirs, and rooftop rainwater harvesting systems can reduce dependence on unpredictable rainfall and ensure a continuous water supply for tea cultivation. This practice is particularly valuable in regions frequently affected by drought, where many tea growers in southern India faces water shortages especially during summer.

Effective Irrigation

Efficient irrigation methods, such as sprinkler irrigation, provide water according to the crop requirements while minimizing water loss. However, drip irrigation can be used by small tea growers. Timely irrigation during prolonged dry spells helps maintain plant growth, sustain the accumulation of quality-related metabolites, and improve both yield and tea quality under changing climatic conditions.

Soil Organic Matter Management

Maintaining adequate soil organic matter through the application of compost, farmyard manure, green manure, shade tree leaves as well as tea pruning litterand other organic amendments improves soil structure, nutrient availability, and water-holding capacity. Healthy soils support vigorous root growth, increase drought tolerance, and contribute to the production of high-quality tea leaves.

Climate-Resilient Tea Cultivars

Developing and cultivating climate-resilient tea cultivars that can tolerate heat, drought, and emerging pests and diseases is an effective long-term adaptation strategy. Already developed varieties such as TV23, TV25, TV26, UPASI-9, UPASI-17 etc. can be used in areas where required. These improved cultivars help stabilize yield and maintain desirable biochemical characteristics even under adverse climatic conditions.

Weather-Based Advisories

The use of weather forecasting and climate advisory services enables tea growers to make informed decisions regarding irrigation, fertilizer application, pruning, harvesting, and pest management. Timely advisories help minimize climate-related risks, improve resource use efficiency, and reduce production losses.

Improved Harvesting and Processing Practices

Adopting appropriate harvesting schedules and optimizing processing steps such as withering, rolling, fermentation, and drying can help preserve important biochemical compounds responsible for tea flavour, aroma, and antioxidant properties. Improved post-harvest management is therefore essential for maintaining tea quality despite climate-induced changes in leaf composition.

These climate-smart strategies can help tea growers adapt to changing climatic conditions while sustaining productivity,

preserving tea quality, and improving the long-term resilience of the tea industry.

6. Conclusion

Climate change is reshaping tea production by altering not only the growth and yield of tea plants but also biochemical composition of tea leaves, which determines beverage quality. Changes in temperature, rainfall, drought, humidity, light intensity, atmospheric CO_2, and altitude influence the accumulation of important metabolites such as catechins, amino acids, caffeine, polyphenols, and aroma compounds, ultimately affecting the flavour, aroma, nutritional value, and market quality of tea. These changes pose significant challenges for tea growers through reduced productivity, declining premium quality, lower income, and reduced export competitiveness. Adopting climate-smart management practices—including improved shade management, efficient water use, soil health improvement, climate-resilient cultivars, weather-based advisories, and better harvesting and processing techniques—will be essential for minimizing the adverse effects of climate change. A combination of scientific innovation, sustainable cultivation practices, and farmer awareness will play a crucial role in safeguarding tea quality, strengthening livelihoods, and ensuring the long-term sustainability of the tea industry.

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Popular Article

Accelerating Adoption of Climate-Smart Agriculture: Challenges and Extension Strategies

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Abstract

Climate change is a major threat to global food security as it impacts the stability and productivity of agricultural systems. Climate-smart agriculture (CSA) is an approach that seeks to transform agriculture to simultaneously meet the goals of increased productivity, adaptation to climate change, and reduced greenhouse gas emissions from agriculture. This article provides an overview of the concept of CSA, its relevance to Indian and eastern Indian, especially West Bengal farming systems, CSA technologies and practices relevant to different farming systems in eastern India and a farmer-centric extension strategy for promoting CSA among farmers. The article also identifies barriers to the adoption of CSA technologies and examines the need for converging research, extension, and farmer's agency in adopting CSA for enhancing climate resilience. This revised edition strengthens the evidence base with additional recent statistical trends, future projections, and sources, and presents a farmer-centric, cyclical extension strategy with an expanded set of recommendations for promoting CSA adoption.

Keywords: Climate-Smart Agriculture; Extension Strategies; Farmer Adoption; Climate Resilience; Sustainable Livelihoods

KEY HIGHLIGHT

- 🌡️ Climate change threatens farm productivity and food security
- 🌱 Climate - Smart Agriculture promotes productivity, adaptation and mitigation
- 🚜 CSA practices strengthen farm resilience and resource efficiency
- ⚠️ Costs, limited credit and weak extension constrain adoption
- 🤝 Farmer-centric extension and institutional convergence can accelerate CSA adoption

1. Introduction

Agriculture has always been a harmonious mix of human labor and nature's bounty. But with changing climatic trends, this age-old harmony has been challenged, requiring a fresh perspective on sustainable farming and living. In India, about 50% of the working-age population either directly or indirectly depends on agriculture, and the sector employs nearly 60% of the country's total workforce while remaining highly exposed to rising temperatures, erratic rainfall, prolonged droughts, and increasing pest and disease pressure (Krishi Science eMagazine, 2025). Erratic monsoon, frequent spells of extreme weather events, and rising temperatures are a challenge for millions of small-scale farmers in Eastern India and the sub-Himalayan foothills of West Bengal. Gandhiji once said that the earth provides enough to satisfy every man's need but not his greed. Today, as we realize the impact of our actions on the planet, we need to rethink our priorities, values, and lifestyle without compromising food production.

> *"All living beings subsist on food; food is produced from rain; rain arises from selfless action (yajna); and yajna, in turn, is born of dutiful human effort."*
> *— Bhagavad Gita, Chapter 3, Verse 14*

This verse, which dates back thousands of years, reflects an understanding of the climate system similar to what scientists today refer to as climate-smart farming. It recognizes the intricate relationships between the atmosphere, rainfall, soil, and human labor, and indicates that climate-smart farming is an essential aspect of farmers' karma (duties). This ancient framing sets the stage for the modern, science-based concept of Climate-Smart Agriculture discussed in this article.

Climate-Smart Agriculture (CSA) is a development concept which promotes a transformative process towards climate-resilient agriculture production and sustainable livelihood security. CSA emphasizes a paradigm shift that promotes a holistic approach to managing agricultural systems (crops, livestock, forests, fisheries) and natural resources (land, soil, water) for simultaneously addressing the interrelated challenges of food security, adaptation and mitigation of climate change, and sustainable management of natural resources.

Dr. M.S. Swaminathan, the father of India's Green Revolution, often emphasizes that the world needs an evergreen revolution to achieve not only food security but also malnutrition-free health security (Swaminathan, 2010). CSA's evergreen, climate-resilience vision has guided the understanding of CSA's role in addressing the challenges of Indian agriculture on which this article reflects. More recent scholarship reinforces this vision: a 2025 systematic review and bibliometric analysis of CSA technologies document a sharp rise in global research output on farmer acceptance and adoption constraints since 2018 (Vasavi et al., 2025, Plant Science Today), while emerging work highlights the growing role of artificial intelligence and remote sensing in supporting CSA decision-making (Mmbando, 2025, Cogent Food and Agriculture).

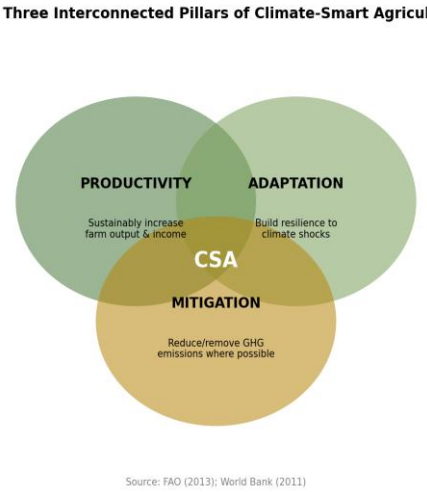


Figure 1: The three interconnected core pillars of the Climate-Smart Agriculture framework

The article examines the concept and principles of CSA; the evidence on climate change's impact on Indian and West Bengal agriculture, including recent statistical trends and future projections; CSA practices relevant to different Indian farming systems; barriers to adopting these practices; and a farmer-centric extension strategy to promote CSA. The article also discusses the convergence of research, extension, and policy for promoting CSA for climate-resilient sustainable agriculture.

2. Climate Change and Its Impact on Indian Agriculture

India is highly vulnerable to climate change because of its diverse physiographic and agro-climatic zones. According to the Intergovernmental Panel on Climate Change (IPCC), climate change could reduce agricultural productivity by almost 20% since 1961, with the maximum impact on tropical and sub-tropical regions (IPCC, 2022). Farmers in eastern India and the Terai region of West Bengal report that the monsoon's timing and intensity have changed considerably in recent decades, with more frequent and severe flash

floods damaging riverine farms. Climate change is also linked to more frequent and severe pest and disease outbreaks that have had a significant impact on Indian farm production.

Small-scale farmers, who comprise most of the farmers in West Bengal, are the worst affected by these changes. These marginal farmers have limited capacity to recover from losses caused by climate change, forcing many into distress sales and even migration. Against this backdrop, CSA emerges as an innovative, transformative, and sustainable approach that supports farming communities in adapting to the impacts of climate change while ensuring food security.

2.1 Recent Statistical Trends

- Rainfall over the rice-growing season has declined by about 7% over the last 30 years, intensifying moisture stress during critical crop stages (Daloz et al., 2021).
- A 42-year analysis (1982–2023) of the West Bengal coastal belt found a statistically significant rise in annual and post-monsoon rainfall, with post-monsoon rainfall increasing more sharply than monsoon rainfall itself — a shift linked to greater cyclone activity and flooding risk (Scientific Reports, 2025).
- Over a century of data (1901–2002) for Gangetic West Bengal shows post-monsoon rainfall rising by 33.87%, winter rainfall falling by 14.83%, and pre-monsoon rainfall falling by 4.03%, indicating that seasonal rainfall distribution — not just annual totals — is shifting (Ghosh, 2018).
- Long-term records for Cooch Behar district (1969–2022), home to UBKV, show detectable change-points in monthly and seasonal rainfall trends using Mann-Kendall and Innovative Trend Analysis methods (Vinay et al., 2024).
- Nationally, in 2023–24 India harvested 113.29 million tonnes of wheat and 137 million tonnes of rice for a population of 1.4 billion, of which 80% depends on government-subsidised grain — underscoring the food-security stakes of any climate-driven yield decline (Business Standard/PTI, 2025).
- A 2025 farm-level survey found that around 91% of Indian farmers now practise at least one CSA measure, though non-adoption persists due to lack of credit, information, and institutional support (Bahinipati, Viswanathan & Singh, 2024, Environmental Development).
- Industry monitoring reports a 15% year-on-year increase in climate-resilient crop adoption in India between July 2024 and July 2025, alongside new sustainable-farming policies introduced by over 60% of Indian states (Farmonaut Agriculture Climate News, 2025).

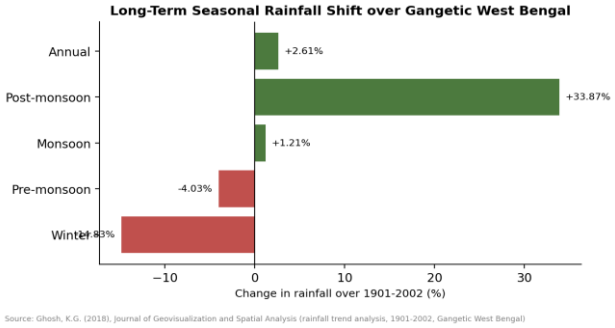


Figure 2: Long-term seasonal rainfall shift over Gangetic West Bengal (1901–2002), showing rising post-monsoon rainfall alongside declining winter and pre-monsoon rainfall. Source: Ghosh (2018).

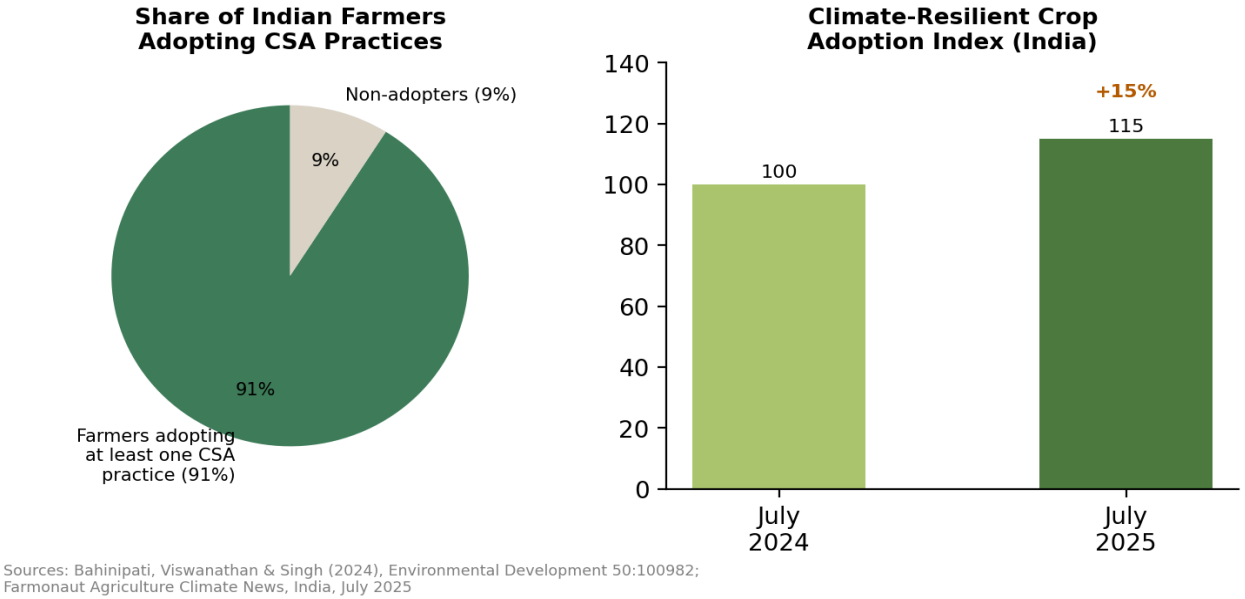


Figure 3: CSA adoption shares among Indian farmers and year-on-year growth in climate-resilient crop adoption. Sources: Bahinipati et al. (2024); Farmonaut (2025)

2.2 Future Prediction Analysis

- Without adaptation measures, rain-fed rice yields in India are projected to fall by 20% by 2050 and 47% by 2080, while irrigated rice yields may decline by 3.5% and 5% respectively over the same horizons (Government of India, PIB, 2023, citing NICRA crop-simulation studies).
- Wheat yields are projected to fall by 19.3% by 2050 and by 40% by 2080, and kharif maize yields by 18% and 23% over the same periods, in the absence of adaptation (PIB, 2023).
- Separately, NICRA data reported in 2025 projects wheat yield losses of 6–25% by 2100 and irrigated rice yield losses of 7% by 2050 and 10% by 2080, reflecting a range across modelling approaches (Business Standard/PTI, 2025).
- A 2026 panel study covering 20 crops across 20 Indian states projects rice and wheat yield reductions of 8.1% and 6.51% respectively by 2080 under current climate trajectories (Mitra et al., 2026, International Journal of Social Economics).
- Under a high-emissions pathway (SSP5-8.5), global wheat yields could fall by 14.1% by 2081–2100, with India's projected decline (−21.7%) exceeding both the global average and the projected US decline (−14.4%) (PMC/Nature-linked study, 2024).
- The IPCC projects that by the end of the 21st century, all-India rainfall could rise by 10–12% with more frequent heavy-rainfall days, while mean annual temperature could rise by 3–6°C — a combination expected to raise pest and disease pressure and accelerate rural-to-urban labour migration (IPCC, 2014; Byjesh et al., 2010).
- Rice-yield loss projections for India through 2100 range from 3% to 22% depending on the emissions scenario used, reflecting the sensitivity of these estimates to future policy choices (Economics of Disasters and Climate Change, 2024).

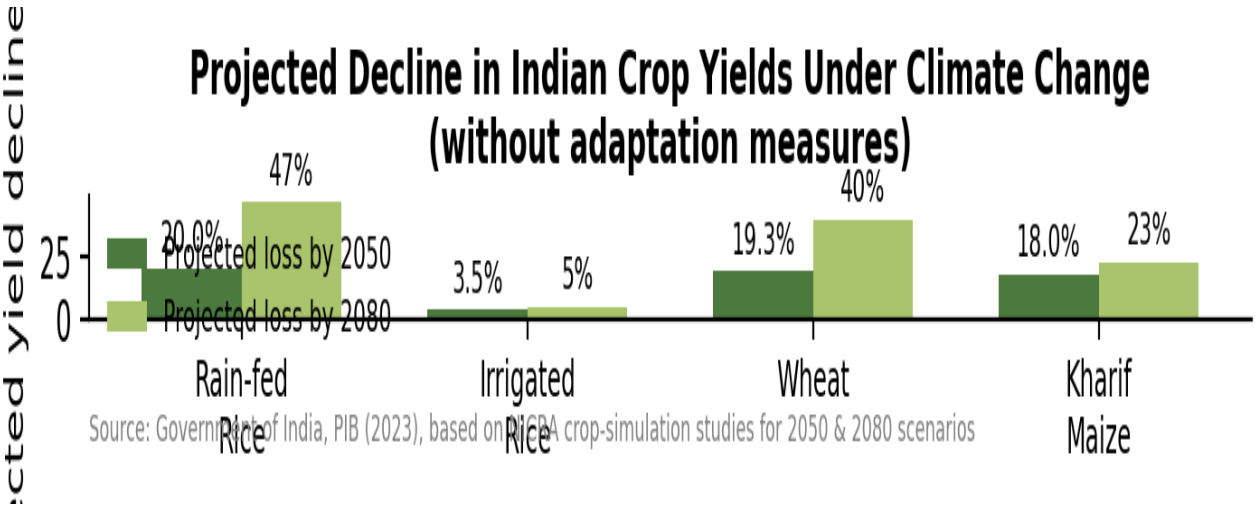


Figure 4: Projected decline in Indian crop yields under climate change without adaptation, 2050 vs. 2080. Source: Government of India, PIB (2023)

3. Understanding Climate-Smart Agriculture (CSA)

According to the Food and Agriculture Organization (FAO), CSA is an approach that promotes agriculture transformation processes needed for achieving food security and greenhouse gas emission reduction in the context of climate change (FAO, 2013). The World Bank defines CSA as agricultural practices that enhance productivity, adapt agricultural systems to climate change, and reduce greenhouse gas emissions from agriculture (World Bank, 2011). A widely cited synthesis in Nature Climate Change further frames CSA not as a single practice but as an integrative approach for aligning agricultural development and food-security policy with the realities of a changing climate (Lipper et al., 2014). CSA works on three mutually reinforcing pillars of increasing agricultural productivity, adapting to climate change, and reducing greenhouse gas emissions (Figure 1).

While the Productivity pillar focuses on boosting farm produce and profits while conserving natural resources, CSA's adaptation pillar aims to make farms and farming communities more resilient to climate change impacts. The mitigation pillar strives to minimize greenhouse gas emissions from agriculture. These pillars represent CSA's holistic approach to transforming agriculture production, emphasizing sustainable development. As the discussion in Section 2 shows, the scale of projected yield losses across India's staple crops is precisely what makes this three-pillar, resilience-oriented approach necessary rather than optional.

4. CSA Practices – A Climate-Smart Toolkit

Several CSA practices have been tried and tested in different parts of the country in farms, research stations, and Krishi Vigyan Kendra (KVK) with promising results. These include water and soil conservation, agroforestry, improved farming practices, and alternate energy. Figure 5 below shows some CSA practices implemented at the Climate-Smart Village.

Conservation tillage and stubble retention, along with solar irrigation, improves organic matter in the soil while reducing fuel consumption and labor. Micro-irrigation (precision drip irrigation) conserves water and ensures yields comparable to conventional irrigation methods. For example, farmers

growing short-season drought-prone crops benefit from micro-irrigation when the rains fail in critical developmental stages. Similarly, farmers in flash flood-prone areas utilize short-duration submergence-tolerant varieties and avoid crop losses. Farmers use agroforestry and alternate land use systems such as cover crops to diversify farm products while reducing the impact of strong winds and high temperatures.

Improved nutrient and pest management ensures that farmers do not rely on chemical pesticides and fertilizers while still reaping healthy yields. Lastly, agromet advisory services allow farmers to time their farming activities based on the weather. Recent research also points to AI-driven advisory tools and satellite-based monitoring — used to track vegetation health and water stress in near real time — as an emerging addition to this toolkit (Mmbando, 2025; Farmonaut, 2025).

5. Barriers to Adopting CSA Practices

There is an extensive CSA technology portfolio that can cushion Indian farmers against the adverse effects of climate change. However, a growing body of recent research has identified an expanded set of barriers to promoting these technologies among resource-poor farmers:

- Lack of large-scale commercial farms: The dominance of small-scale, fragmented farms in India limits the use of certain technologies such as drip irrigation and mechanized tilling.
- High initial costs of technologies: Farmers cannot afford the huge initial expenditure required to adopt these technologies, a situation worsened by limited credit access for small-scale farmers.
- Limited extension service coverage: A high farmer-to-extension-worker ratio limits the number of farmers who can be reached with extension advice and services.
- Low risk-bearing capacity: Farmers are highly risk-averse and therefore reluctant to adopt innovations without proper training and demonstrated experience.
- Lack of access to credit and crop insurance: Limited penetration of institutional credit and low awareness of schemes like PMFBY reduce farmers' capacity to absorb the risk of trying new practices (Bahinipati et al., 2024).
- Land fragmentation and tenancy constraints: Small, scattered, or tenanted landholdings make it difficult to justify investment in capital-intensive CSA technologies (Mishra et al., 2025, Odisha study).
- Inadequate region-specific climate and decision-support information: A lack of localized, real-time climate data hampers adaptive planning at the farm level (Krishi Science eMagazine, 2025).
- Weak market linkages and value chains: Poor access to remunerative markets discourages farmers from investing in climate-resilient but sometimes lower-volume crop varieties.
- Gender-related constraints: Women farmers, who perform a substantial share of farm labour, often have unequal access to land titles, credit, training, and extension contact, limiting household-level CSA uptake (Barooah et al., 2023, Agricultural Systems).
- Policy and institutional coordination gaps: Slow policy implementation and limited coordination across departments and schemes hinder the scaling of CSA (Krishi Science eMagazine, 2025).
- Limited digital and last-mile connectivity: Gaps in mobile network access and digital literacy constrain the reach of ICT-based agromet advisories in remote and hilly parts of eastern India.

6. Extension Strategy for Advancing CSA Adoption

Farmers are key climate change agents in promoting CSA practices for enhancing production, adapting to, and mitigating climate change impacts. Effective agricultural extension services play a crucial role in facilitating knowledge exchange between researchers, policymakers, and farming communities and accelerating the uptake of CSA practices among farmers. Figure 6 below sets out a farmer-centric, participatory, cyclical extension strategy for promoting CSA, supported by the following components:

- Awareness raising: Sensitizing farmers to climate change trends and the rationale for CSA through village meetings, mass media, and mobile-based agro-advisory alerts.
- Capacity building: Structured training through Farmer Field Schools (FFS), Krishi Vigyan Kendra (KVK) programmes, and short courses covering both technical skills and climate literacy.
- On-farm demonstration (FLD): Front-Line Demonstration trials that let farmers see CSA technologies performing under their own local conditions, building trust and confidence.
- Participatory need assessment: Using tools such as Participatory Rural Appraisal (PRA) to ensure that recommended CSA practices match local resource constraints and farmer priorities.
- Farmer-to-farmer and lead-farmer models: Training local 'champion farmers' as peer educators to extend reach beyond what formal extension staff can cover alone.
- ICT and mobile agro-advisory services: Expanding SMS, app-based, and satellite-supported advisories to deliver real-time, localized weather and crop guidance.
- Public-private partnerships (PPP): Engaging agri-tech firms, input suppliers, and NGOs in technology transfer, financing, and last-mile service delivery.
- Farmer Producer Organizations (FPOs): Strengthening collective platforms so smallholders gain bargaining power, shared access to machinery, and pooled credit for CSA investments.
- Convergence with insurance and credit schemes: Building farmer awareness of PMFBY and institutional credit lines so risk-averse farmers have a safety net when adopting new practices.
- Gender-inclusive extension: Actively including women farmers in trainings, demonstrations, and leadership roles within farmer groups.
- Monitoring, feedback, and course correction: Structured feedback loops so that farmer experience with CSA technologies is fed back to researchers and extension planners to fine-tune recommendations.

Finally, farmers can adopt these practices and provide feedback to fine-tune the technologies and make them more farmer-friendly, closing the loop of the extension cycle shown below.

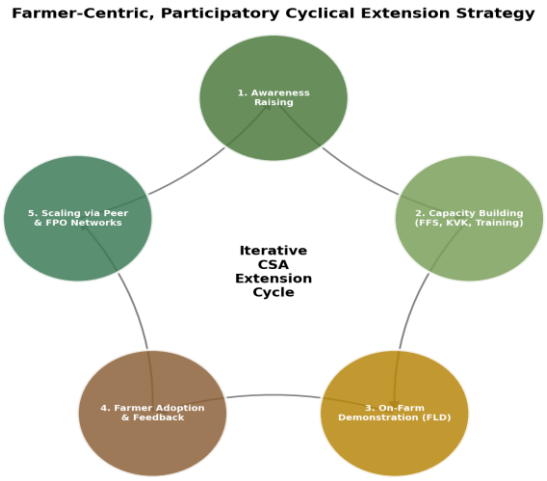


Figure 6: Iterative, participatory farmer-to-farmer extension strategy cycle for CSA promotion

7. Strengthening Institutional Networks for Advancing CSA

Several institutional frameworks exist in the country to support CSA promotion and

adoption. The National Innovations in Climate Resilient Agriculture (NICRA) and National Mission for Sustainable Agriculture (NMSA) programs and the Pradhan Mantri Fasal Bima Yojana (PMFBY) crop insurance scheme are vital structures promoting and supporting climate-smart agriculture practices. Complementary schemes such as the Pradhan Mantri Krishi Sinchayee Yojana (efficient irrigation), Neeranchal (watershed development), and the Paramparagat Krishi Vikas Yojana (organic farming, with a national target of bringing 10% of cultivated area under organic farming) further widen this institutional support base (GOI, 2021; Praveen & Ramachandran, 2020). The convergence of research institutions, State Agricultural Universities (SAUs) such as UBKV, and local government agencies is critical in accelerating the adoption of CSA practices.

8. Conclusion

CSA is a transformative and innovative approach crucial for enhancing the production, adaptive capacity, and resilience of Indian agriculture. The article highlights the importance of CSA in light of the adverse effects of climate change on Indian agriculture, especially Eastern India, and the recent statistical evidence and future projections confirm that the scale of this challenge is significant and growing. The article also identifies several CSA technologies that are viable for promoting sustainable farming in the region.

Finally, the article proposes a cyclical, farmer-centric extension strategy — with awareness, capacity building, participatory need assessment, ICT-enabled advisory, institutional convergence, and structured feedback as its key components — as the most promising route to closing the gap between CSA's proven potential and its ground-level adoption.

> *"The nation that destroys its soil destroys itself."*
> *— Franklin D. Roosevelt*

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Popular Article

Climate Change and Emerging Livestock Diseases: Strengthening Advisory Systems for Climate-Resilient Animal Health

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Abstract

Climate change is increasingly influencing the occurrence, distribution, and severity of livestock diseases, posing significant challenges to animal health, food security, and rural livelihoods. Rising temperatures, erratic rainfall, extreme weather events, and changing vector ecology are creating favourable conditions for the emergence and re-emergence of infectious and vector-borne diseases, while simultaneously reducing animal resilience through heat stress and environmental pressures. These changing disease dynamics demand a transition from conventional reactive disease control to proactive, climate-smart animal health management. Strengthened livestock advisory systems play a pivotal role in enhancing preparedness by integrating climate information, disease surveillance, early warning systems, digital technologies, and participatory extension approaches. Timely, location-specific advisories enable farmers to adopt preventive measures such as vaccination, improved biosecurity, vector control, and climate-resilient management practices, thereby reducing economic losses and improving livestock productivity. Furthermore, the adoption of the One Health approach fosters collaboration among veterinary, public health, environmental, and extension agencies to address the interconnected risks posed by climate-sensitive and zoonotic diseases. This article highlights the relationship between climate change and emerging livestock diseases, discusses the importance of resilient advisory systems, and outlines key strategies for strengthening extension services to support sustainable livestock production and safeguard the livelihoods of livestock-dependent communities under changing climatic conditions.

Keywords: Climate change, Climate-smart livestock management, Emerging diseases, Livestock advisory systems.

KEY HIGHLIGHT

- 🌡️ Climate change is reshaping livestock disease patterns and risks
- 🦠 Emerging diseases are expanding with changing vector ecology and weather
- 🐄 Climate stress weakens livestock health, productivity and resilience
- 📡 Climate-informed advisories can enable timely disease prevention
- 🤖 Digital tools and early warning systems strengthen disease surveillance
- 🤝 One Health collaboration is vital for climate-resilient animal health.

1. Climate Change and Livestock Health

Climate change has emerged as a major global challenge affecting agricultural and livestock production systems. Rising temperatures, erratic rainfall, prolonged droughts, floods, cyclones, and changing humidity

patterns are altering ecosystems and increasing the vulnerability of livestock to climate-related stresses. Although considerable attention has been given to the impacts of climate change on crop production, its implications for livestock health and disease dynamics are equally significant. Livestock support global food security, nutrition, employment, and rural livelihoods, with more than one billion people depending directly or indirectly on livestock for their sustenance. In countries such as India, livestock contribute substantially to agricultural income while providing milk, meat, fibre, manure, and livelihood security for millions of smallholder farmers (Thornton *et al*., 2009).

Climate change is also reshaping the epidemiology of livestock diseases by influencing pathogen survival, vector distribution, and host susceptibility. Rising temperatures and altered precipitation patterns favour the proliferation of vectors such as mosquitoes, ticks, biting flies, and midges, while extreme weather events compromise animal immunity, disrupt production systems, and facilitate disease transmission among livestock, wildlife, and humans. Consequently, diseases such as Lumpy Skin Disease, Bluetongue, African Swine Fever, and several tick-borne infections are expanding into new geographical regions, causing substantial economic losses and posing significant public health concerns through zoonotic transmission (Bett *et al*., 2017).

Addressing these emerging challenges requires integrated livestock advisory systems that combine climate information, disease surveillance, extension services, digital technologies, and community participation. Climate-resilient livestock production depends not only on improved husbandry practices but also on timely, evidence-based advisory services that enable farmers to anticipate disease risks and implement preventive interventions.

1.1 Climate–Disease Nexus: Livestock disease occurrence is determined by the dynamic interaction among the host, pathogen, and environment. Climate change primarily alters the environmental component by modifying temperature, rainfall, humidity, and ecological conditions, which in turn influence pathogen persistence, vector abundance, and host susceptibility. Even subtle climatic variations can disrupt this balance and increase the risk of disease emergence and transmission (Baylis & Githeko, 2006).

2. Climate-Driven Changes in Livestock Disease Dynamics

Climate change alters livestock disease epidemiology by modifying environmental conditions that regulate pathogen survival, vector abundance, and host susceptibility. Rising temperatures, changing rainfall patterns, increasing humidity, and frequent extreme weather events collectively increase the emergence, transmission, and geographical spread of climate-sensitive livestock diseases (Calvin *et al*., 2023).

2.1 Rising Temperature: Increasing temperatures accelerate pathogen replication and enhance the survival and seasonal activity of vectors such as mosquitoes, ticks, and biting flies. Heat stress also reduces feed intake, productivity, reproductive performance, and immune competence, increasing livestock susceptibility to infectious diseases.

2.2 Altered Rainfall Patterns: Changes in rainfall influence disease transmission by creating favourable breeding habitats for vectors and increasing pathogen persistence. Heavy rainfall and flooding promote mosquito proliferation and water contamination, whereas

prolonged droughts increase animal congregation around scarce resources, facilitating disease transmission and nutritional stress.

2.3 Increasing Humidity: High humidity enhances the environmental survival of bacteria, fungi, ticks, mites, and *Culicoides* biting midges, thereby prolonging vector activity and increasing the risk of vector-borne diseases such as Bluetongue (Mellor *et al*., 2000).

2.4 Extreme Weather Events: Floods, droughts, cyclones, and heatwaves disrupt livestock production by damaging housing, reducing feed and water availability, interrupting veterinary services, and suppressing animal immunity. These conditions create favourable circumstances for disease emergence and post-disaster outbreaks (Calvin *et al*., 2023).

2.5 Changing Vector Ecology: Climate change is expanding the geographical range and seasonal activity of arthropod vectors. Warmer temperatures and altered precipitation enable vectors to colonize higher altitudes and previously disease-free areas, increasing the transmission of several vector-borne livestock diseases and emphasizing the need for climate-informed surveillance (Baylis & Githeko, 2006).

3. Climate-Sensitive Emerging and Re-emerging Livestock Diseases

Climate change is accelerating the emergence, re-emergence, and geographical expansion of several transboundary livestock diseases by influencing pathogen survival, vector ecology, and host susceptibility. Rising temperatures, altered precipitation, and increasing climatic variability have intensified the spread of climate-sensitive diseases, posing serious threats to livestock productivity, food security, and global animal health (Bett *et al*., 2017).

3.1 Lumpy Skin Disease (LSD): Lumpy Skin Disease (LSD) is an economically important transboundary viral disease of cattle that has expanded rapidly from Africa to the Middle East and Asia, including India. Transmission occurs primarily through biting insects, whose populations increase under warm and humid conditions. Clinically, LSD is characterized by fever, skin nodules, reduced milk yield, infertility, and weight loss, leading to considerable economic losses through mortality, production decline, movement restrictions, and disease control measures (Bhuiyan*et al*., 2026).

3.2 Bluetongue: Bluetongue is a climate-sensitive viral disease transmitted by *Culicoides* biting midges, primarily affecting sheep but also cattle, goats, and wild ruminants. Rising temperatures enhance vector abundance, shorten viral incubation, and prolong transmission periods. Clinical signs include fever, oral lesions, lameness, respiratory distress, and mortality in susceptible breeds, reflecting the close association between climate change and vector-borne disease spread (MacLachlan & Mayo, 2013).

3.3 Tick-Borne Diseases: Increasing temperatures and humidity have expanded the distribution of ticks, contributing to the growing incidence of babesiosis, theileriosis, anaplasmosis, and ehrlichiosis. Besides transmitting pathogens, tick infestations reduce livestock productivity through blood loss, skin damage, stress, and impaired growth and reproduction (Jongejan & Uilenberg, 2004).

3.4 African Swine Fever (ASF): African Swine Fever (ASF) is a highly contagious disease of domestic and wild pigs with severe economic consequences. Although climate change is not the primary driver of ASF, environmental changes can influence the ecology of wild boars, soft ticks, and contaminated environments,

indirectly affecting disease persistence and transmission. The continuing spread of ASF emphasizes the importance of strengthened surveillance and biosecurity measures (Dixon *et al*., 2020).

3.5 Peste des Petits Ruminants (PPR): Peste des Petits Ruminants (PPR) remains a major viral disease of sheep and goats. Climate-induced heat stress, feed scarcity, and increased animal movement weaken immunity and facilitate disease transmission. While vaccination remains the most effective control strategy, climate-informed advisory services and efficient surveillance are essential for improving vaccination coverage and outbreak prevention (Parida *et al*., 2015; Verma *et al*., 2026a).

4. Economic, Social and Environmental Impacts of Emerging Livestock Diseases

Climate-sensitive livestock diseases have far-reaching consequences that extend beyond animal health, affecting agricultural productivity, food security, rural livelihoods, public health, and national economies (Verma *et al*., 2025). Disease outbreaks disrupt livestock production, increase financial risks for farmers, and destabilize livestock value chains, thereby undermining sustainable rural development.

4.1 Reduced Livestock Productivity: Emerging diseases impair animal growth, reproduction, and production performance, resulting in reduced milk yield, weight gain, fertility, meat and fibre quality, and increased mortality. Heat stress further decreases feed intake and feed efficiency, leading to substantial productivity losses and reduced farm profitability (Thornton *et al*., 2009).

4.2 Increased Production Costs: Disease outbreaks increase production costs through greater expenditure on veterinary care, medicines, vaccination, vector control, improved housing, nutritional supplementation, and labour. These additional costs disproportionately affect smallholder farmers, reducing profitability and increasing economic vulnerability.

4.3 Food and Nutritional Insecurity: Declines in livestock productivity reduce the availability of milk, meat, and eggs, compromising the supply of high-quality protein and essential nutrients. This threatens household food and nutritional security, particularly among vulnerable populations (Davis*et al*., 2025).

4.4 Market and Trade Disruptions: Transboundary livestock diseases frequently trigger movement restrictions, market closures, export bans, and price fluctuations, causing substantial economic losses throughout the livestock value chain and affecting producers, traders, processors, and consumers (Thompson *et al*., 2024).

4.5 Social Implications: Beyond economic losses, recurrent disease outbreaks contribute to financial insecurity, indebtedness, psychological stress, reduced educational investment, and migration from rural areas. Consequently, climate-sensitive livestock diseases represent not only an animal health issue but also a significant socio-economic and rural development challenge requiring integrated climate-resilient interventions.

5. Climate Change and Zoonotic Diseases

Approximately 60–75 per cent of emerging infectious diseases affecting humans originate from animals. Climate change influences the ecology of many zoonotic pathogens by altering wildlife habitats, vector populations, and human–animal interactions. Some important climate-sensitive zoonotic diseases (**Fig.1)** include:

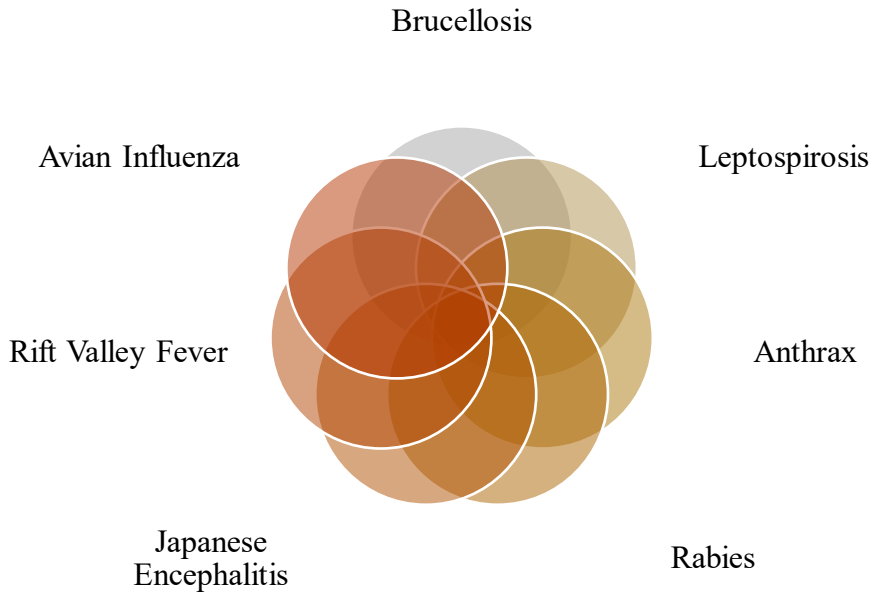


Figure 1. Major climate-sensitive zoonotic diseases influenced by climate change.

Floods, droughts, habitat fragmentation, and changing land-use patterns increase contact among wildlife, livestock, and humans, facilitating spillover of pathogens. This highlights the importance of adopting a One Health approach that recognizes the interconnectedness of human, animal, and environmental health.

6. Challenges in Existing Livestock Advisory Systems

Traditional livestock advisory systems have played a crucial role in improving animal husbandry and disease management. However, climate change has exposed several limitations that necessitate advisory services to become timelier, climate-informed, technology-enabled, and preventive. Strengthening these systems is essential to improve disease preparedness, enhance farmer decision-making, and build resilient livestock production systems (Verma*et al.*, 2026b).

6.1 Limited Last-Mile Service Delivery: Despite considerable progress in veterinary extension, many remote and resource-poor communities continue to have limited access to timely advisory services. Shortages of trained personnel, inadequate transportation, difficult terrain, and weak communication infrastructure often delay the dissemination of critical disease information. Consequently, farmers frequently receive advisories only after disease outbreaks have occurred, reducing the effectiveness of preventive interventions.

6.2 Reactive Rather than Preventive Approaches: Most existing advisory systems remain largely treatment-oriented, emphasizing disease control after outbreaks instead of disease prevention. Climate-resilient advisory services should prioritize risk assessment, disease forecasting, preventive vaccination, biosecurity measures, and climate-informed management decisions to minimize disease incidence and associated economic losses (Thornton *et al.*, 2009).

6.3 Poor Integration of Climate Information: Meteorological information is seldom translated

into practical recommendations that support livestock management. Integrating weather forecasts with disease surveillance can enable farmers to make informed decisions regarding vaccination schedules, heat stress mitigation, vector control, housing management, and emergency preparedness, thereby strengthening adaptive capacity (Calvin *et al*., 2023).

6.4 Weak Disease Surveillance Systems: Early disease detection remains one of the weakest components of livestock health management due to under-reporting, delayed laboratory diagnosis, fragmented institutional coordination, and inadequate real-time digital surveillance. These deficiencies often delay outbreak response, allowing diseases to spread before effective control measures can be implemented (Thompson *et al*., 2024).

6.5 Low Digital Literacy Among Farmers: Although digital technologies have expanded the reach of livestock advisory services, their effectiveness is constrained by limited digital literacy, poor internet connectivity, language barriers, and inadequate awareness of digital platforms. Strengthening farmers' digital competencies through capacity-building programmes and user-friendly advisory tools is therefore essential for maximizing the benefits of ICT-enabled livestock extension (Verma*et al*., 2026b).

7. Characteristics of a Climate-Smart Livestock Advisory System

Climate-smart livestock advisory systems should integrate climate intelligence, digital technologies, and participatory extension approaches to deliver timely, evidence-based, and farmer-oriented services. Such systems enhance disease preparedness, support informed decision-making, and strengthen the resilience and sustainability of livestock production under changing climatic conditions. The keycharacteristics shown in Fig.2.

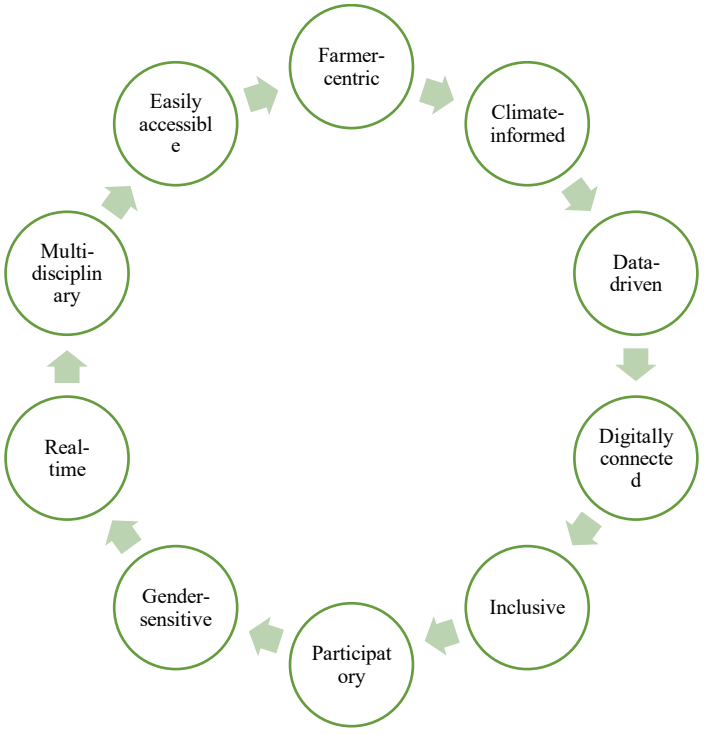


Figure 2. Key characteristics of an ideal climate-smart livestock advisory system.

8. Integrating Climate Information into Livestock Advisory Services

Integrating climate information into livestock advisory systems enables the translation of weather forecasts into timely, location-specific management recommendations. Such climate-informed advisories (Table1) support preventive decision-making, enhance disease preparedness, and strengthen the resilience of livestock production systems.

Table 1. Climate-informed advisory recommendations for enhancing livestock health resilience under changing climatic conditions.

Climate Information	Advisory Recommendation
Heat wave forecast	Increase water availability, provide shade, avoid transportation during afternoon hours
Heavy rainfall	Improve drainage, disinfect sheds, vaccinate susceptible animals before rains
High humidity	Intensify surveillance for mastitis and fungal infections
Drought forecast	Prepare fodder reserves and conserve drinking water
Increased vector activity	Begin insecticide spraying, tick control, and vaccination where appropriate

9. Digital Transformation of Livestock Advisory Systems

Digital technologies have revolutionized livestock advisory services by enabling rapid, location-specific, and evidence-based dissemination of animal health information. ICT-enabled platforms improve disease surveillance, strengthen farmer–veterinarian communication, and facilitate timely management decisions, thereby enhancing the climate resilience of livestock systems (Rose *et al*., 2021).

9.1 Mobile-Based Advisory Applications: Mobile applications support disease diagnosis, vaccination scheduling, feeding and breeding management, weather-based advisories, and remote veterinary consultation, improving farmers' access to timely expert recommendations.

9.2 Social Media and Messaging Platforms: Platforms such as WhatsApp enable rapid dissemination of disease alerts, weather warnings, vaccination reminders, and best management practices. Multimedia sharing further facilitates preliminary disease assessment and real-time veterinary guidance (Rose *et al*., 2021).

9.3 SMS-Based Advisory Services: SMS remains an effective communication tool in areas with limited internet access by delivering timely alerts on disease outbreaks, weather forecasts, vaccination schedules, and emergency advisories in local languages.

9.4 Artificial Intelligence in Disease Advisory: Artificial intelligence integrates climate, surveillance, and epidemiological data to forecast disease outbreaks, identify high-risk areas, support diagnosis, and guide preventive interventions, thereby improving climate-smart livestock health management (Michie *et al*., 1995).

10. Early Warning Systems for Predictive Disease Management

Climate-smart Early Warning Systems (EWS) combine climate information, disease surveillance, GIS, remote sensing, and AI to predict disease risks before outbreaks. Timely dissemination of alerts through digital platforms

enables preventive interventions such as vaccination, vector control, and biosecurity, while coordinated action among meteorological agencies, veterinary services, researchers, and local communities strengthens preparedness and reduces climate-related livestock losses.

Conclusion:

Climate change is rapidly reshaping the epidemiology of livestock diseases, posing significant threats to animal health, food security, and the livelihoods of livestock-dependent communities worldwide. Addressing these emerging challenges requires a strategic transition from conventional reactive disease management to proactive, climate-smart approaches supported by robust and integrated livestock advisory systems. The integration of early warning systems, climate information, disease surveillance, digital technologies, and the One Health approach can substantially enhance disease preparedness, risk prediction, and preventive interventions. Furthermore, strengthening veterinary extension services, fostering community participation, and investing in innovative advisory platforms will empower farmers to build resilient livestock production systems and promote sustainable livestock development under increasingly variable and changing climatic conditions.

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Agri-Sphere
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Popular Article

Impacts of Climate Stressors on Tea Cultivation: Consequences and Adaptive Strategies with Special Reference to Darjeeling Tea Clones

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Abstract

Tea, derived from the evergreen shrub *Camellia sinensis* (L.) O. Kuntze, is one of the most widely consumed beverages globally, holding immense socio-economic importance in many tropical and subtropical countries. However, tea cultivation is increasingly threatened by climate change, which is continuously affecting growth, yield and quality of the produce. The current study summarized the overview of climate change and its effects on tea plants, plant's responses to major abiotic climate stressors, including heat, cold, drought, waterlogging, elevated CO_2, and nutrient stress and key adaptive strategies to mitigate climate impacts on tea plantations. The current findings have marked major progress in this topic recently but there are significant research lacunae in understanding the long-term responses of tea plants to climate stressors and application of sustainable approaches to ensure uninterrupted tea production in this changing climate scenario.

Keywords: Climate resilience, Tea production, Climate stressors, Climate change response, Adaptation strategies

KEY HIGHLIGHT

- Climate stress threatens tea yield and quality
- Heat, drought, frost and waterlogging disrupt plant growth
- Changing climate is intensifying pest and disease risks
- Resilient clones can sustain productivity under stress.
- Shade trees, agroforestry & water management enhance resilience
- Breeding and research should combine quality with climate tolerance

Introduction

Tea (*Camellia sinensis* L.) is an important agroeconomic commodity that supports the livelihoods of millions of planters, workers and stakeholders cultivating, manufacturing and selling tea in the tropical and subtropical regions across Asia, Africa, and Latin America. However, climate change increasingly threatening the sustainability and productivity of tea since the beginning of twenty-first century. Tea grows well in ecologically sensitive regions characterized by moderate temperatures (13°C to 26°C), well-distributed rainfall (1500-2000 mm), high humidity, and suitable soil conditions i.e., acidic soil (Pan *et al.*, 2022; Rajan *et al.*, 2024). Perfectly aligning with

these conditions, major tea-producing countries are in Asia, with China (producing 48.9% of global tea), India (contributing around 20%), and Sri Lanka leading followed by African nations like Kenya, Malawi, Rwanda, Tanzania, and Uganda (Rajan *et al.*, 2024). Tea cultivation and consumption have also expanded to other Asian countries, including Korea, Japan, Vietnam and Indonesia (Pan *et al.*, 2022). Deterioration of these environmental parameters directly influence growth, yield, quality and biochemical nature of tea. Temperature rise, uneven rainfall, prolonged droughts, heat waves and occurrence of extreme weather conditions have adversely affected tea-growing ecosystems ultimately leading to low yield, alteration in flush patterns, increased pest infestation and disease, and decline of quality (Rajan *et al.*, 2024). Being a perennial crop tea may exhibit long productive lifetime but a minimal ability to survive under changing environment and extreme climate conditions though rapid adaptation (Rajan *et al.*, 2024). Therefore, there is an urgent need to employ strategies including development of climate-resilient tea characterized by their enhanced tolerance to environmental stresses such as drought, heat, waterlogging, frost, salinity and emerging pest and disease outbreak capable of maintaining stable yields and desirable quality under diverse abiotic and biotic stress conditions. Moreover, tea comprises two major botanical varieties: *Camellia sinensis* var. *sinensis* and *Camellia sinensis* var. *assamica*. The China type is more tolerant to drought, environmental stress, and frost, whereas the Assam type is more susceptible to drought and cold (Rajan *et al.*, 2024). Their contrasting climate adaptations provide valuable genetic resources for developing climate-resilient tea varieties under changing climatic conditions. Recent reports on climate change and its effect on tea production have received widespread attention worldwide (Jayasinghe and Kumar, 2020; Rajan *et al.*, 2024). Earlier researchers reported the reduction in tea production due to effects of both heat and cold extremes in the four major tea producers (Baruah and Handique, 2021; Jayasinghe and Kumar, 2020; Muoki *et al.*, 2020). Particularly, extreme cold reduced the annual tea production by >50% (Hilal and Ismail, 2020; Yan *et al.*, 2021). Since 2010, Korea recorded a decreased in tea production by up to 15% due to frost damage as recurrent low temperatures, drought and strong winter winds (Hwang and Kim, 2012).

Climate change and its impact on tea plants

Tea is a climate-sensitive plant as already described consequently heat stress, frost damage and uneven precipitation patterns have already caused deterioration of tea quality; physiological and structural damage; reduction of photosynthetic efficiency and enzyme activity; water loss; imbalance metabolism; stunted growth; water stress or waterlogging related issues ultimately affecting worldwide tea production (Rajan *et al.*, 2024). Indirect impacts include pest and disease dynamics due to shifting climate conditions (Jayasinghe and Kumar, 2019; Muoki *et al.*, 2020; Rajan *et al.*, 2024).

Impact on tea growing regions

Climate change exhibited moderate to severe effects on tea production trends. Indian subcontinent has been expected to be more vulnerable to the effects of climate change due to its population which may experience the adverse effects in the agriculture sector (Habib-ur-Rahman *et al.*, 2022).

China

Rising temperatures and altered precipitation patterns and drought affected tea production in Zhejiang province, one of the highest tea yielding region. Whereas Fujian province experienced risks from cold stress (Jayasinghe and Kumar, 2021; Rajan *et al.*, 2024). Studies have already revealed huge economic losses (of

around 59 billion RMB) in China due to extreme climate events like heatwaves (Rajan *et al.*, 2024).

India

Studies marked consequences of rising temperature, increase in wind velocity, erratic rainfall, and drought in India tea production (Baruah and Handique, 2021; Das *et al.*, 2021). Assam recorded a decline up to 3.8% due to exceeding temperatures (Duncan *et al.*, 2016). Additionally, these changes have altered the tea pest landscape with occurrence of 'new looper' (*Hyposidra talaca*) in the recent years in the northeastern India (Subba *et al.*, 2025).

Other tea growing countries

Major declines were recorded in Kenya (−23.73%), Sri Lanka (−22.22%), and Turkey (−10.34%) in the last decade compared to the previous one (Rajan *et al.*, 2024). Jayasinghe and Kumar (2019, 2020) have done pioneer research in climate change and its impact on tea in Sri Lanka. In Sri Lanka, reduced rainfall and drought have reduced tea yield and production. In Kenya, altered precipitation has caused both flooding and drought, leading to 14-20% yield loss and 6-19% plant mortality. A severe frost event in Nandi Hills in 2012 caused economic losses of approximately 9.6 million USD (Rajan *et al.*, 2024). Overall, tea yield and quality are significantly impacted by the increased outbreak of pests and diseases driven by climatic warming (Rajan *et al.*, 2024). Using SSP2-4.5 and SSP5-8.5 scenarios developed for the IPCC Sixth Assessment Report (AR6) to project future greenhouse gas emissions and climate change, Kim *et al.*, (2023) projected an expansion of suitable tea-growing areas to the south, west, and east coasts of South Korea.

Responses of Tea Plants to Different Climate Stressors

Temperature stress

Tea plants usually grow well in moderately cold weather condition ranging from 13°C to 26°C. Deviation in this optimum temperature range leads tea plants to exhibit distinct physiological and biochemical responses (Fig. 1) (Arefin and Hossain, 2022). Heat stress may cause reduction of chlorophyll content; impairment of the photosynthetic apparatus; decreased stomatal conductance (Muoki *et al.*, 2020) which lowers growth rates and overall yield (Rajan *et al.*, 2024). Cold stress also negatively impacts the photosynthetic capacity (Oh and Koh, 2014) leading to decreased growth and yield (Li *et al.*, 2020). Significant physical injury leaf browning, wilting, stunted growth, and alterations in metabolite biosynthesis (Lee, 2015) are also associated to tea plant health during colder periods. Korea once recorded a massive damage (70-90% damage of tea plants) due to cold stress (Hwang and Kim, 2012). As response, tea plants were reported to exhibit alteration in several biochemical pathways; activation of antioxidant pathways (like superoxide dismutase and peroxidase) and higher rate of catechins production as natural defense compounds (Li *et al.*, 2020; Samynathan *et al.*, 2021; Rajan *et al.*, 2024).

Water stress

Normal range of annual precipitation for tea cultivation is 1500-2000 mm (Arefin and Hossain, 2022). Water stress majorly affects the leaf morphology by inducing the closure of stomata; decrease in leaf thickness, reduction of transpiration (Safaei Chaeikar *et al.*, 2020; Rajan *et al.*, 2024). Decreased polyphenol content and increased proline and total sugar concentration have also been reported as water stress induced biochemical response (Safaei Chaeikar *et al.*, 2020). Prolonged drought can lead to leaf shedding, reduced leaf size, and, ultimately, lower yields (Hajiboland, 2018; Waheed *et al.*, 2012). Whereas excessive rainfall causing waterlogging condition is also harmful for the roots leading towards suffocation by reducing oxygen availability in the soil, ultimately leading to root damage and reduced nutrient uptake (Nasrullah *et al.*, 2022). Flooding stress significantly impacts the synthesis of quality constituents such as gallic acid and caffeine (Jeyaramraja *et al.*, 2003). To overcome this stress tea plant adapts several physiological and biochemical strategies including drought Tolerance mechanism: deep root systems; osmotic adjustment to retain cellular water etc. (Damayanthi *et al.*, 2011; Rajan *et al.*, 2024).

Increased CO_2

Elevated CO_2 levels stimulate photosynthesis and promote greater growth in tea plants due to increased carbon availability. Enhanced

biomass production and potentially higher tea yields; alteration in the composition of tea leaf metabolites; increased carbohydrate content and reduction of nitrogen-containing compounds such as amino acids and proteins etc. are consequences of increased CO_2 levels (Ahammed *et al.*, 2020; Rajan *et al.*, 2024). Under nutrient-limited conditions, tea plants may exhibit stunted growth, reduced leaf area, and lower chlorophyll content, all of which negatively impact photosynthetic efficiency (Rajan *et al.*, 2024). Nutrient stress can also exacerbate the effects of other climate stressors, such as temperature and water stress, further reducing the plant's ability to cope with environmental challenges. Overall responses of tea plants to different climate stressors have been summarized in the Fig. 1.

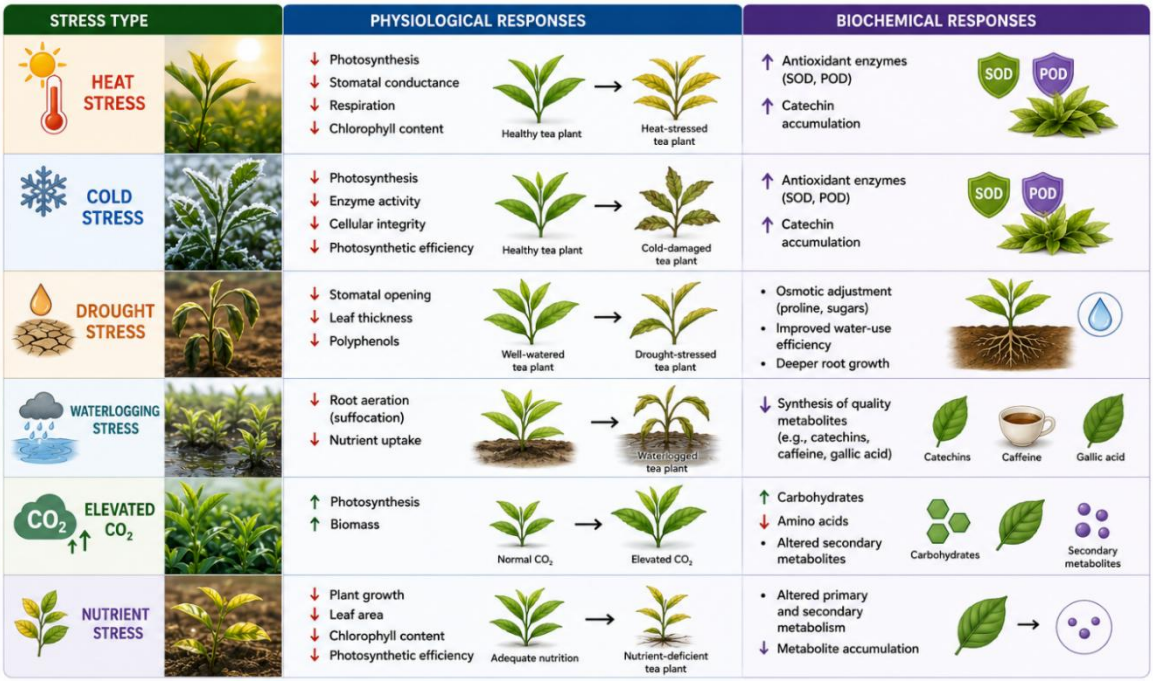


Figure. 1: Physiological and biochemical responses of tea plants to climate change-associated abiotic stresses

Adaptive Strategies in Tea Cultivation

Climate change has been significantly affecting tea cultivation, ultimately hampering the livelihoods of farmers. The essential strategies (reported by Rajan *et al.*, 2024) aimed at mitigating the effect of climate change has been summarized in Table 1.

Table 1. Key adaptation strategies in tea cultivation

Strategy	Key Approaches	Main Benefits
Agricultural practices	Planting of shade trees, intercropping, mulching, agroforestry, soil and water management	To reduce heat and drought stress, to conserve moisture, to improve yield and quality
Genetic improvement	Climate-resilient cultivars, conventional breeding, marker-assisted selection, gene editing	Tolerance to heat, drought, frost, waterlogging, pests, and diseases

Pest and disease management	**Integrated Pest Management (IPM), biological control, cultural practices, targeted pesticide use**	**Pest and disease control while reducing chemical dependence**
Future innovations	Long-term climate studies, elevated CO_2 (FACE) experiments, advanced biotechnology	Development of effective climate adaptation strategies and resilient tea production

Adaptive Potential of Darjeeling Tea Clones under Changing Climate

Darjeeling exhibits a unique collection of elite tea clones that that can play a crucial role in enhancing climate resilience under changing environmental conditions. Among the released clones, RR17/144 (Rungli Rungliot 17/144) has consistently been recognized as one of the most drought-tolerant cultivars and is therefore considered an important genetic resource for cultivation under increasing water scarcity. In contrast, T78 (Tukdah 78) is valued for its high yield, vigorous growth, and comparatively better performance under moisture-limited conditions, while T383 has shown stable field performance and has been recommended for commercial cultivation in Darjeeling (Fig. 2). T78 and T383 have shown comparatively better tolerance to moisture stress and fluctuating temperatures, whereas AV2 (Ambari Valai 2) remains the benchmark clone for exceptional cup quality and aroma, although it is generally regarded as more sensitive to drought and other environmental stresses than RR17/144 (DTRC 1996-97; Hazra *et al.* 2021). The antioxidant traits of Darjeeling tea may serve as useful biochemical markers for identifying climate-resilient tea germplasm. Consequently, future breeding programmes should combine the superior beverage quality of clones such as AV2 with the drought resilience and stress-adaptive characteristics of clones like RR17/144 and T78 to develop cultivars capable of sustaining both productivity and premium quality under future climate scenarios.

Clone	Full Form	Key Strengths	Stress Tolerance	Special Value
AV2	AMBARI VALAI 2	• Exceptional cup quality and aroma	More sensitive to drought and other environmental stresses	Benchmark clone for premium quality
T78	TUKDAH - 78	• High yield • Vigorous growth • Performs well under moisture-limited conditions	Better tolerance to moisture stress and fluctuating temperatures	High yield and stress-adaptive clone
T383	TUKDAH - 383	• Stable field performance • Recommended for commercial cultivation	Better tolerance to moisture stress and fluctuating temperatures	Reliable and widely recommended for Darjeeling
RR17/144	Rungli Rungliot 17/144	• Consistently drought-tolerant • Important genetic resource	Most drought-tolerant among the clones	Key clone for cultivation under increasing water scarcity

Figure 2: Characteristics of four elite Darjeeling tea clones having climate-resilient potentials for sustaining productivity and quality

Conclusion

Climate change poses a major threat to sustainable tea cultivation, necessitating the adoption of climate-smart management practices, climate-resilient cultivars, and integrated pest management. Future research should focus on optimizing breeding techniques for developing climate-resilient tea varieties with ability to tolerate different stresses or a combination of stress factors (drought, heat and pests), that more accurately mimic real field environments. Additionally, investigations into sustainable pest management practices, improved soil health under climate stress, and the socio- economic impact of climate adaptation on tea farming communities will be critical to enhance tea resilience and ensure long-term productivity under changing climatic conditions.

Declarations

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Competing interests: The authors declare that they have no competing interests.

Declaration of Generative AI: During the preparation of this manuscript, the authors used ChatGPT-4 for the purpose of grammar clarity and preparation of Fig. 1. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the accuracy and integrity of the work.

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Popular Article

Carbon Management in Soil for Sustainable Agriculture

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Abstract

Indian soils are inherently low in organic carbon, ranging between 0.9 and 5.9 g kg^{-1}, owing to predominantly dryland farming, tropical climatic constraints and accelerated topsoil erosion. Soil organic carbon (SOC), constituting the largest terrestrial carbon reservoir, underpins soil fertility, aggregate stability, water-holding capacity, and microbial functioning, thereby determining agroecosystem resilience and productivity. Intensive tillage, monocropping, residue burning, and imbalanced fertilization have progressively depleted SOC stocks, exacerbating land degradation, nutrient mining, and greenhouse gas emissions. Consequently, soil carbon management (SCM) has emerged as a pivotal nature-based solution, integrating conservation agriculture, integrated nutrient management, cover cropping, agroforestry, and biochar application to restore carbon stocks and mitigate climate change. Global initiatives such as the "4 per 1000" programme, alongside Indian schemes including NMSA and PKVY, reinforce policy-driven carbon sequestration efforts. Consequently, holistic SCM strategies are imperative for safeguarding long-term soil health, ecological stability, and sustainable agricultural productivity.

Keywords: SOC, Soil health, Soil fertility, SCM, Sustainable agriculture

KEY HIGHLIGHT

- Carbon Sink: Soil holds ~2200 Pg of carbon, but intensive farming has depleted agricultural stocks by 30–70%.
- Soil Health: High organic carbon boosts fertility, water retention, microbial diversity, and crop resilience.
- Smart Practices: Combines conservation agriculture, cover cropping, agroforestry, and biochar application.
- Tech & Markets: Utilizes digital soil mapping, remote sensing, and carbon credit farming to financially reward farmers.
- Policy Action: Driven by global initiatives like "4 per 1000" and national programs like India's Soil Health Card.

1. Introduction

The levels of soil organic carbon (SOC) are considered as an indicator of soil fertility and directly affects the soil parameters which greatly influences its quality and functions (Kaith et al., 2023). Soil is the largest reservoir of carbon (C) in the world at an estimated 2200 Peta gram (Pg) with 1500 Pg being SOC. On the other hand, soil inorganic carbon (SIC) ranges between 700 and 1000 Pg (Lal, 2004). Indian soils are very low in the content of organic C ranging from 0.9 to 5.9 g kg-1 as a result of the specific climatic (69 % of dry land farming) and geographical conditions (higher top soil erosion) (Rai et al., 2009). Even small changes in the soil carbon stocks can significantly influences the concentration of atmospheric carbon dioxide (CO2), further impacting global climate change. Photosynthesis

by plants can transfer CO2 to the soil by roots, in addition other sources of C that soil may receive are crop residues, plant litters and root exudates (Batista-Silva et al., 2018). This continuous shift in the soil with change of carbon (Pandao et al., 2024) makes it a carbon source or a carbon sink depending on the land use and environmental changes.

Soil carbon changes with high intensity cultivation, over-till, combustion of residues, deforestation and imbalanced application of fertilizer are associated with reduction in soil productivity and increased in greenhouse gas (GHG) emissions. As awareness of the challenges of climate change, food insecurity and land degradation grow, carbon management is coming into its own as a focus in the field of sustainable agriculture. Soil carbon management (SCM) consideration is a land management approach which not only sequesters carbon in the soil but also aims to reduce its loss from the soil or increases the carbon stored in the soil. It is necessary because soil carbon improves fertility, structure, water retention and microbial activity, directly supporting crop yield and resilience. It links to sustainable agriculture by maintaining long-term soil health, reducing dependency on chemical inputs, mitigating climate change through carbon sequestration and ensuring ecological balance for future productivity (Meel et al., 2026). Therefore, SCM is one of the most potential nature-based solution (NBS) to be implemented for the environment and sustainable agricultural development.

2. Global Status of Soil Carbon

Numerous estimates of CO2 stocks of global soils have been published over the last 70 years to enable estimation of potential CO2 emissions from soil under land use and land cover change (LULCC) and climate change scenarios (Don et al., 2011). However, more recent studies have reported a global soil estimate of approximately 1417-1500 Gt C stored in 1 m depth, and 716 Gt organic C stored in the top 30 cm (Kochy et al., 2015). Estimates of SOC stocks below 1 m are less numerous, globally. Global SOC stocks in deeper soils (upto 3 m) are estimated at 2344-3000 Gt, which are generally depleted due to the high rate of organic matter degradation, low biomass production and high land use intensity. The Food and Agriculture Organization (FAO) estimates the amount of soil organic carbon to be around 1,500-2,400 Gt, depending on the depth of the soil sample. But this carbon is not evenly divided. Northern Europe, Canada, Alaska, Siberia and peatland ecosystems have the highest amounts of carbon stored, while pools of carbon in dry lands of Africa, Australia, Central Asia and parts of South Asia are relatively small (Fig.1). Soil carbon loss has been large in agricultural soils compared to natural soils which make them a significant target for C restoration and sequestration.

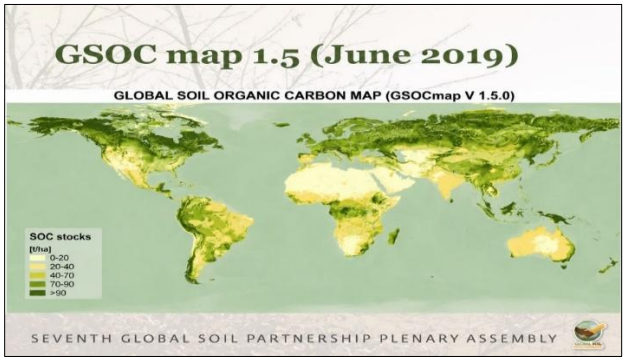


Figure 1: Global distribution of soil organic carbon stocks (GSOC map Version 1.5)

3. Source and Composition of Soil Organic Matter

The organic carbon comes from plants, animals, anthropogenic activities and microorganisms (Fig. 2). Dead organisms and waste products from

living ones undergo a degradation process to be converted to a stable carbon pool in the soil and microbes are the major drivers of carbon sequestration. The component parts of soil organic matter are presented in fig. 3. Mineralization of organic matter by microorganisms is a catalytic degradation of complex organic molecules (proteins, fat and carbohydrates) to an inorganic compound, which releases nutrients (N, P, S, K) that can be used by plants and microorganisms, and CO2 into air. This process can promote an increase in biomass production and carbon sequestration in plants and microbial biomass (Gan et al., 2020).

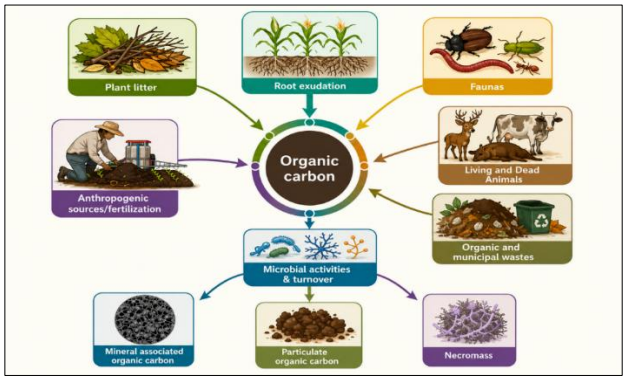


Figure 2: Conceptual diagram illustrating the various sources of soil organic matter and their transformation process into stable organic carbon pool

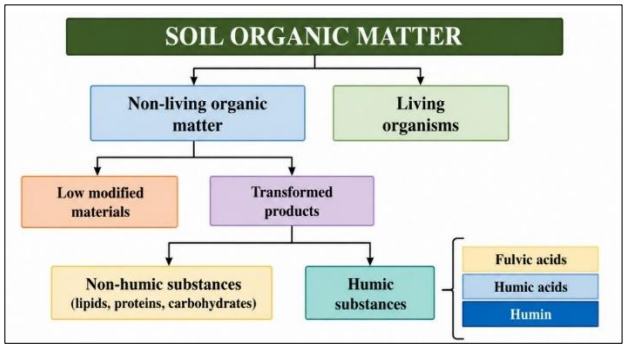


Figure 3: Principal components of soil organic matter (Source: FAO, 2005)

4. Importance of Soil Carbon in Sustainable Agriculture

a) Soil Fertility and Nutrient Cycling

Soil organic carbon (SOC) improves soil fertility by increasing nutrient availability, cation exchange capacity, and nutrient retention. It also supports microbial decomposition, ensuring a continuous supply of essential nutrients for plant growth (Saha et al., 2024; Lal, 2020).

b) Soil Structure and Erosion Control

SOC enhances soil aggregation, improves soil structure, and increases water infiltration while reducing surface runoff and soil erosion. Stable soil aggregates protect valuable topsoil from degradation and maintain long-term soil productivity (Blair et al., 1995; Saha et al., 2026).

c) Crop Productivity and Water Retention

Higher SOC improves soil water-holding capacity, aeration, and root development leading to better crop growth and increased yields, particularly under drought and other environmental stresses (Oldfield et al., 2019; Lal, 2020).

d) Soil Biodiversity and Ecosystem Functioning

Soil carbon serves as the primary energy source for microorganisms, earthworms, and other soil fauna. A carbon-rich soil supports diverse biological communities that enhance nutrient cycling, organic matter decomposition, and disease suppression (Lehmann & Kleber, 2015).

e) Climate Change Mitigation and Environmental Sustainability

Soil acts as a major terrestrial carbon sink by storing atmospheric CO_2 as organic carbon, thereby reducing greenhouse gas concentrations. Increasing SOC through sustainable land management contributes to climate change mitigation while improving ecosystem resilience (Lal, 2004).

Soil Carbon Depletion

Natural ecosystems keep carbon input and output in a dynamic balance. Unfortunately, this balance has been dramatically upset through the anthropogenic perturbation of ecosystems over the past one hundred years. The transformation of land use and land cover mostly through agricultural expansion and industrialization has led to an overall reduction of soil organic matter content across the major global crops and livestock systems (Sanderman et al., 2017). This reduction has an impact particularly on the nutrient retention and cycling processes of agricultural systems causing a reduced productivity (Oldfield et al., 2019) besides being one of the causes for rising atmosphere concentrations of greenhouse gases (Lal, 2015).

It is found by researchers that agricultural activities cause loss of soil organic carbon of between 30 to 70 percent depending on soil type, climate and management. Per Herrick et al. (2013), a considerable decrease in SOC and deterioration in the soil structure might very easily lead to "edaphic droughts" which may persist under ordinary or "normal" growing (i. e. precipitation) conditions. The presence of heavy metals in soil also inhibited organic matter decomposition through chelate formation, as pollutants kill helpful bacteria, decomposition is delayed (Tamang et al., 2026).

5. Need for Management of C in soil

Soil carbon mainly SOC, governs soil fertility, structure, water-holding capacity and microbial activity. Managing soil C is essential because it directly influences crop productivity, nutrient cycling, and soil aggregation, reducing erosion risk. Declining SOC due to intensive tillage, monocropping, and residue removal leads to soil degradation and reduced resilience to climate stress. Proper C management (through organic amendments, conservation tillage, cover cropping) enhances carbon sequestration, mitigating atmospheric CO_2 and climate change, while sustaining long-term soil health and agricultural productivity (Lal, 2004).

6. Global and Indian Initiatives for Soil Carbon Management

The growing recognition of soil carbon's numerous potentials has sparked several international initiatives. The "4 per 1000 Initiative: Soils for Food Security and Climate" is arguably one of them - a very prominent one initiated by France at the COP21 in 2015. It aimed at increasing soil organic carbon worldwide by 0.4% every year which could not just compensate a significant portion of greenhouse gas emissions but also lead to food security through agriculture and raise agricultural productivity (Jean-Francois et al., 2019). Australia has launched soil carbon projects under its Emissions Reduction Fund (ERA) being first to do so, with farmers earning rewards for employing methods that boost the level of soil carbon (White, 2022). The USA encourages farmers to conserve by using cover crops, not disturbing the soil (conservation tillage) and carbon farming (carbon sequestration activities, etc.) mainly through USDA conservation programs. The European Union has introduced carbon farming in their strategy for a European Green Deal and in the policy structure that governs farming. But, by adopting conservation agriculture techniques and integrating the activities of crops, livestock and forestry, Brazil has a lot of success from carbon farming. To enhance global soil management efforts, technical guidelines for and policy structures around sustainable soil management have been formulated by various organisations like the Food and Agriculture Organization (FAO), Intergovernmental Panel on Climate Change (IPCC), Global Soil Partnership (GSP) and United

Nations Convention to Combat Desertification (UNCCD).

India has recognized the soil carbon as a component of long-term agriculture sustainability. But, about two-thirds of agricultural soils in India have low soil organic carbon mainly due to tropical climatic conditions, continuous intensive cultivation, removal of residues, and nutrient mining. Several national programs have been put forward to deal with these situations, namely National Mission for Sustainable Agriculture (NMSA), Soil Health Card Scheme, Paramparagat Krishi Vikas Yojana (PKVY) and National Innovations on Climate Resilient Agriculture (NICRA). These initiatives aim at conservation agriculture, integrated nutrient management, residue recycling, organic farming, agroforestry and balanced fertilizer use for improving soil health. Latest trends in carbon markets and Green Credit Programme once again shows the Indian commitment for soil carbon sequestration as part of climate-resilient agricultural development. (Qayum, 2025).

7. Strategies and Practices for Soil Carbon Management

To build more carbon in soil, we have to focus management strategies, that not only bring more carbon into the soil, but also reduce the loss of already existing carbon in the soils, together. Such practices must be tailored to the type of soil, local weather, cropping system and the socio-economic situation of the communities to ensure their sustainability over a long period of time.

A. Agronomic Practices

a. Conservation Agriculture

Conservation agriculture (CA) is one of the most effective approaches for improving soil carbon. It is based on three core principles that include minimum soil disturbance, permanent soil cover and diversified crop rotations. The amount of carbon input also has a significant effect on the increase of SOC through CA. It is evident that the type of crop, the level and length of cropping also influence the carbon input into the soil (Nayak et al., 2022). The use of deep-rooted plants with high above and below-ground biomass and increased number of crops per year could improve the capacity of CA to store carbon (Palm et al., 2014). The effects of the components of CA applied singly and together on SOC in tropical agro-ecosystems show that the rate of increase in SOC ranged from 0.16 to 1.01 t ha-1 yr-1 which only contributed to a minor extent to carbon mitigation (Powlson et al., 2016).

b. Organic Amendments and Integrated Nutrient Management

Most organic amendments serve as a source of beneficial microbes, nutrients and carbon for replenishing soil carbon stock and enhancing soil biological and biochemical processes (Fig.5) (Enebe et al., 2025). For instance, the addition of farmyard manure in a rice-wheat cropping system has been reported by Duxbury (2001) to promote the accumulation of SOC in the ranges of 0.08 to 0.98 Mg C ha−1. Integrated nutrient management (INM) helps to reduce reliance on synthetic chemical fertilizers and enhances soil health, especially SOC (Das et al., 2014). Long-term INM in the rice-wheat system has been shown to increase soil organic matter (Brar et al., 2013), influence labile and non-labile C (Chaudhary et al., 2017). Thus, INM impacts biogenic emissions of CH_4 and N_2O by changing the pattern of C mineralization and denitrification rates (Kaur et al., 2025).

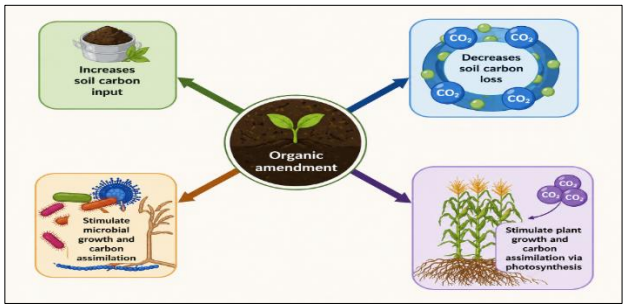


Figure 5: Contributions of organic amendment in soil carbon sequestration (Source: Enebe et al., 2025)

c. Cover Cropping and Crop Diversification

Cover cropping practice has been identified as an efficient management strategy that increases the amount of C stored in the soil through higher C inputs than those achieved with no cover cropping (Sainju et al., 2007). The C sequestration rate, however, depends on cover crop species, with nonlegumes having higher rates than legumes due to larger C/N ratios. According to a recent meta-analysis, SOC increased globally by 16 % with cover crops compared to no cover crop (Jian et al., 2020), with a C sequestration rate of 167 kg C ha−1 yr−1 (Poeplau and Don, 2015). Crop diversification (CD), which involves utilising rotation, intercropping, and multiple cropping techniques that helps in mitigating SOC losses and enhancing soil carbon sequestration (Hufnagel et al., 2020).

d. Agroforestry System

Agroforestry can be defined as a land use concept which implies integration of trees into the agricultural system. This practice allows for increasing carbon stocks both above and below ground. These systems enhance this to 50–75 t C ha−1 (Zomer et al., 2016). Agroforestry system is one of such beneficial land use systems that are known for more C sequestration potential than pastures and annual cropping systems (Fig.6). The change in carbon stocks of the soils through agroforestry is determined by the number of tree species, their density and climate but generally it is between changes for agricultural and natural forest systems. (Chatterjee et al., 2018). Deep-rooted trees recycle nutrients from deeper soil layers, reduce erosion, and enhance litter deposition, thereby increasing SOC. The agroforestry system has the potential to store 5.3 Gt C in 944 Mha with higher potential in tropical and sub-tropical regions around the globe (Shi et al., 2018).

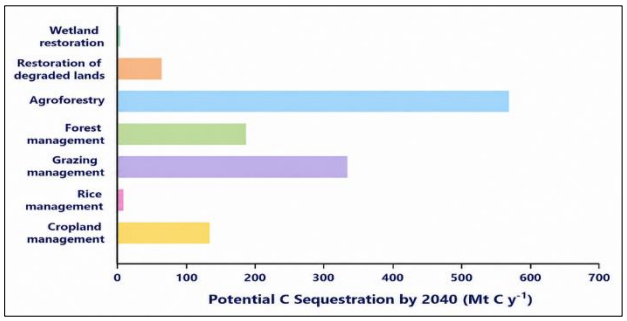


Figure 6: The potential of carbon sequestration through various land use systems and management options (Source: IPCC, 2000)

e. Biochar Application

Biochar is produced by complete carbonization of organic matter through pyrolysis (or other processes), thus transforming it into a carbon-based polymer resistant to further decomposition. The half-life of biochar in the soil can range from several hundred to several thousand years, depending on the conditions of its formation (Lehmann, 2007). It is able to retain about 50% of the initial C, while burning or decomposition can only retain about 3% and 10-20%, respectively (El-Naggar et al., 2018). Biochar acts as both a source and sink of C in the soil. It is evident from research that biochar treated plot has ability to sequester more carbon as compare to non-biochar treated plot (Blanco-Canqui et al., 2022). It is estimated that biochar can offset 12% of the annual net anthropogenic emissions of CO2 (Woolf et al., 2010). The mitigation potential for CO2 at a global scale by

using biochar through existing pyrolysis plants was estimated to be 6.6 Mt C yr-1 and a net revenue of $177 million at a carbon price of $50 t-1 CO2 (Han et al., 2021) (Fig. 7).

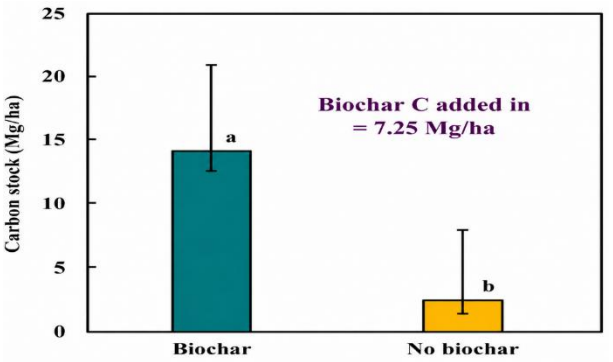


Figure 7: Comparison in Biochar and Non-biochar on Soil C stock (Source: Blanco-Canqui et al., 2022)

B. Technological Approaches

a. Digital Soil Mapping and Remote Sensing

Technological advances in GIS, remote sensing, and big data analytics have been crucial in refining digital SOC maps by integrating various environmental covariates such as topography, vegetation indices, and climatic factors (Jin et al., 2017). In more than the last two decades, a lot of novel algorithms and techniques based on machine learning and deep learning have been used to improve digital soil and SOC mapping and prediction instead of traditional geostatistical approaches (Odebiri et al., 2021).

b. Carbon Credit Farming

Carbon farming aims to reduce atmospheric CO2 levels by encouraging enhanced carbon storage in soils and biomass. Hence, a carbon credit is a proof that a state or an organization has made a payment for the reduction of carbon dioxide from the atmosphere (Saini and Verma, 2024). According to Kaisto, carbon credits are licenses that give the right to the owner to emit a particular amount of CO2 or other greenhouse gases. (GHGs).

C. Carbon Management Index (CMI)

The carbon management index (CMI) can be used to monitor the soil over time and it also tells whether a new system or practice is declining or rehabilitating the soil (Sodhi et al., 2009). The CMI was estimated using the following formulas (Blair et al., 1995):

$$\text{Carbon Pool Index (CPI)} = \frac{\text{Sample total carbon (mg kg}^{-1})}{\text{Reference total carbon (mg kg}^{-1})} \quad \text{..... Eq. 1}$$

$$\text{Lability of Carbon (L)} = \frac{\text{Carbon in fraction oxidized by KMnO4}}{\text{Carbon remaining unoxidized by KMnO4}} \quad \text{..... Eq. 2}$$

$$\text{Lability Index (LI)} = \frac{\text{Lability of carbon in sample soil}}{\text{Lability of carbon in reference soil}} \quad \text{..... Eq. 3}$$

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100 \quad \text{..... Eq. 4}$$

8. Future Prospects

The direction of managing soil carbon lies in the combination of scientific development, sustainable practices in agriculture and backing from different levels of policy. Climate change and land degradation are driving global food production to a point where environmental sustainability is as important as productivity. Climate-smart agriculture, regenerative agriculture and carbon farming are new methods to boost soil carbon and at the same time reduce greenhouse gas emissions. Knowledge in soil microbiome, recent technological developments in molecular biology and artificial intelligence, plus remote sensing and digital soil mapping provide an enhanced insight into and a better monitoring of soil carbon dynamics. To provide financial incentives for farmers adopting carbon-sequestering practices, carbon markets and payment for ecosystem services are a good tool. In a country like India, future strategies should concentrate on making farmers more aware, increasing the quality of extension services, encouraging recycling of crop residues, pushing expansion of conservation agriculture and promoting the development of public-private

partnerships for carbon farming. Higher funding on research and development, better policies and training programs to harness the potential of soil carbon management in sustainable agriculture and climate change mitigation.

9. Conclusion

Managing soil carbon is one of the important nature-based solutions that supports the improvement of soil health, mitigation of climate change and sustainable food production. Soil is the largest terrestrial carbon reservoir, as well as moderating global carbon cycling and harnessing agricultural productivity and maintaining ecosystems. Intense cultivation, deforestation, erosion and digging of the soil, burning of residues and unsustainable land use, had led to a depletion in soil organic carbon, which affects soil productivity and its contribution of greenhouse gas emissions. The implementation of sustainable farming techniques like conservation agriculture, sustainable nutrient management, cover cropping, agroforestry, retention of crop residues and wastes, organic amendment, biochar application and precision agriculture can act to restore soil carbon, improve the cycling of nutrients in soils, water-holding capacity, biodiversity and crop resilience. Scientific and technological innovations, along with good governing policies and farmers' involvement are key to achieving long-term climate resilience, soil health and food security through soil carbon management and improvement at both globally and local level in line with national and global initiatives.

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Next-Generation IPM Strategies for Climate-Resilient Agriculture

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Abstract

Climate change is one of the greatest threats to agricultural productivity worldwide, affecting greatly the incidence, distribution and severity of insect pests, plant diseases and weeds. Rising temperatures, unpredictable rainfall, elevated atmospheric carbon dioxide concentrations, and frequent extreme weather events have accelerated pest development, expanded the geographical distribution of invasive species, and increased the frequency of pest outbreaks. These changes have challenged the effectiveness of conventional Integrated Pest Management (IPM) strategies, which were developed under relatively stable climatic conditions. Consequently, there is an urgent need to transform traditional IPM into a more adaptive, technology-driven, and climate-responsive system. Next-generation IPM integrates advances in artificial intelligence, precision agriculture, remote sensing, unmanned aerial vehicles, Internet of Things (IoT), molecular biology, climate forecasting, and ecological engineering with conventional IPM principles. This integrated approach facilitates early pest detection, real-time monitoring, predictive analytics, and targeted interventions while reducing pesticide dependence and conserving ecosystem services. The present article discusses the impact of climate change on pest dynamics, emerging technologies that are reshaping pest management, ecological innovations for enhancing agricultural resilience, and future directions for developing sustainable crop protection systems under changing climatic conditions.

Keywords: Climate change, IPM, Artificial Intelligence, Precision Agriculture

KEY HIGHLIGHT

- 🌡️ Climate change is shifting pest distribution, outbreaks and crop losses.
- 🤖 AI, IoT and remote sensing enable early detection and predictive pest management.
- 🎯 Precision technologies support targeted interventions and reduce pesticide use.
- 🧬 RNAi and gene editing offer precise, sustainable pest-control solutions.
- 🌿 Ecological engineering and biocontrol strengthen natural pest regulation.
- 🚜 Farmer capacity and digital access are crucial for scaling NG-IPM.

Introduction

There is an intrinsic dependence of agriculture on climatic conditions and even small changes in environmental factors substantially influence in crop production and insect pest dynamics. There has been a significant temperature increase in the global climate during the last century which correlated with changes in other climatic parameters such as rainfall patterns, humidity, the amount of carbon dioxide in the atmosphere, and occurrence of extreme climatic events like droughts, floods, cyclones, and heat waves. These climatic changes have led to the enhancement of many arthropod insect pest, plant pathogenic microorganisms, and invasive species, while many pest control techniques have become less effective. Since insects are poikilothermic, climate change significantly influences their survival, reproduction, dispersal, voltinism, and geographical distribution.

Integrated Pest Management (IPM) is one of the most sustainable approaches for managing agricultural pests. Conventional IPM emphasizes ecological balance with minimising pesticide applications, thereby protecting beneficial organisms and reducing environmental contamination. However, the rapidly changing climate has introduced new challenges that conventional IPM alone cannot adequately address. Increasing pest invasions, pesticide resistance, shifting pest paradigm and unpredictable weather conditions require more intelligent, adaptive and data-driven pest management systems. Consequently, the concept of Next-Generation Integrated Pest Management (NG-IPM) has emerged, integrating modern digital technologies, molecular tools, ecological engineering, and predictive analytics into traditional IPM frameworks to improve agricultural resilience and sustainability.

Climate Change and Changing Pest Dynamics

Climate change affects pests through multiple interacting mechanisms that influence their biology, ecology, and interactions with crops and natural enemies. Rising temperatures increase insect metabolism, shorten developmental period, accelerate fecundity and often allow insects to produce more generations. Many economically important pests are becoming more abundant and causing greater crop losses than previously observed. Furthermore, warmer winters enhance the overwintering survival of many insects, enabling them to establish permanent populations in regions where they were previously unable to survive.

Changes in precipitation patterns also play a key role in pest dynamics. Irregular rainfall, prolonged droughts and excessive moisture influence both pest and natural populations. While heavy rainfall may suppress certain soft bodied insects through direct mortality, it may simultaneously promote outbreaks of fungal and bacterial diseases by creating highly humid microclimates. Conversely, drought stress often weakens plant defense mechanisms, making crops more susceptible to insect feeding and pathogen infection.

Elevated atmospheric carbon dioxide further complicates pest management by altering plant physiology. Increased carbon dioxide generally enhances photosynthesis but also changes the carbon-to-nitrogen ratio of plant tissues, reducing their nutritional quality for herbivorous insects. Consequently, many chewing insects compensate by consuming greater amounts of foliage, leading to increased crop damage despite lower nutritional content. Moreover, climate change has facilitated the expansion of invasive pests into previously unsuitable habitats. Species such as the fall armyworm, whiteflies, aphids, and brown planthopper have expanded their geographical ranges considerably, threatening agricultural production across diverse agroecosystems. These complex interactions underscore the necessity of developing climate-resilient pest management strategies capable of responding to continuously changing environmental conditions.

Evolution of Next-Generation Integrated Pest Management

The evolution of Next-Generation Integrated Pest Management represents a paradigm shift from reactive pest control to proactive, predictive, and precision-based crop protection. Unlike conventional IPM, which primarily depends on periodic field scouting and fixed economic threshold levels, NG-IPM utilizes continuous monitoring systems, advanced computational models, and real-time environmental information to support timely decision-making. Various apps that integrate the digital technologies enables farmers to detect pest infestations before economic damage occurs and to implement site-specific

interventions that minimize pesticide use while maximizing control efficiency.

NG-IPM also aims towards ecological sustainability; however, it incorporates technological innovations that will significantly improve surveillance, forecasting, diagnostics and management. Artificial intelligence, Internet of Things (IoT), precision agriculture, remote sensing, genomic tools and climate forecasting collectively provide an intelligent framework for adaptive pest management under rapidly changing climatic conditions.

Artificial Intelligence and Digital Technologies in Pest Management

Artificial intelligence became one of the most transformative technologies in modern agriculture. Machine learning algorithms and deep learning models that are capable of identifying insect pests and plant diseases by analyzing images captured through smartphones, drones or automated field cameras. These intelligent systems distinguish between healthy and infested plants, estimate pest population densities and generate recommendations for suitable management strategies. AI-powered decision-support systems integrate information from weather stations, pest monitoring networks, previous outbreak records, and crop growth models to forecast pest outbreaks and optimize control measures.

The Internet of Things has further revolutionized pest surveillance by enabling continuous monitoring of environmental conditions using interconnected sensors deployed throughout agricultural fields. These sensors record temperature, humidity, soil moisture, leaf wetness, wind speed and insect trap catches in real time, transmitting data to cloud-based platforms for analysis. Such continuous monitoring allows early detection of conditions favourable for pest development and facilitates timely implementation of preventive measures.

Precision agriculture complements these technologies by enabling site-specific pest management. Global Positioning Systems (GPS), Geographic Information Systems (GIS), automated sprayers and variable-rate application technologies allow pesticides to be applied only where needed, substantially reducing chemical inputs, production costs, and environmental contamination. Unmanned aerial vehicles equipped with multispectral and thermal cameras provide rapid assessments of crop health, enabling early detection of stress associated with insect feeding before visible symptoms become apparent.

Remote Sensing and Climate-Based Pest Forecasting

Remote sensing technologies have become indispensable components of climate-smart agriculture. Satellite imagery, drone-based sensors, and multispectral imaging systems provide detailed information on vegetation health, chlorophyll content, canopy temperature, and crop water status. These indicators help identify areas experiencing pest-induced stress at very early stages, allowing farmers to implement localized interventions before infestations spread extensively.

Climate-based forecasting models further enhance pest management by integrating meteorological variables such as temperature, rainfall, relative humidity, solar radiation, and wind speed with pest developmental models. Degree-day accumulation models, ecological niche modeling, and species distribution models predict pest emergence, migration, and population growth with increasing precision. These forecasting systems provide valuable early warning alerts that enable farmers to shift from reactive pesticide applications toward preventive management strategies.

Molecular Innovations in Next-Generation IPM

Advances in molecular biology have introduced highly precise pest management tools that complement ecological approaches. RNA interference (RNAi) technology represents one of the most promising innovations in sustainable pest management. By introducing double-stranded RNA molecules that silence essential insect genes, RNAi selectively disrupts critical physiological processes, leading to pest mortality while minimizing impacts on beneficial organisms and the surrounding environment. Because RNAi targets species-specific genetic sequences, it offers remarkable specificity compared with broad-spectrum chemical insecticides.

Similarly, CRISPR-Cas gene-editing technology has opened new possibilities for developing insect-resistant crop varieties, suppressing pest reproduction, interrupting pathogen transmission, and enhancing the efficiency of biological control agents. Molecular diagnostic techniques based on DNA barcoding, polymerase chain reaction (PCR), and next-generation sequencing facilitate rapid identification of invasive pests, cryptic species, pesticide resistance genes, and emerging plant pathogens, thereby improving surveillance and biosecurity.

Ecological Engineering and Biological Innovations

Despite remarkable technological advancements, ecological principles remain fundamental to climate-resilient IPM. Ecological engineering seeks to manipulate agricultural ecosystems in ways that enhance biodiversity and strengthen natural pest regulation. Diversified cropping systems, intercropping, trap cropping, flowering strips, cover crops, hedgerows, and agroforestry systems create habitats that support predators, parasitoids, pollinators, and other beneficial organisms. These ecological interventions reduce pest colonization, improve biological control, and increase overall ecosystem stability.

Biological control continues to play a central role in NG-IPM through the use of microbial biopesticides such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and entomopathogenic nematodes. These biological agents provide environmentally friendly alternatives to synthetic pesticides while minimizing risks to non-target organisms. Recent research has also highlighted the importance of insect microbiomes in influencing pest physiology, immunity, and pathogen transmission, opening new avenues for microbiome-based pest management strategies.

Challenges and Future Perspectives

Although Next-Generation IPM offers tremendous opportunities for sustainable agriculture, several challenges hinder its widespread adoption. High initial investment costs, limited digital infrastructure, inadequate technical expertise, and poor accessibility for smallholder farmers remain significant barriers, particularly in developing countries. Regulatory frameworks governing RNAi technologies, gene editing, and novel biological products also require further refinement to ensure safe and responsible deployment. Moreover, climate uncertainty continues to influence the reliability of predictive models, emphasizing the need for continuous model validation and adaptive management.

Future research should focus on integrating artificial intelligence, climate forecasting, genomic technologies, autonomous robotic systems, biosensors, and ecological engineering into comprehensive decision-support platforms. Greater collaboration among entomologists, agronomists, climatologists, computer scientists, engineers, economists, and policymakers will be essential for developing scalable and farmer-friendly IPM solutions. Capacity building, digital literacy, and

supportive public policies will also play crucial roles in facilitating the adoption of climate-smart pest management technologies.

Conclusion

Climate change is transforming agricultural pest dynamics at an unprecedented rate, threatening global food security and challenging the effectiveness of conventional pest management approaches. Next-Generation Integrated Pest Management represents a major advancement in sustainable crop protection by combining ecological principles with emerging technologies such as artificial intelligence, precision agriculture, remote sensing, Internet of Things, molecular biology, climate forecasting, and ecological engineering. These integrated approaches enable earlier pest detection, more accurate forecasting, targeted interventions, and reduced reliance on synthetic pesticides while conserving biodiversity and ecosystem services. As agriculture continues to confront increasingly complex climatic challenges, the successful implementation of NG-IPM will depend on interdisciplinary research, technological innovation, farmer participation, and supportive policy frameworks. By embracing these innovations, climate-resilient agriculture can achieve enhanced productivity, environmental sustainability, and long-term food security.

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Climate Smart Villages: Bridging Science and Farming Communities

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Abstract

As climate change increasingly threatens global food security and smallholder livelihoods through erratic weather and environmental degradation, Climate-Smart Agriculture (CSA) has emerged to simultaneously improve productivity, adaptation, and emission mitigation. To translate these goals into local action, the Climate-Smart Village (CSV) approach serves as a practical model that combines location-specific technologies, institutional services, and community participation. This article examines the concept, significance of CSVs, and also analyses the role of agricultural extension as the critical bridge between research, policy, and farmers. Extension systems are essential for climate literacy, technology dissemination, participatory planning, risk communication, and institutional strengthening. They also support capacity building, climate information delivery, and stakeholder coordination at the grassroots level. It can be concluded that the success of CSV depends not merely on technological innovation, but on strong advisory systems, inclusive local institutions, convergence with public programs, and context-specific implementation models. Thus, effective extension services enhance farmer participation, strengthen adaptive capacity, and facilitate the scaling of climate-resilient practices across diverse agricultural systems.

Keywords: Climate smart village, climate resilience, extension role, challenges

KEY HIGHLIGHT

- Climate-Smart Villages integrate technologies, climate information and community participation for resilient agriculture.
- Extension services connect climate science with farmers.
- Climate information enables timely farm decisions and risk management.
- Participatory institutions promote inclusive, locally relevant solutions.
- Scaling requires finance, digital connectivity and institutional convergence.

Introduction

Global agriculture is increasingly jeopardized by the accelerating pace of climate change. Climatic disruptions such as rising temperatures, erratic rainfall, frequent droughts, flooding, and pest surges are actively undermining agricultural yields and rural livelihoods of smallholder farmers in developing economies like India. Climate change projections using computer simulation modelling revealed that in the absence of adoption of adaptation measures will reduce rainfed rice yields by 20% in 2050 and 47% in 2080 scenarios while, irrigated rice yields by 3.5% in 2050 and 5% in 2080 scenarios, wheat yield by 19.3% in 2050 and 40% in 2080 scenarios. As per Intergovernmental Panel on Climate Change (IPCC) protocols, ICAR-NICRA assessed risk and vulnerability 651 agricultural districts and identified 310 districts as vulnerable out of which 109 districts were categorized as 'very highly' and 201 districts as 'highly' vulnerable (PIB, 2024).

The Hague Conference on Agriculture, Food Security, and Climate Change in 2010 gave

the concept of Climate-Smart Agriculture (CSA) for transforming agricultural systems under climate stress. CSA aimed to increase agricultural productivity to support increased incomes, food security by increasing adaptive capacity at multiple levels (from farm to nation); and reducing greenhouse gas emissions (Campbell *et al.,* 2014). To support the farmers in adopting climate resilient agriculture practices ICAR has launched National Innovations in Climate Resilient Agriculture (NICRA) project in 2011 to implement customized technological solutions based on the principles of Climate Smart Extension (CSE) i.e., adaptation, mitigation, innovation, knowledge sharing and contextualization. To manage and recover from climate risks, communities must be mobilized and empowered in the decision-making process. Under National Innovations in Climate Resilient Agriculture (NICRA) project of ICAR, different interventions were planned under four modules, i.e. natural resource management, crop production, livestock and fisheries, and institutional interventions. Specific interventions under each module for a particular village were need based and decided based on climatic vulnerability and resource situation of that village. On global level, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) in collaboration with national programmes, launched climate-smart villages (CSV) as models of local actions in 2011 with 15 climate-smart villages in West Africa, East Africa and South Asia including Haryana, Bihar, Punjab, Andra Pradesh and Karnataka (India) (CCAFS, 2015).

Government programmes like National Mission for Sustainable Agriculture (NMSA) also implemented to deal with the impact of climate change on agriculture. NMSA has three major components i.e. Rainfed Area Development (RAD); On Farm Water Management (OFWM); and Soil Health Management (SHM). Various programmes such as Soil Health Card (SHC), Paramparagat Krishi Vikas Yojana (PKVY), Mission Organic Value Chain Development in North Eastern Region (MOVCDNER), Per Drop More Crop, National Bamboo Mission (NBM) etc. were subsequently implemented to make Indian agriculture more productive, sustainable, and climate resilient.

Concept Of Climate Smart Villages

The CSV approach is a key part of the agriculture research-for-development (AR4D) agenda to address climate change challenges for food security. The Climate-Smart Village (CSV) approach is a participatory research strategy testing local technological and institutional solutions for climate change in agriculture. Utilizing multi-stakeholder platforms, it generates location-specific portfolios that boost farm productivity, build climate resilience, and reduce greenhouse emissions. it seeks to analyse socioeconomic and gender-related constraints to technology adoption while providing scalable evidence aligned with national development plans (Aggarwal et al, 2018).

Key components in a Climate-Smart Village

1.Climate smart technology
2. Climate smart information services
3. Village development plan
4. Local knowledge and institutions

Climate-smart village approach implementation

The implementation of Climate-Smart Villages follows a cyclical four-step process comprising baseline assessment, portfolio design, evidence generation, and scaling. This framework integrates climate risk assessment, participatory technology selection, empirical validation, and policy engagement to facilitate the adoption and scaling of climate-smart interventions across farming systems (Aggarwal *et al*., 2018; Westermann *et al*., 2018).

- **Site selection and Baseline assessment:** Climate-Smart Village is selected based on

- its climate risk profile, alternate land use options, and on the willingness of farmers and local government to participate in the project. Baseline assessment Identifies local climate risks, vulnerabilities, natural and socioeconomic resources, institutional capacities, and gender division of labour.
- **Participatory prioritization of interventions** with farmers and local stakeholders to prioritize and test which climate smart technologies and approaches are best suited to their local conditions. Focus group discussions involve farmers in a choice experiment using dummy money to indicate which actions they would most willingly carry out (Kumar & Jangir, 2017).
- **Portfolio design:** Develops context-specific portfolios across weather, water, seed, carbon, and market-smart domains via multi-stakeholder group discussions
- **Farmer categorization** or targeting for demonstration and diffusion
- **Capacity building** for local staff, NGOs, and community groups
- **Evidence generation**: Tests interventions on collaborative research platforms (including CGIAR, national agricultural research systems, NGOs, and private-sector players, farmers and their institutions) to evaluate institutional benefits, synergies, and trade-offs of technologies from both individual demographic perspectives—including men, women, and youth—and the aggregate community landscape using surveys, demonstration plots, farmer group evaluations, ICT-based feedback tools and modelling
- **Institutional mechanisms** such as village committees, custom hiring centres, and cattle development centres
- **Scaling Up:** Drives horizontal expansion promoting local adoption through farmer-to-farmer learning networks, local government plans and vertical integration into large-scale agricultural investments and national development policies.

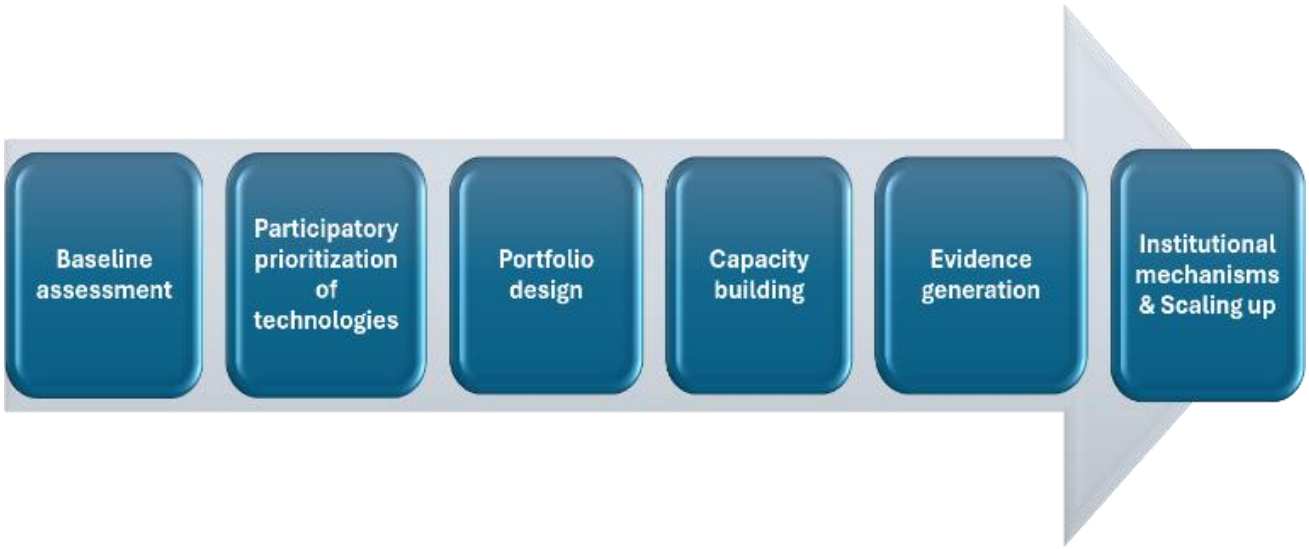


Figure1: Steps in implementing climate smart village model

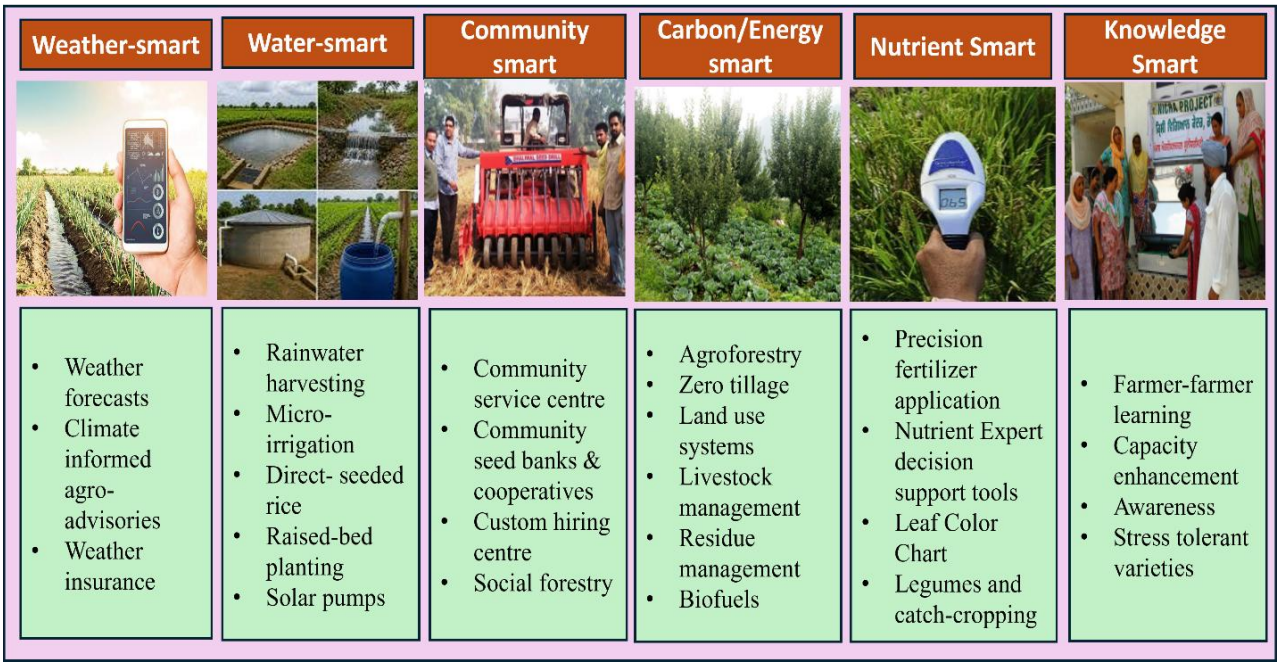


Figure 2: CSV Portfolio design

Role Of Agricultural Extension Systems

Climate Smart Villages (CSV) are being established and managed by the Village Climate Resilience Management Committee (VCRMC). Agricultural extension services are critical in driving the adoption of climate-smart agriculture. Extension contacts, frequency of farm visits, and access to localized climate information significantly increase a smallholder farmer's capacity to adapt to changing weather patterns.

1. Climate literacy and awareness building

Many farmers are aware that weather patterns are changing, but they may not distinguish between seasonal fluctuations and long-term climate trends. Climate awareness programmes were used to sensitise people about climate change, its consequences and effects on farming.

2. Technology dissemination and capacity building

CSA often involves practices that require new knowledge - such as precision nutrient management, raised bed planting, direct seeded rice, agroforestry design, alternate wetting and drying, or irrigation scheduling. Dissemination of appropriate climate resilient technology (such as portable soil testing kits, farm mechanization equipment for small holdings, grain storage bags, improved crop varieties etc.), irrigation management were carried out by extension agents. Extension provides demonstrations, training, and on-field troubleshooting that make these practices adoptable.

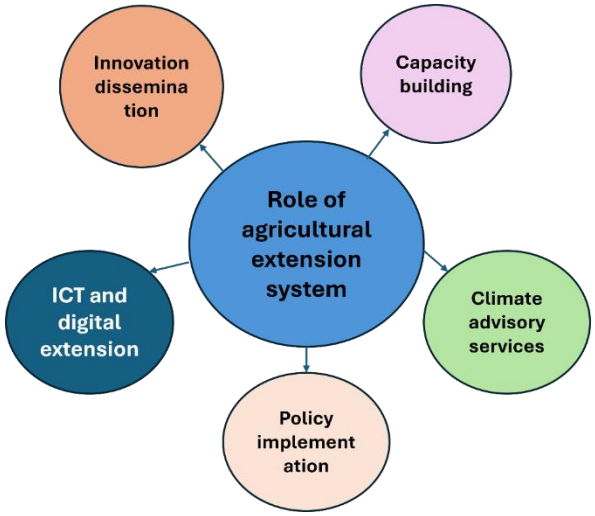


Figure 3: Role of agricultural extension system

3. Delivery of climate information services

Weather-based agro-advisories are among the most scalable CSA tools. Extension systems help farmers use forecasts to decision inputs: when to sow, whether to irrigate, which crop to select, whether to apply fertilizer, or how to manage pest risk. Jaldoot - community level extension professional acts as a local extension worker who has knowledge on all water related activities to help the farmers in different activities involved in water budgeting, construction of water ponds, bore wells, etc. Community Based Disaster Management (CBDM) approach used to build capacity of communities to reduce the impacts and to cope with disasters more effectively. Under this Disaster Risk Reduction (DDR), map of a village was prepared under which the points or places of the villages which are sensitive to climatic disaster were identified and then trainings conducted for the villagers (Rupan *et al*., 2018).

4. Strengthening local institutions

Village Climate Management Committees, farmer groups, women's organizations, custom hiring centres, seed banks, and producer groups all need facilitation. Extension often plays the convening and strengthening role, especially in linking communities with government schemes and private services.

5. Inclusion of women, youth, and marginal farmers and policy design

Adoption barriers are not uniform. Women farmers often face weaker access to land titles, credit, advisory services, and mechanization. Marginal farmers may lack liquidity for even low-cost innovations. Extension captures farmer experiences, barriers, local innovations, and unintended consequences. Feedback is used for adaptive research and for improving policy design.

Examples Of Climate Smart Villages

1. Dabri and Kaleth villages of Tehri Garhwal district of Uttarakhand under ATARI Zone 1

KVK has organized more than 100 capacity building programmes on climate resilient technologies benefited about 2765 farmers. The farmers of villages were earlier facing climatic vulnerabilities due to cold wave, frost during winter and water stress during summer. Water harvesting tanks have been constructed which harvest about 150,000 litres of water being used for irrigating crops. There was increase in command area from 2.0 ha to 3.5 ha by using water harvesting tanks constructed under this project. The demonstrations on drought tolerant crop varieties such as Pant Ranichauri Jhangora (PRJ-1) of Barnyard millet, Pant Ranichauri Mandua (PRM-1) and VL Mandua 324, VL Arhar-1 and Pant Arhar-291 etc. were organized to sustain yields under drought situations. Twenty polyhouses were constructed at the farmers' fields to mitigate cold wave effect, production of off-season vegetables and nursery raising of vegetable crops. The intervention has resulted into increasing the net income of farmers up to Rs. 10000- 15000/ per annum. Animal health camps were regularly organized at the village level for general health check-ups, vaccination and deworming of all domestic animals. Various farm machineries such as power tiller, power weeder and wheat, paddy and mandua thresher were made available to the farmers at reasonable rated on Custom Hiring Basis (Singh *et al*., 2021).

2. Said-Sohal village of Kathua, Jammu & Kashmir- under ATARI Zone 1

Erratic rainfall and recurrent droughts were the major climate-related challenges affecting farmers in the region. Under NICRA project, Krishi Vigyan Kendra Kathua demonstrated the effectiveness of climate resilient agricultural practices in the farmer's field for wider adoption. Improved irrigation potential with

rain water harvesting tanks, promoting in-situ soil moisture conservation measures like ploughing across the slope, deep summer ploughing and minimum tillage in more than 70 ha and adoption of short duration varieties have led to increase in the cropping intensity from 168% to 240%. The introduction of short-duration paddy varieties, namely NDR-97 (coarse rice) and PB-1509 (basmati rice), contributed substantially to higher farm incomes by enabling timely cultivation and reducing climate-related production risks. In the livestock sector, the use of mineral mixtures and Urea Molasses Mineral Blocks (UMMB) was promoted to address nutritional deficiencies, leading to adoption by over 20% of the village farmers. Farmers now cultivate Napier and Setaria sp. and practice silage making, which has made the village self-sufficient in fodder production (Singh *et al*., 2021).

Challenges In The Adoption Of Csv's

Despite its potential, the Climate-Smart Village approach faces several challenges. Limited extension manpower, inadequate training, financial constraints, low investment capacity of farmers, limited adoption of proven technologies, poor rural connectivity, and low digital literacy can hinder effective implementation. Many CSA technologies require upfront cost, labour, or risk-taking. Smallholders may hesitate even when long-term benefits are clear. Access to subsidy, credit, insurance, and rental services is therefore crucial. Moreover, climate-smart technologies are often highly context-specific, making it difficult to replicate successful models across diverse agroecological regions.

Conclusion

CSVs serve as an important paradigm shift toward resilient and sustainable agricultural development by adopting a holistic strategy that combines improved crop management, water conservation, livestock management, agroforestry, renewable energy, and risk management practices to enhance resilience against climate variability. Effectiveness of CSV's depends mainly on strong agricultural extension systems which are capable of linking climate science with local realities. Through knowledge dissemination, capacity building, institutional development, participatory learning, and digital advisory services, agricultural extension transforms scientific innovations into practical actions that improve farmers' resilience. As climate risks continue to intensify, strengthening climate-smart extension will be critical for scaling Climate-Smart Villages and ensuring sustainable livelihoods, food security, and environmental sustainability for future generations. However, CSVs are not a one-size-fits-all solution, but rather a dynamic model that evolves in tandem with the changing climate landscape.

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Nature-Based Solutions for Sustainable Agriculture in Climate-Vulnerable Coastal Regions

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Abstract

Sea-level rise, cyclonic storm surges, salinity intrusion, and erratic rain are increasingly affecting coastal regions of South Asia where they threaten the livelihood of smallholder farming communities. Traditional engineering solutions, like concrete levees and seawalls, are often expensive, environmentally damaging, and poorly adapted for the ever-changing nature of coastlines over long periods of time. Because they align with nature, only diverse and multifunctional systems of natural resources not only support the provisioning of ecosystem services but also protect the livelihood of local communities, help communities to adapt to climate change (increase resilience), Nature-based Solutions (NbS) present an ecologically sound and cost-effective alternative for building resilient agricultural systems. This article offers reasoning for why NbS targets coastal agriculture, reviews some of the most salient approaches (including mangrove-agroforestry buffers, saline-tolerant crop diversification, integrated rice-fish systems and bio-engineered soil and water conservation), discusses extension strategies required to ensure these interventions are scaled productively with smallholder farmers. Finally, it concludes that NbS success is a multidimensional issue not only involving ecological design but requiring progressive participatory extension, enabling policy and institutional co-functioning thus proposing NbS itself as keystone of climate-smart and sustainable agriculture in vulnerable coastal geographies.

Keywords: Nature-based Solutions (NbS), Coastal Agriculture, Climate Resilience, Agroforestry, Extension Strategies

KEY HIGHLIGHT

- 🌊 Coastal agriculture faces rising salinity, sea-level rise, cyclones, storm surges & erratic rainfall
- 🌿 Nature-based Solutions (NbS) offer cost-effective, adaptive alternatives to conventional infrastructure
- 🌴 Mangrove–agroforestry buffers reduce storm and salinity impacts while supporting livelihoods
- 🌾 Crop diversification & rice–fish systems enhance productivity & resilience
- 👩‍🌾 Participatory extension enables farmer-led adoption, climate advisories and local capacity building
- 🏛️ Policy convergence and finance are essential for scaling NbS sustainably.

Introduction

The Sundarbans region of West Bengal covering the southern districts of North and South 24 parganas, is a unique landmass occupying the lowest part of the Ganges delta and fragmented by various distributaries and tidal channels. This littoral tract is one of the most productive yet vulnerable agro-ecological systems in this world. It sustains high population density, grow rice and aquaculture-based livelihoods, house rich biodiversity, yet this region is also at the frontline of climate change impacts. Coastal agriculture, especially in such crucial deltaic locations like Sundarbans (east India & Bangladesh), is affected by factors such as rising sea levels, enhanced cyclones features, increasing tidal flooding and gradual salinisation of soils and ground-water. Farmers

have also reported decreasing yields of traditional rice varieties often cultivated in the coastal regions, reduced availability of fresh water, and higher reliance on external inputs to control saline stress in those regions.

In this context, nature-based solutions have been identified as a low-cost alternative for alignment of agricultural productivity and ecosystem resilience. NbS encompass a range of actions in protecting, sustainably managing and restoring natural or modified ecosystems and contributing to addressing societal challenges in ways that will be effective and adaptive while simultaneously providing human well-being and biodiversity benefits. Unlike grey infrastructure, NbS find their value in the multiple co-benefits they deliver—mangrove restoration buffers storm energy, traps sediment, aids groundwater recharge, sequester carbon and provide alternative livelihood options such as fisheries, apiculture and non-timber forest products for local communities (Barbier, 2016).

Climate Vulnerability in Coastal Regions

Coastal agricultural systems face a specific set of climate pathways that reinforce and interact with each other. Saltwater intrusion, decreased inflow of freshwater from upstream, relative sea-level rise, and salinisation of soil and water are probably the most common and widespread threats degrading extensive areas of arable land in crucial agricultural regions to becoming inhospitable to traditional crop types. Episodic yet catastrophic damage is done to standing crops, embankments and aquaculture ponds by cyclones and storm surges; erratic monsoon patterns disrupt the timing of sowing and harvesting. In low-lying deltas, the risk of permanent flooding is compounded by land subsidence, frequently aggravated by overexploitation of aquifers.

No matter what the stressors, they do not work in isolation of sense of human vulnerability. Coastal agriculture in a post-covid world Smallholder and marginal farmers, who make up the bulk of coastal agricultural households, have poor access to credit, insurance and climate information services which limits adaptive capacity. This particularly affects women farmers and landless labourers who have limited control over productive assets and decision making. As such, an effective resilience-building strategy for coastal agriculture has to deal with the biophysical drivers of vulnerability and socio-economic constraint on adaptive capacity.

Nature-Based Solutions: Concept and Rationale

Nature-Based Solutions (NbS): Nature-based Solutions involve designing and implementing interventions that recognize the fundamental principle that nature matters. Healthy ecosystems provide essential regulating services that deliver significant ecological, cultural, and economic benefits, often complementing or substituting engineered infrastructure. These ecosystem services include coastal protection, water purification, carbon sequestration, erosion control, flood regulation, and microclimate regulation.

In the agricultural context, NbS integrate ecological processes directly into farming systems rather than treating conservation and agricultural production as competing land uses. By enhancing biodiversity, improving soil health, conserving water resources, and strengthening ecosystem resilience, NbS promote sustainable and climate-resilient agricultural production. This approach is particularly relevant in coastal regions, where the land–sea interface is highly dynamic. Conventional hard shoreline armouring often disrupts sediment transport, tidal propagation, and fish migration, whereas Nature-based Solutions maintain these natural processes while reducing climate risks and supporting sustainable livelihoods.

The concept of NbS in coastal agriculture is based on three underlying rationales. So, what are the first: cost effectiveness — living shorelines and vegetative buffers tend to have lower upfront capital costs than their concrete embankment counterparts, and can even self-heal after they sustain damage. Secondly, the co-benefits: NbS provide climate adaptation or biodiversity conservation or carbon sequestration, and act as diversified income from livelihoods; while single-purpose grey infrastructure works alone. Limited capacity for adaptation: although ecosystems like mangroves and wetlands can migrate and adapt to slowly rising sea levels, built structures have zero capacity for such long-term resilience and adaptation.

Adaptation Strategies for Coastal Agriculture Using Nature Based Solutions

Some NbS practices with the potential to improve the resilience of coastal farming systems to climate change are summarised below.

Mangrove and Agroforestry Buffers

The restoration and protection of mangrove belts on the sea-front edge of agricultural land reduces incident wave energy and impacts from storm surge within adjacent fields and embankments. Complementary agroforestry systems of salt-tolerant trees e.g. Casuarina, Avicennia and coconut in association with field crops stabilise soils, moderate the microclimate and buffer crop gardens against salinity while generating additional income from timber, fuelwood or fruit.

Saline-Tolerant Crop Diversification

For instance, forecasting global climate change effects and trends and breeding of salinity tolerant rice varieties with pulses and inert halophytic vegetables increases the cropping systems diversity by controlling soil salinity (Liu et al., 2022). These crops are integrated with managed wetland patches that facilitate natural drainage and salt leaching during the monsoon season, resulting in limited long-term salt accumulation within the root zone.

Integrated rice-fish and rice-shrimp systems

Integrated aquaculture-agriculture systems enable farmers to grow fish or shrimp in rotation with rice-based crops, depending on the salinity season. These systems utilize brackish water, which would otherwise make land unfit for cropping; fish waste also supplies nutrients that can decrease fertiliser needs in the ensuing rice crop.

Biological soil and water conservation

Vegetative measures (grass strips, live check dams and reed-bed filtration along field bunds and canal edges) reduce erosion, filter agricultural runoff and increase groundwater recharge. Rebuilt and created wetlands can also act as a sponge, storing all that extra stormwater runoff from flooding during storms.

Coastal Shelterbelts and Windbreaks

This will include the use of multi-row shelterbelts of wind-firm tree species around farm boundaries to achieve reductions in wind speed and consequent cyclone-induced crop damage, Reduction in evapotranspiration losses during and after storms; as well as habitat corridors for pollinators and natural predation of pests.

Extension Strategies for Scaling Nature-Based Solutions

The ecological validity of NbS has been well-documented, but scaling up their uptake is heavily reliant on the design of extension strategies that facilitate active farmers' participation rather than passive reception. Below are some strategies that in particular apply to coastal transformation programmes:

- Participatory demonstration plots: Creating places where farmers can observe saline-tolerant varieties and agroforestry models instead of only relying on top-down guidance in building local confidence.

- Farmer field schools: organised, season-long groups engaging in hands-on practice and learning through group exchanges on integrated rice-fish systems and bio-engineering techniques.
- Community nurseries: The mangrove and agroforestry saplings are raised at a decentralised level by self-help groups to help ensure local ownership while producing supplementary income
- Enhance climate information and early-warning systems: integrating extension services with location specific weather and salinity advisories through mobile platforms to inform farm-level decisions in a timely manner.
- Convergence with livelihood diversification schemes: Geographically working to merge NbS promotion with apiculture, other non-timber forest product value chains and eco-tourism initiatives to strengthen the econometric case for conservation-positive farming.

Gender-responsive extension: Gender-sensitive training, access to inputs and participation in decision-making platforms for women farmers, who often play a key role in homestead-level agroforestry and kitchen gardens.

Policy Perspectives and Institutional Support

To scale nature-based solutions in coastal agriculture, the key is to enable policy frameworks that go beyond pilot projects. Mangroves and wetlands must be acknowledged in land-use planning as an ecosystem with a protective role that should look to reduce their use for generation of rapacious aquaculture or built structures. Payment-for-ecosystem-services schemes, blended climate finance and index-based crop insurance offer financial instruments that can help bridge the transition costs smallholders incur while adopting diversified NbSs compatible systems. Coastal resilience transcends conventional administrative silos; hence, convergence across departments is a prerequisite, namely those of agriculture, fisheries and forestry as well as disaster management (Spalding et al., 2014) with growing references to ecosystem-based adaptation in national and state climate action plans, translating these commitments into district level implementation supported by extension personnel and monitoring systems remains an ongoing target for policy makers.

Challenges and the Way Forward

Nature-based solutions are promising, but there are substantial implementation challenges. Many farmers do not have formal land titles which leads to tenure insecurity and discourages long-term investment in tree-based systems. Households under immediate subsistence pressure are discouraged from taking up agroforestry and mangrove restoration because of multi-year lags before full protective and economic benefits are realized. Availability of relevant advisory support for farmers is restricted not only by insufficient time, but also due to gaps in technical knowledge on ecological design among frontline extension staff as well. Long term ecological returns need to be made compatible with short term livelihood needs, which requires blended and strategic investment in capacity building, secure and equitable access to coastal commons.

Ensuring NbS implementation to support this, integrating remote sensing and participatory monitoring tools can be used to track over time the effects of NbS interventions — generating evidence that is useful not only in boosting farmer confidence but also on policy advocacy (looking ahead). The approaches, tools and methods for adaptation in one area often take much longer to be applied in other contexts, but cross-learning of coastal regions with similar challenges (for example through Farmer Exchange visits or regional knowledge

platforms) can further accelerate the adoption and scaling of solutions that are appropriate for their respective contexts.

Conclusion

Nature-based solutions thus provide a robust scientific and economical solution for enhancing climate resilience in coastal agricultural systems. By building on ecological processes that mitigate climate change impacts, amongst others, mangrove-agroforestry buffers and saline-tolerant crop diversification integrated with saltwater aquaculture systems and engineered conservation measures help smallholder farmers to adapt against salinity intrusion, storm surges and shifting rainfall patterns. Realising the ecological potential of these solutions, however, requires participatory and gender-responsive extension strategies linked to livelihood diversification, land-use policies, and institutional convergence that view coastal ecosystems as productive infrastructure per se. With climate risks increasing in severity, and cost-effectiveness, mainstreaming nature-based solutions into coastal agricultural extension will be the very fulcrum for achieving a resilient and sustainable rural transformation.

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Popular Article

Climate-Smart Agripreneurship: Creating Green Livelihood Opportunities for Rural Youth: Lessons from the Eastern Himalayan Region

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Abstract

Agriculture in the Himalayan region is undergoing a paradigm shift due to climate change, low profitability of traditional crops, and changing market needs. These challenges, however, create opportunities for climate-smart agripreneurship, which promotes sustainable agriculture while at the same time considering value addition, entrepreneurship development, technological innovations, and market development. Climate-smart agriculture encourages young people to invest in different enterprises using their resources and skills instead of traditional farming. The article discusses recent research and development and case studies in the Eastern Himalaya region on diverse forms of agripreneurship such as speciality coffee, diversified farming, floriculture, value addition of tea, and digital marketing. The article also highlights the role of extension services, entrepreneurship training, digital technologies, and the carbon economy in supporting sustainable agriculture and climate-smart agripreneurship. The study finds that focus on youth entrepreneurship alongside climate change adaptation and mitigation strategies is the future of Himalayan agriculture.

Keywords: Climate-Smart Agriculture; Agripreneurship; Himalayan Agriculture; Rural Youth; Green Livelihoods

KEY HIGHLIGHT

- 🌧️ **Climate Challenge:** Himalayan farming faces rising climate and market risks.
- 🌱 **Diversification:** Mixed farming, horticulture, floriculture, and agroforestry build resilience.
- ☕ **Green Enterprises:** Coffee, tea, spices, and floriculture offer new opportunities.
- 💡 **Value Addition:** Processing, branding, and digital marketing increase farm value.
- 🤖 **Climate-Tech:** AI, drones, IoT, and digital platforms enable new agribusinesses.
- 🤝 **Youth & Livelihoods:** Training, incubation, FPOs, and market linkages can create green jobs.

Farming Under Pressure: Climate Challenges in the Himalayas

The Himalayan region has been a hotbed for agricultural activities for generations together since it is a repository of diversity and knowledge. Farming activities are the primary source of income for the people residing in the Himalayas as there is a wide variety of produce that can be reaped from this region. From rare wild flowers and vegetables to grasses and animals, all have contributed to this region being the source of great diversity and agricultural wealth. The economies of the Himalayan region are highly dependent on the agriculture sector and is also vulnerable to the pressures of smallholder farmers, climate, water scarcity, pests, and market forces. Mountainous farming is more reliant on natural resources than lowland farming, thus exposing

it to greater climate risks and variability than agriculture in the lowlands (Food and Agriculture Organization of the United Nations [FAO], 2021). According to the Intergovernmental Panel on Climate Change (2022), mountains are among the most vulnerable regions to climate change impacts because of their highly diverse and sensitive ecosystems, drastic changes in precipitation patterns, and exposure to extreme weather conditions. These aspects can have adverse effects on agriculture, water availability, biodiversity, and the livelihoods of millions of people. It further explains that building climate resilience to safeguard food systems is extremely vital and can be achieved through diversification at the local level and adaptation to environmental changes (Intergovernmental Panel on Climate Change, 2023).

Agriculture in the Himalayan region is therefore undergoing a gradual transformation. Instead of cultivating a few traditional crops, many farmers are now considering diverse systems that include horticultural, floricultural, plantation crops, livestock, and value-added agricultural commodities. Diversification is being undertaken to increase income and reduce risks, and to some extent, diversification is also being driven by climate change considerations. Lama et al. (2018) report that within the hilly region of North Bengal, farm management systems have steadily transitioned from being purely dependent on a narrow range of traditional crops to a more diverse system of vegetables, fruits, and ornamental plants cultivation, enhancing income security. The Food and Agriculture Organization of the United Nations (2024) recognizes that future agrifood systems will be expected to increase productivity, raise resilience, conserve natural resources, and create economic opportunities in a way that allows capturing emerging trends. It, therefore, proposes that for the Himalayan region, transitioning from traditional methods of cultivation to more innovative livelihood options that would allow youth to acquire entrepreneurial skills is key. The challenge of adapting agriculture to the impacts of climate change will only be possible if the next generation embraces climate-smart agriculture as a viable economic option, which is the underlying principle of climate-smart agripreneurship.

Climate-Smart Agriculture: From Adaptation to Opportunity

Farmers, today, are faced with a plethora of challenges which includes - need to increase food production, adapt to the changing climate, conserve the environment, and maintain profitability. Climate-Smart Agriculture (CSA) has been proposed as agricultural development that enhances food security while also building resilience to climate change and sustaining the environment (Lipper et al., 2014). This concept promotes the use of specific technologies across various agricultural systems to achieve productive, adaptable, and sustainable agriculture, which includes crop diversity, agroforestry, integration, horticultural crops under protected cultivation, water-saving techniques, and improved management of soil nutrients. The Climate-Smart Agriculture Sourcebook views sustainable productivity, adaptation, and conservation as objectives that can be simultaneously achieved, not as separate goals (Food and Agriculture Organization of the United Nations, 2017). Effective implementation of CSA requires not only technology but also support services such as extension and market access, credit, and training (Food and Agriculture Organization of the United Nations, 2024).

In the Himalayan region, many farmers have adopted CSA practices such as mixed farming, terrace farming, agroforestry, organic farming, and high-value horticultural crops (Food and Agriculture Organization of the United Nations, 2021). There has also been a shift from traditional farming methods to mixed

cultivation of horticultural, medicinal plants, plantation, vegetables, livestock and fishery with consequent diversification of products and agribusiness enterprises (Lama et al., 2018). Thus, CSA has been viewed by many as an entry point for adopting multiple enterprises with value addition and leveraging local resources.

Climate-Smart Agripreneurship in Practice

The farmers in the Himalayan region have been changing their cropping patterns. One of the best examples in this regard is the shift from large cardamom to coffee cultivation in the Kalimpong hills. The yield of large cardamom has been dwindling due to various factors like poor productivity, disease, and market demands, so farmers are giving way to other medicinal plants (Dhungana et al., 2023). Coffee growing is said to be a biodiversity-friendly activity as compared to large cardamom farming, and it can also thrive in the mountainous Himalayan terrain (Jha et al., 2014). As per the latest reports, more than 1,200 farmers are growing coffee in the Kalimpong hills, breaking the century-old tea culture (The Times of India, 2025).

In this regard, it is pertinent to note that the regional farmers are heavily focused on value addition to the produce. Syang's (Syangbo's Living Food and Beverages Pvt. Ltd.) agripreneurs have created a portfolio of products including kombucha, sparkling Darjeeling tea, botanicals, and tea vinegar using organic Himalayan tea leaves and are now recognized under the APEDA Bharati Top 100 Startups programme for their innovative approach to agripreneurship. Similarly, Himalis Agro Commodities Pvt. Ltd., based in Kalimpong, has also been leveraging its Himalayan spices and organic products to create value-added processed food and specialty coffee products. Daammee is another agripreneur from Kurseong that is marketing its range of indigenous products including Dalle Khorsani, pickles, and Kalimpong Noodles. Further, Himalayan Organic Life is a start-up that connects the buyers with the Himalayan farmers through digital marketing.

Floriculture is another area that has the potential to bring substantial benefits to the farmers of the Kalimpong hills. The region has a comparative advantage in regard to the climate for growing orchids and other ornamental plants and flowers. Experts have found that orchid farming, protected floriculture, and nursery cultivation offer a higher profit margin than many other commercial crops on a relatively small landholding (De & Medhi, 2015). Further, collective farming helps in reaping more benefits for the farmers. The collective effort of farmers in Mineral Spring Sanjukta Vikas Sanstha, Darjeeling, has helped the cooperative in accessing premium markets by focusing on organic farming and Fairtrade certification while also promoting community-based value addition (Darjeeling Ladenla Road Prerna [DLR Prerna], 2015).

Together, the above mentioned initiatives show that climate-smart agripreneurship is a developing concept that has already been realized in the Himalayan region. From crop diversification, value addition and processing, floriculture, farmer producer organizations (FPOs), and digital marketing, the entrepreneurs have found a way to make profit while being eco-friendly. Moreover, by promoting and intensifying partnerships between farmers, FPOs, researchers, extension agencies, business incubators, financial institutions, and markets, the process will allow for scaling up. Consequently, it will lead to expanding business networks, providing market opportunities, promoting value addition, and generating green job opportunities for the Himalayan region's young people (World Bank, 2012; Food and Agriculture Organization of the United Nations [FAO], 2024; Thakur, 2020).

Climate-Tech and Emerging Green Livelihood Opportunities

The next step in the development of Himalayan agri-business will be increasingly shaped by the impact of technologies, as well as adaptation to climate change. Such technologies as artificial intelligence, remote sensing instruments, drones and Internet of Things, and digital platforms have facilitated improved crop management, efficient use of water, better decision making in farm production, and created opportunities for tech-savvy young people to engage in technology-based enterprises (Fuentes-Peñailillo et al., 2024). Taking advantage of coffee, tea, cut-flowers, and organic spices potentials, hill entrepreneurs should consider value addition and processing options in order to create a market for finished products in addition to primary production. The ICAR-ATARI Model Training Course on Innovative Entrepreneurial Approaches in Hill Farming System reveals that appropriate scientific management in combination with entrepreneurial ability and production of value-added commodities in demand can considerably improve farm income (Thakur et al., 2020).

Agro-ecosystems across the Himalayas are expected to benefit from the rising need in climate smart technologies and practices, such as agroforestry, conservation agriculture, organic farming, and ecological restoration of degraded ecosystems in order to sequester more carbon in forests and soil through nature-based solutions. Such an initiative has the potential to diversify farm income in the Himalayan state through carbon credit trading and accessing climate finance, in addition to sustaining biodiversity and providing other essential ecosystem services, if proper policy instruments, incentives and institutional frameworks are put in place at upstream and downstream levels of the carbon value chain (Maraseni et al., 2021). However, currently, small-scale farmers across the Himalayas are not in a position to participate in the carbon markets, and there is a need to build capacities of local institutions, FPO and other relevant agencies in order to generate knowledge and skills in carbon trading, carbon-credit certification, and other related aspects.

Building Green Livelihoods Together

The future of Himalayan agriculture lies in its ability to adapt to the changing climate and its potential to deliver livelihood opportunities to the local people. The case studies presented in the article provide valuable insights into the need for climate smart agripreneurship that integrates sustainability, value addition, and community-based approaches to make farming a preferred choice for the younger generations.

Achieving climate-smart agripreneurship requires the combined efforts of universities, Krishi Vigyan Kendras, FPOs, extension agencies, banks, and other private entities. These stakeholders need to invest more in promoting entrepreneurship development, digital literacy, business incubation, and market linkages through well-structured capacity-building programs. It is worth noting that Himalayan farmers do not need a complete overhaul of the existing systems. Instead, they need a focused approach that builds on what is already working well in the region. The area has a wealth of biodiversity and unique agro-climatic conditions that can be leveraged to promote niche products that attract premium prices in the market. Furthermore, local knowledge and experience can contribute immensely to innovation and development, provided they are coupled with the right entrepreneurial skills. Finally, climate-smart agripreneurship will enable the region to graduate from the current agricultural practices and create a new breed of young agripreneurs who are passionate about farming and contribute significantly to the local economy.

To build enterprises around these opportunities, the Himalayan region needs agri-incubation centres to help scale up these ideas. These centres could be created, which offer technical mentoring, business incubation

services, financial support, product development, branding, digital marketing, and market linkages to promote mountainous agriculture and related products and technologies. Thus, by creating agri-incubation platforms, farmers, researchers, entrepreneurs, investors, and policy-makers are brought on a common platform, and the idea of climate-smart enterprises could be promoted, which would help in keeping the youth engaged in farming, leading to sustainable, climate-resilient livelihood options. This will further make the Himalayas a model Himalayas of climate-smart, entrepreneurship-driven mountainous development in the country.

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Popular Article

Future of Orchid Diversity under Changing Climate in the Eastern Himalayas: Challenges, Opportunities and Conservation Strategies

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Abstract

The Eastern Himalayas represent one of the world's most important biodiversity hotspots and contain over 70% of India's orchid diversity, making the region a global focus for orchid conservation and sustainable utilization. Orchids play a crucial role in ecological stability, floriculture, ecotourism, and rural livelihoods, while also providing unique genetic resources for the development of enhanced decorative cultivars. However, orchid diversity throughout the region is seriously threatened by rapid climate change, which is marked by rising temperatures, unpredictable rainfall, changed phenological patterns, and an increase in the frequency of extreme weather events. The distribution, regeneration, and long-term survival of orchids are being impacted by these climatic changes, habitat fragmentation, deforestation, infrastructure development, illicit harvesting, and dwindling pollinator and mycorrhizal fungal populations. With a focus on Sikkim's orchid-rich environments, this article explores the possible effects of climate change on orchid diversity in the Eastern Himalayas. To preserve orchid diversity in the midst of changing climatic circumstances, strategies like habitat preservation, tissue culture, seed banking, cryopreservation, species distribution modeling, and community involvement are crucial. Climate-smart orchid farming and sustainable use can help conserve biodiversity and generate income at the same time. A collaborative approach involving researchers, policymakers and local communities is crucial to safeguard the unique orchid wealth of the Eastern Himalayas for future generations.

Keywords: Orchid diversity, Climate change, Eastern Himalayas, Floriculture, Climate-smart conservation

KEY HIGHLIGHT

- 🌸 **Orchid Wealth:** Eastern Himalayas host nearly 70% of India's orchid diversity.
- 🌡️ **Climate Threat:** Rising temperatures and erratic rainfall threaten orchid survival.
- 🏔️ **Habitat Loss:** Forest fragmentation, deforestation, and illegal harvesting intensify risks.
- 🌱 **Conservation:** In situ protection, seed banking, and cryopreservation safeguard diversity.
- 🧬 **Biotechnology:** Tissue culture and molecular tools support orchid conservation and propagation.
- 🤝 **Community Action:** Climate-smart cultivation and local participation can conserve orchids and create livelihoods.

Introduction:

The Eastern Himalayas are often described as one of the most spectacular repositories of biodiversity on Earth. Stretching across Sikkim, Arunachal Pradesh, the Darjeeling Himalaya, Bhutan, parts of Nepal, and Northeastern India, this mountain landscape encompasses tropical forests, temperate woodlands, alpine meadows, and snow-covered peaks within a relatively short geographical distance. The region's remarkable ecological diversity has made it one

of the 36 global biodiversity hotspots, supporting thousands of plant species, many of which are unique to the planet. Orchids hold a unique position among these biological gems due to their remarkable diversity, intriguing flower architecture, and enormous ornamental value. Orchids are members of the Orchidaceae family, which is one of the largest families of flowering plants with over 1,300 species in India and about 30,000 species globally. The Eastern and Northeastern Himalayan region is home to nearly 70% of all orchid species in India, making it the richest center of orchid variety in the nation. The cold, humid mountain climate, abundant rainfall, dense woods and wide altitudinal range provide good habitats for both terrestrial and epiphytic orchid. From the tropical plains at 300 m to alpine highlands above 4,000 m, different orchid species occupy diverse ecological niches. The brilliant flowers of Cymbidium, Dendrobium, Vanda, Coelogyne, Bulbophyllum, Paphiopedilum, Pleione and Calanthe draw botanists, orchid enthusiasts and tourists from throughout the world. The cool, humid mountain climate, abundant rainfall, dense forests and wide altitudinal range provide ideal habitats for both terrestrial and epiphytic orchids. From the tropical valleys at 300 m to alpine regions above 4,000 m, different orchid species occupy distinct ecological niches. The colourful blooms of *Cymbidium*, *Dendrobium*, *Vanda*, *Coelogyne*, *Bulbophyllum*, *Paphiopedilum*, *Pleione* and *Calanthe* attract botanists, orchid enthusiasts and tourists from around the world.

Beyond their aesthetic appeal, orchids play important ecological roles. Their intimate relationships with pollinating insects, birds and mycorrhizal fungi make them important components of healthy forest ecosystems. Many orchids serve as indicators of habitat quality because they thrive only under stable environmental conditions. Consequently, changes in orchid populations often reflect broader ecological disturbances within mountain forests.

The Eastern Himalayas have also become an important centre for commercial orchid production. Cut flowers and potted orchids contribute significantly to the global floriculture industry, while native species provide valuable genetic resources for breeding improved hybrids with enhanced flower quality, colour diversity and environmental adaptability. In states like Sikkim, orchid cultivation has emerged as a promising enterprise that combines economic development with biodiversity conservation.

The Eastern Himalayas: an orchid paradise

The high orchid variety of the Eastern Himalayas is primarily owing to its outstanding climatic and geographical complexity. Altitude causes significant changes in temperature, precipitation, humidity, soil properties, and forest composition, resulting in a variety of microhabitats that are ideal for various orchid species. In temperate and subtropical woods, epiphytic orchids predominate and grow on tree trunks and branches without causing damage to their host plants. Through specialized aerial roots wrapped in velamen tissue, these orchids absorb moisture from rainfall, mist, and air humidity. On the other hand, lithophytic orchids inhabit cliffs and rocks covered in moss, whereas terrestrial orchids grow directly in the forest soil filled with decomposed organic matter.

Sikkim, despite occupying only roughly 0.2% of India's geographical area, is particularly rich in orchid species. More than 500 orchid species, or about 40% of all orchids in India, are found in the state. Orchids that are adapted to various ecological zones thrive in its altitudinal gradient, which ranges from about 300 m to more than 8,500 m above sea level. Many rare and endemic orchid species can be found in the woodlands of Khangchendzonga National Park, the Fambong Lho Wildlife Sanctuary, Maenam Wildlife Sanctuary, and Barsey Rhododendron

Sanctuary. Numerous of these have contributed to international breeding programs and have substantial horticultural value. Because of their long-lasting flowers, broad colour range, and exceptional vase life, Cymbidium species have significantly changed the floriculture industry. In a similar vein, the worldwide cut flower market is dominated by Dendrobium hybrids because of their abundant blossoming and ability to adapt to sheltered cultivation. In breeding programs to create cultivars resistant to disease and climate change, native Himalayan species have been useful parents.

In addition to its aesthetic significance, a number of orchids are used in traditional medicine and cultural customs. While some species have religious importance for the local communities, others have historically been utilized in indigenous healthcare systems. The public's interest in orchid-rich landscapes has grown as ecotourism has grown in popularity, offering more motivation for their preservation. have substantial horticultural value and have supported global breeding initiatives.

Climate Change: a new challenge for Himalayan orchids

Orchids are among the plant groups most susceptible to fast climate change, despite their extraordinary evolutionary adaptation. Orchids have extremely specific ecological needs that make them more vulnerable to environmental disruptions, in contrast to many other flowering plants. The Himalayan region has seen discernible warming in recent decades. Research shows that average temperatures are rising, winter snowfall is decreasing, monsoon rainfall is erratic, and extreme weather events including landslides, cloudbursts, and extended dry spells are occurring more frequently. Mountain ecosystems, especially the habitats that sustain native orchid populations, are already being impacted by these climate shifts.

For successful growth, many orchid species need stable forest conditions, constant high humidity, and limited temperature fluctuations. Seed production, pollen viability, and flowering time can all be impacted by even slight temperature increases. In a similar vein, variations in rainfall affect the soil conditions necessary for terrestrial species and the moisture availability needed by epiphytic orchids. Orchids' reliance on mycorrhizal fungus is an equally significant but frequently disregarded feature. Because orchid seeds are so tiny, they don't have enough food to germinate. In the early phases of development, they are totally dependent on symbiotic fungi for nutrition.

Another significant vulnerability is pollination. With a small number of insect pollinators, many orchids have developed specialized interactions. Reproductive success may drastically decrease if climate change causes flowering to occur either earlier or later than the appearance of these pollinators. These mismatches have already been noted in a number of mountain ecosystems across the globe, and future warming scenarios are predicted to make them more prevalent.

Climate change and its impact on orchid diversity

The Himalayan region is thought to be extremely susceptible due to its delicate mountain ecosystems, and climate change has become one of the biggest threats to biodiversity globally. According to predictions made by the Intergovernmental Panel on Climate Change (IPCC), the Himalayan region will continue to see changes in precipitation patterns, rising temperatures, and an increase in the frequency of extreme weather events throughout this century. The range, quantity, and survival of orchid species are anticipated to be significantly impacted by these changes.

The upward shift in species distribution is one of the most obvious effects of climate change. Many orchid species are progressively migrating to higher altitudes where climatic conditions are

still favourable as temperatures rise. There are restrictions on this natural movement, though. Because they have little or no chance of moving higher, species that are already thriving close to alpine regions are extremely vulnerable to local extinction. For a number of endemic Himalayan orchids, this phenomenon, sometimes known as the 'mountain-top extinction risk' presents a significant conservation problem. Another significant issue is shifting rainfall patterns. For good growth, orchids require high air humidity and steady moisture. Epiphytic orchids are especially affected by decreased humidity levels in forest canopies caused by irregular monsoon rains, extended dry periods, and decreased cloud cover. On the other hand, severe rainfall and cloudbursts can cause landslides that uproot host trees that maintain orchid populations and damage forest habitats.

Habitat degradation

Forest fragmentation alters microclimatic conditions by increasing light intensity, reducing humidity and exposing orchids to temperature fluctuations. Because many epiphytic orchids need humid, shady conditions, fragmented woods are becoming less and less suited for their existence. The situation is made worse by the illegal gathering of wild orchids. Despite legislative protection, a number of appealing species of Paphiopedilum, Cymbidium, Dendrobium, and Vanda are still harvested from natural forests for ornamental trade. Once wild populations are reduced, recovery is challenging due to slow growth rates and minimal spontaneous regeneration.

Commercial importance of native orchids

Orchids play a significant role in the global floriculture industry, despite being generally appreciated for their beauty. Every year, international trade in cut flowers, potted plants, and landscaping supplies brings in billions of dollars. The development of commercially successful hybrids grown all over the world has been greatly aided by native Himalayan orchids. Cymbidium species are prized for their extended vase life, graceful flower spikes, and appropriateness for sheltered culture. High-quality cymbidium flowers may be produced in Sikkim and other Himalayan states due to their favourable climate, which presents substantial prospects for floriculture focused on exports**.** Similarly, *Dendrobium* orchids have become one of the most popular cut flowers due to their continuous flowering habit and wide adaptability. Native Himalayan germplasm contributes valuable traits such as disease resistance, cold tolerance and unique flower colours that can be incorporated into future breeding programmes.

Climate-smart conservation strategies

The future of orchid diversity in the Eastern Himalayas depends on adopting integrated conservation strategies that combine ecological restoration, modern biotechnology, climate science and community participation. Conservation efforts should not only focus on protecting existing populations but also enhance their resilience to future climatic changes.

In situ conservation:

The conservation of orchids involves protecting the natural habitat of the species, encouraging orchid biodiversity, and ensuring the survival of the rare species of orchids. The in situ conservation of species is most desirable for orchids as it ensures their natural growth, proliferation, and perpetuation, which allow the process of evolution to continue as part of the natural ecosystem. The protection of natural habitats by establishing sanctuaries, biosphere reserves, and forest reserves; the salvation of plants from degraded and threatened habitats and their culture in orchidarium, botanical gardens, and other rescue centers; and the propagation of threatened plants through in vivo/in vitro approaches and their re-introduction into well-protected habitats are among other measures suggested for orchid

conservation. The most effective approach to the in-situ conservation of orchid species takes into account the life history traits of the species and the roles of mycorrhizal fungi and pollinators.

Protecting species in their natural habitat is known as in situ conservation. This approach focuses on overall habitat protection and ensures the conservation of species and its associated biota. Under the Wildlife (Protection) Act, protected areas (PAs) in the form of national parks and sanctuaries are established in India with an emphasis on faunal wealth, while they may also include orchid habitats. Establishing orchid sanctuaries is a focused approach. A few have been attempted in the states of Arunachal Pradesh and Sikkim. A biosphere belt with trans boundaries is another way of conservation of natural habitat for orchids and epiphytes. India has an intricate protective area network (PAN) comprising 86 national parks and 480 wildlife sanctuaries covering approximately 4.66% of the total geographical area of the country and is expected to further expand in the future. This PAN protects the species that are present in those forests. Unfortunately, many important and endangered orchid species lie outside the PAN (viz., *Vanda coerulea* in Meghalaya, *Paphiopedilum wardii* and *P. spicerianum* in Assam, and *Renanthera imscootiana* in Arunachal Pradesh). At present, the orchids also figure prominently in the Red Data Book prepared by the International Union for Conservation of Nature (IUCN).

Ex situ conservation:

The ex-situ method is the preservation of germplasm outside the natural habitat. According to the Orchid Conservation Alliance (OCA), "preservation of natural orchid habitat preserves the orchids, their pollinators, their genetic diversity, and other fauna, as well as the birds, frogs, insects, reptiles, and mammals in the forests where they live. However, considering the difficulties orchids face from habitat degradation, unsustainable harvesting, and climate change, this will not be enough on its own. In many situations, overcoming these obstacles will also need a combination of ex situ conservation in seedbanks and living collections, transplantation, and the creation of new habitats. According to the 2006 Gran Canaria Declaration II on Climate Change and Plant Conservation, 'ex situ collections have a key role to play in securing the conservation of wild plant species as natural resources, as an insurance policy for the future, as a basis for restoration and reintroduction programs, and as support for adaptation of livelihoods to climate change and shifting climate zones.' The ex-situ conservation principle refers to off-site selection and storage of genetically representative seeds and, where applicable, somatic tissues, regeneration of plants from the stored material, continued cultivation of species to produce conservation units.

Orchid seed bank

Long-term security is provided by ex situ conservation techniques like seed banking and propagation, which are essential parts of any integrated conservation strategy. One orchid capsule produces millions of seeds. However, they lack the functional endosperm and require specific mycorrhizal association for germination under natural conditions; consequently, the percentage of germination is low. Asymbiotic techniques have been used to germinate a large number of orchids, with germination rates as high as 90%. It has been proven that orchid seed banking is a crucial method for preserving the maximum amount of genetic diversity in a minimum amount of space. It may also make it possible to preserve important material for any future reintroduction and habitat restoration initiatives.

Cryobiotechnology

It is now necessary to preserve plant genetic resources for an extended period of time, and this has been accomplished by an innovative technique called cryopreservation. It is beneficial for maintaining plant germplasm in

its original form and is a useful technique for extending the life of a plant species that is in danger of going extinct. By using this technique, the plant material remained in the non-dividing phase and all of the activities, i.e., biochemical and biophysical, were seized when the material is subjected to -196 °C under liquid nitrogen.

Role of biotechnology in orchid conservation

Plant biotechnology has revolutionized orchid conservation and commercial production. Tissue culture and micropropagation enable rapid multiplication of elite and endangered orchid species from small plant tissues under sterile laboratory conditions. These techniques reduce pressure on natural populations while supplying disease-free planting material for cultivation and restoration programmes. Orchid conservation is also supported by recent developments in molecular biology. While molecular markers aid in evaluating genetic variation among populations, DNA barcoding assists in precise species identification. These resources are useful for choosing genetically varied parent plants for breeding and conservation initiatives.

Predicting the future through climate modelling

Climate modelling has emerged as an important tool for biodiversity conservation. Researchers can forecast how suitable habitats can change under future climatic scenarios using Geographic Information Systems (GIS), ecological niche modeling, and Species Distribution Models (SDMs).

Community Participation:

Conservation cannot succeed without the active participation of local communities. Indigenous people of the Eastern Himalayas possess valuable traditional knowledge regarding orchid distribution, flowering seasons and sustainable harvesting practices. Community-managed forests have already demonstrated their effectiveness in protecting biodiversity in several Himalayan regions. Encouraging local people to cultivate commercially valuable orchids through tissue-culture-derived planting material can reduce illegal collection from forests while generating additional income. Nature education programmes, orchid festivals, biodiversity parks and eco-tourism initiatives can increase public awareness about the ecological and economic importance of orchids. Schools, universities, non-governmental organizations and local self-help groups should be actively involved in these efforts.

Conclusion

The future of orchid diversity in the Eastern Himalayas depends on our ability to balance conservation with sustainable utilization in the face of a changing climate. Rising temperatures, erratic rainfall, habitat degradation and increasing anthropogenic pressures threaten the survival of many native orchid species, particularly those with narrow ecological requirements and restricted distributions. Conserving this unique floral wealth requires an integrated approach that combines in situ habitat protection, ex situ conservation through tissue culture, seed banking and cryopreservation, climate-based species distribution modelling, ecological restoration and active participation of local communities. Promoting climate-smart orchid cultivation and sustainable commercialization can further reduce pressure on wild populations while enhancing rural livelihoods and supporting the floriculture sector. With coordinated efforts from researchers, policymakers, conservation agencies and local stakeholders, the Eastern Himalayas can continue to serve as a global centre of orchid diversity, ensuring that these remarkable plants remain an integral part of the region's biodiversity, economy and cultural heritage for generations to come.

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Popular Article

Climate-Smart and Sustainable Agriculture for a Resilient Future: Relevance to Darjeeling Tea Plantations

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Abstract

Darjeeling tea is highly sensitive to climatic conditions that determine its yield and quality. Climate change, characterized by rising temperatures, altered rainfall patterns, prolonged droughts, and increased incidence of pests and diseases, poses a significant threat to the sustainability of Darjeeling tea plantations. Studies indicate a decline in annual rainfall and a rise in mean maximum temperature in the region, adversely affecting tea productivity, soil health, and ecosystem stability. This review highlights the impacts of climate variability on tea cultivation and explores climate-smart agricultural practices for enhancing resilience. Sustainable interventions such as biochar and biofertilizer application, soil conservation measures, rainwater harvesting, agroforestry, and balanced nutrient management can improve soil fertility, moisture retention, and climate adaptation. Integrating scientific innovations with traditional ecological knowledge is essential to safeguard the productivity, quality, and global reputation of Darjeeling tea under changing climatic conditions.

Keywords: Darjeeling tea, climate change, climate-smart agriculture, biochar, biofertilizers, soil conservation, resilience

KEY HIGHLIGHT

- **Climate Threat:** Rising temperatures and changing rainfall threaten tea yield and quality.
- **Rainfall Decline:** Darjeeling has experienced declining rainfall and rising temperatures.
- **Soil Health:** Biochar, biofertilizers, and balanced nutrition improve soil resilience.
- **Water Management:** Rainwater harvesting and efficient irrigation reduce drought stress.
- **Agroforestry:** Shade trees regulate temperature, enhance biodiversity, and support carbon storage.
- **Resilient Tea:** Climate-smart practices, resilient cultivars, and traditional knowledge can safeguard Darjeeling tea.

Introduction

Darjeeling tea, known as the "Champagne of Teas," is well-known throughout the world for its distinct flavor, scent, and quality. The climate, altitude, soil features, and traditional production methods of the area have a significant impact on the unique qualities

of Darjeeling tea. However, the production of tea in the Darjeeling hills is severely hampered by climate change. Tea yield and quality are threatened by rising temperatures, unpredictable rainfall patterns, protracted dry spells, degraded soil, and an increase in insect and disease rates. In this regard, Darjeeling tea plantations' long-term resilience and viability depend on climate-smart and sustainable farming methods. Tea cultivation depends on appropriate temperatures and evenly distributed rainfall, notwithstanding the diversity of climates. Tea bush cultivation is susceptible to climate change due to its unique climatic niche. Therefore, it is anticipated that the production of tea would be significantly impacted by global warming, which will likely affect both the amount and quality of tea (Wijeratne, 1996; Dutta, 2014; Duncan *et al.*, 2016; Gunathilaka *et al.*, 2016; Jayasinghe and Kumar 2021). All of the major tea-producing regions appear to have experienced significant recent changes in the average and maximum temperatures as well as the rainfall pattern (Wijeratne *et al.*, 2007). In addition to experiencing increasing climate stress, tea plants are impacted by both excessive and insufficient water. The concentration of secondary metabolites, which are crucial for the quality of tea, is affected by changing climatic circumstances. Due to increased soil erosion, pests, and illnesses that are becoming more resistant, climate change is predicted to reduce both the quantity and quality of tea produced (Ahmed, 2014). However, tea plantations appear to become less productive as temperatures rise over an ideal level (Patra *et al.*, 2013; Ahmed, 2014; Wijeratne, 1996). This could have detrimental economic and social repercussions, especially for tea farmers, workers on tea estates, and tea traders, given the significance of the tea crop to the major production regions. Tea farmers must develop techniques to adapt to climate change in order to continue producing tea in the future.

Climate Characteristics of Darjeeling

Anthropogenic climate change is one of the most pressing issues facing humanity worldwide. Current research findings at the local, regional, and global levels have shown that it has complex ramifications. Research conducted in the Indian setting likewise confirms that the mean maximum temperature is on the rise and the mean minimum temperature is on the rise, albeit slightly. According to a study of meteorological data, precipitation in mainland India has been very steady over the past century, with a slight positive tilt. However, it has also been noted that between 1901 and 2000, rainfall in the Himalayan region drastically decreased. The average annual rainfall in Darjeeling, a high rainfall zone with a long-term average of 2800 mm, has drastically decreased by 470 mm, or 16% annually. Additionally, a significant drop in precipitation has been linked to an unusual rise in Darjeeling's mean maximum temperature, which has risen by 2.5 degrees Celsius throughout the aforementioned time frame. Additionally, with a 90% confidence level, the Mann-Kendall Test verifies the existence of a statistically significant rising trend in mean maximum temperature and a statistically significant declining trend in precipitation. The sharp rise in mean maximum temperature and sharp fall in rainfall will have detrimental ecological effects because they will cause glacial recession, which will have a significant effect on the region's water resources. It may have detrimental effects on pastoral communities, agriculture, environment, and livelihood patterns. It may also worsen the region's hydro-meteorological situation. The current study offers information that planners, policymakers, and environmentalists can utilize to create practical plans to mitigate the effects of climate change in the delicate Middle Himalayan Region (Bhat and Rather (2018).

Impact of Climate Change on Darjeeling Tea

The viability of Darjeeling tea plantations is being more and more threatened by climate change. Tea

growth, yield, and quality are being negatively impacted by rising temperatures, unpredictable rainfall patterns, extended dry periods, and extreme weather events like landslides and heavy rainfall. Concurrently, decreased soil biological activity, nutrient depletion, and soil erosion are lowering soil resilience and production. The prevalence of pests and illnesses has also increased due to changing climatic conditions, creating new difficulties for the production of tea (Patra *et al.*, 2013).

Climate-Smart Practices for Darjeeling Tea Plantations

Climate-smart and sustainable farming methods are increasingly crucial to Darjeeling tea's future in order to solve these problems. Applying biochar and biofertilizers can boost soil health, increase moisture retention, improve nutrient availability, and encourage beneficial microbial activity. On steep slopes, soil conservation techniques like mulching, contour planting, cover crops, and vegetative barriers help prevent soil erosion and preserve soil fertility. Rainwater collection and effective water management assist reduce drought stress, while agroforestry systems with appropriate shade plants offer temperature regulation, biodiversity enhancement, and carbon sequestration benefits.

Building Climate Resilience in Darjeeling Tea

Studies demonstrated the significant impact of climate variability on Darjeeling tea by emphasizing the connection between increasing temperatures and rainfall patterns. High temperatures during the summer and monsoon seasons have an impact on tea production; on the other hand, higher temperatures during the winter and high rainfall during the summer advantageous for tea yields (Wijeratne, 1996; Wijeratne *et al.*, 2007; Ahmed, 2014). Research revealed that the monsoon months were the only ones with the most rainfall and the winter months had the lowest temperatures, which had a negative impact on the increase of tea output. Although the data showed an increase in rainfall, there remained seasonal variability. This also applied to temperature. Because the necessary rainfall and temperature were not occurring in the necessary months in Darjeeling area, both climatic parameters had a detrimental impact on the tea production. As a result, the tea yield decreased over time and unsustainable yields were attained.

Rainfall anomalies may be beneficial in some circumstances, but can provide unstable yields. Excessive rain at unfavorable times ruins the distinct flavor of tea.

Consequently, developing climate-resilient tea cultivars becomes a crucial step in reducing the adverse effects of these environmental shifts. Breeding strategies that emphasize drought and heat resilience should be prioritized in order to maintain production. Better resource management techniques, such as collecting rainwater and optimizing irrigation systems, can sustain production despite erratic rainfall patterns. Additionally, combining modern scientific techniques with traditional farming knowledge might lead to resistance.

Darjeeling tea farms can become more resilient to climate variability by combining these climate-smart treatments with balanced nutrient management. Sustainable farming methods provide a practical solution to preserve Darjeeling tea's production, quality, and international reputation for future generations by strengthening ecosystem stability, preserving natural resources, and increasing soil health (Yin *et al.*, 2024; Kumar *et al.*, 2024).

Conclusion

This study ends by emphasizing the critical impact that climatic variability has on the yield and overall production of tea in the Darjeeling region, since rising temperatures and changed rainfall patterns have a detrimental effect on tea yields. This is particularly troublesome from a socioeconomic

perspective because Darjeeling's tea production sustains the lives of thousands of workers and the local economy. Research and development expenditures are crucial in order to identify more resilient tea cultivars, enhance water management techniques, and look into innovative farming practices that can support tea production in light of changing climate circumstances. The necessity of a comprehensive approach to climate adaptation that supports the Darjeeling tea community through social and economic policies in addition to agricultural practices is also highlighted by this study. Future initiatives should integrate traditional knowledge and ecological practices with scientific insights to promote the sustainability of the tea business. Additionally, artisan methods, natural farming, tree protection, and community-driven strategies should be prioritized for strong and diverse growth.

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Popular Article

Precision Agronomy: Integrating Sensors, AI and Decision Support Systems for Climate Adaptation

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Abstract

Climate change is a major challenge to agricultural and allied sectors, increasing droughts, heat stress, erratic rainfall, floods, and pest outbreaks, which adversely effects the productivity and resource availability. Precision agronomy has emerged as a modern technology to improve climate resilience by integrating sensors, Artificial Intelligence (AI), and Decision Support Systems (DSS). Sensors monitor the crop, soil and environmental conditions, provide real time information on soil moisture, nutrient status, crop health and weather parameters. While Artificial Intelligence (AI) tools analyzes these data to identify patterns and predict crop stress, optimize irrigation and nutrient management and support timely interventions. Decision Support Systems (DSS) combine sensor data with AI models to provide site specific and location specific recommendations that improve farm management, resource use efficiencyand sustainability in production.

Keywords: Precision agronomy, Climat change, Sensors, Artificial Intelligence (AI), Decision Support Systems (DSS) etc.,

KEY HIGHLIGHT

- **Smart Monitoring:** Sensors provide real-time information on soil, crop, and weather conditions.
- **AI-Powered Decisions:** AI analyzes field data to predict crop stress and optimize farm management.
- **Site-Specific Farming:** GPS, GIS, remote sensing, and DSS enable precise, location-specific recommendations.
- **Resource Efficiency:** Precision technologies optimize water, nutrients, pesticides, energy, and other inputs.
- **Climate Adaptation:** Early stress detection and predictive decisions help farmers manage climate risks.
- **Sustainable Agriculture:** Integrated digital technologies improve productivity, resilience, and long-term sustainability.

Introduction

India is an agriculture-dependent country and it plays a major role in Indian economy. A large population depends on Agriculture and allied sectors for livelihood. Climate is one of the major factors affecting its production. Changes in climatic parameters like temperature, rainfall and other variables directly or indirectly influence agriculture productivity. According to the World Economic Forum (2024), India's agricultural output could decline by 16% by 2030, leading to a 2.8% drop in GDP. Therefore, adopting the agriculture and allied sector to climate change is very essential for sustainability in production. To address these challenges, precision agriculture has emerged as a modern technology that uses Sensoers for Moisture, Temperature, Salinity, Nutrient status etc., Artificial intelligence (AI) Tools and Decision Support systems (DSS) to support Climate resilient Agriculture. Precision Agriculture (PA) is also known as Smart farming (SF) or Precision Farming (PF) is a management strategy that uses data and technology to ensure crops and soil receive exactly what they

need for optimum health and productivity-minimizing waste, inputs, and environmental impact (Liao et al., 2012). It Primarily aims at optimizing profitability and protecting environment through efficient use of inputs based on temporal and spatial variability of soils and crops. Both sensors based and satellite image-based technologies have been developed and are being promoted in the developed world. This review summarizes recent advances in precision agronomy, focusing on the integration of sensors, artificial intelligence (AI), and decision support systems (DSS) for climate adaptation. It discusses their applications in improving resource use efficiency, crop productivity and resilience to climate variability, while highlighting current challenges and future research opportunities.

Effect or of Climate Change on Indian Agriculture

Rising Temperatures: Higher temperatures negatively impact crop yields. Research shows that for every 1°C rise in temperature, wheat yields may drop by 4-5%. Rice, maize, and other staples could face similar declines. World Economic Forum (2024).

Erratic Rainfall Patterns: The Indian monsoon, which provides nearly 70% of the country's annual rainfall, has become increasingly unpredictable. Delayed or deficient monsoons affect crop cycles and yields. Excess rainfall leads to water logging, damaging crops like paddy and sugarcane.

Increased Frequency of Extreme Weather Events: Droughts reduce water availability for irrigation, affecting crop productivity. Cyclones in coastal states such as Odisha, West Bengal, and Andhra Pradesh damage crops and disrupt supply chains. Between 2015 and 2021, India lost 33.9 million hectares of crops due to excess rains and an additional 35 million hectares due to drought (World Economic Forum, 2024).

Water Scarcity and Irrigation Challenges: Over 50% of India's agriculture is monsoon dependent, making it highly vulnerable to erratic rainfall.

Pest and Disease Outbreaks: Increased humidity fuels fungal and bacterial diseases in crops such as wheat, rice, and vegetables.

Need for Precision Agronomy

The increasing impacts of climate change have made conventional farming practices less effective in meeting the growing demand for food while conserving natural resources. Uniform application of irrigation water, fertilizers, and pesticides often ignores the spatial and temporal variability within agricultural fields, leading to inefficient input use, higher production costs and environmental degradation. Therefore, there is a growing need for precision agronomy, which focuses on site-specific crop and soil management based on real-time field information. Figure 1 shows the significant element of precision agronomy such as sensors, remote sensing, Global Positioning System (GPS), Geographic Information System (GIS), Artificial Intelligence (AI), and Decision Support Systems (DSS) to monitor crop and soil conditions and support timely management decisions. These technologies enable efficient use of water, nutrients, and crop protection inputs, improve productivity and profitability, and reduce environmental impacts (Evert et al., 2023). By providing early detection of crop stress, optimizing resource use, and improving resilience to climatic variability, precision agronomy has become an important approach for achieving climate-resilient and sustainable agricultural production.

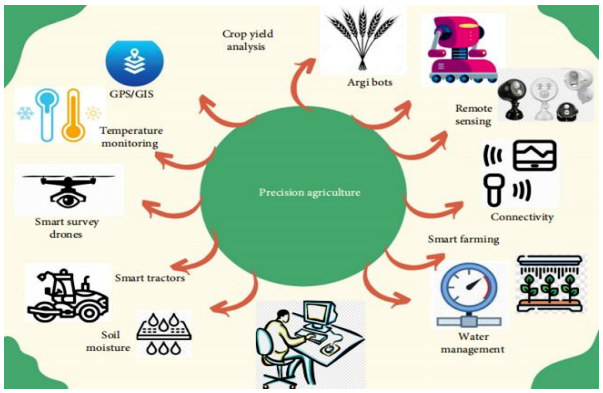


Figure 1. Framework of advanced technologies Precision Agriculture (Aarif et al., 2025)

Technologies used in Precision Agronomy

1. Sensors in Precision Agronomy:

Sensors are among the most important technologies in precision agronomy, providing real time information on soil, crop and environmental conditions to support site specific crop management (SSCM). They enable continuous monitoring of field variability, allowing farmers to make timely and informed decisions regarding irrigation, fertilization, pest management and other agronomic practices (Aarif et al., 2025). The use of sensors improves input-use efficiency, enhances crop productivity, minimizes environmental impacts, and contributes to sustainable agricultural production under changing climatic conditions. The major technologies ude in precision agriculture are summerized in table 1.

Table 1. Major Sensor technologies used in Precision agriculture and their applications

Category	Examples	Applications	References
Soil Sensor	Moisture content, Temperature, EC, pH, Nutrient availability	Irrigation scheduling, Water use efficiency Real-time information on soil fertility, Variable Rate application Techniques (VRTs).	(Aarif et al., 2025; Das et al., 2012).
Crop Sensor	Chlorophyll meters, Canopy reflectance sensors, Multispectral and Hyperspectral imaging sensors, IR thermography, Canopy temperature sensors, and Normalized Difference Vegetation Index (NDVI) sensors	monitor plant growth, physiological status, and crop health throughout the growing season	Das et al., 2012
Weather and Environmental sensors	Air temperature, Relative Humidity, Rainfall, Windspeed, Solar radiation, Atmospheric pressure, and Evapotranspiration Sensors	Localized weather information that assists farmers in scheduling irrigation, fertilizer application, and crop protection measures	Das et al., 2012
IoT Sensors	Wirless sensors, Sensor networks	Remote monitoring, AI Based decision making, Smart management	Kalpakis and Tang 2008

Sensors related to Remote sensing	**Unmanned Aerial Vehicles (UAVs) equipped with multispectral, hyperspectral, and thermal sensors**	**yield prediction, crop monitoring, resource optimization, and decision-making**	**Kalpakis and Tang (2008); Donta et al., 2022**
Integrated sensor Networks	AI-Decision support system, Field sensors	Decision support, real time management, Location specific recommendations	Lu et al., 2022

Despite their numerous advantages, sensor technologies face several challenges, including high installation costs, calibration requirements, maintenance needs, environmental interference, limited operational lifespan, and concerns regarding data security and privacy. (Aarif et al., 2025).

2. Global Positioning System (GPS):

The GPS is a navigation system based on a network of satellites that helps users to record positioning information (latitude, longitude and elevation) with an accuracy of between 100 and 0.01 m. GPS allows farmers to locate the exact position of field features, such as soil type, pest occurrence, weed invasion, water holes, boundaries and obstructions. There is an automatic controlling system, with light or sound guiding panel (DGPS), antenna and receiver.GPS satellite broadcast signals that allow GPS receivers to calculate their position. The GPS provides the same precise guidance for field operations. The system allows farmers to reliably identify field locations so that inputs (seeds, fertilizers, pesticides, herbicides and irrigation water) can be applied to an individual field, based on performance criteria and previous input applications.

3. Geographic Information System (GIS):

Use of GIS began in 1960. This system comprises hardware, software and procedures designed to support the compilation, storage, retrieval and analysis of feature attributes and location data to produce maps. GIS links information in one place so that it can be extrapolated when needed. Computerized GIS maps are different from conventional maps and contain various layers of information (yield, soil survey maps, rainfall, crops, soil nutrient levels and pests). GIS helps convert digital information to a form that can be recognized and used. GIS is a kind of computerized map, but its real role is using statistics and spatial methods to analysis. A farming GIS database can provide information on: filed topography, soil types, surface drainage, subsurface drainage, soil testing, irrigation, chemical application rates and crop yield. Once analyzed, this information is used to understand the relationships between the various elements affecting a crop on a specific site.

4. Artificial intelligence:

Precision farming is being transformed by AI, enabling new opportunity to address climate-resilient crop management. AI breakthroughs offer a complex response to quickly changing climate, rising global food consumption and environmental sustainability. This examined how machine learning (ML), remote sensing, Internet of Things (IoT), and data analytics synergistically produce adaptive and resilient agricultural methods (Patil et al., 2025). AI transforms farming by boosting decision making, resource efficiency, and climate change mitigation.

Precision farming using AI allows real time monitoring and predictive analytics for proactive crop management. AI combined with IoT and sensor technologies has greatly

increased resource utilization. AI-powered irrigation systems with soil moisture sensors optimize water distribution in water-scarce areas (Patil et al., 2025). AI soil and crop analysis guides precision nutrient management, reducing fertilizer waste and contamination. These advances show how AI promotes sustainable agriculture while lowering its environmental impact. Figure 2 presents the integration of Artificial Intelligence (AI) tools in precision agronomy for real time monitoring, decision making, and sustainable crop production.

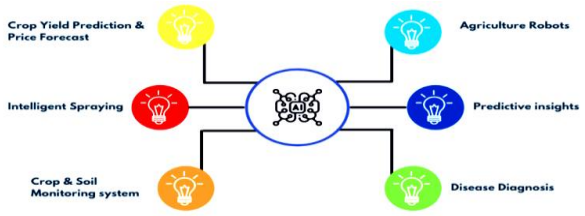


Figure 2. AI tools and their applications in precision agronomy (Bharat Agritech, 2025)

5. Decision Support Systems (DSS):

Precision farming employs advanced technologies such as computers, sensors, Global Positioning Systems (GPS), and remote sensing devices to monitor environmental conditions and optimize crop development (Duhan et al., 2017). However, the development of Decision Support Systems (DSS) to facilitate precise decision-making remains a significant challenge (McBratney et al., 2005). Decision Support Systems (DSS) play a vital role in precision agronomy by converting field data into practical farm management decisions. They integrate information from sensors, GPS or GIS, remote sensing, weather stations, and Artificial Intelligence (AI) to provide site specific recommendations. DSS assists farmers in irrigation scheduling, nutrient management, pest and disease control, and crop monitoring. It also supports yield prediction and efficient resource utilization by analyzing real-time and historical data. By optimizing the use of water, fertilizers, and pesticides, DSS reduces production costs and minimizes environmental impacts. Furthermore, DSS helps farmers adapt to climate variability through timely and data-driven decision-making. Overall, DSS enhances productivity, profitability, resource-use efficiency, and sustainability, making it an essential component of modern precision agronomy.

Integration of DSS with Sensors and Artificial Intelligence

Precision agriculture relies on continuous data collection from sensors, satellite imagery, soil sampling, GPS field mapping, remote sensing, and IoT devices. These data are integrated into Decision Support Systems, where Artificial Intelligence (AI) and advanced analytical techniques process the information to generate location-specific recommendations for crop management. Furthermore, the successful implementation of precision irrigation requires a comprehensive DSS capable of analyzing and synthesizing data from multiple sources (Lu et al., 2022).

IoT-based farm management information systems further strengthen DSS by automating data collection, processing, planning, tracking, decision-making, and management of farming activities. Ensuring the security and confidentiality of farmers' data is essential, highlighting the need for secure data handling and ethical considerations in precision agriculture.

Applications of Decision Support Systems:

Decision Support Systems play a vital role in agricultural management by increasing input profitability while ensuring the sustainable use of natural resources (Pavithra et al., 2023). By utilizing information from satellite imagery, soil sampling, GPS field mapping, and other data sources, DSS enables customized agricultural practices that match the specific conditions of each field. These systems support precision irrigation, nutrient

management, pest and disease management, crop monitoring, and yield optimization.

Application of Precision agronomy for Climate Adaptation:

Climate change has increased the frequency of droughts, heat waves, erratic rainfall, floods, and pest outbreaks, posing serious challenges to agricultural production. Precision agronomy provides an effective approach to address these challenges by integrating sensors, Artificial Intelligence (AI), Decision Support Systems (DSS), Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing, and Internet of Things (IoT) technologies. These technologies enable site-specific crop management and support climate adaptation through efficient resource utilization, early stress detection, and data-driven decision-making. The major applications of precision agronomy technologies for climate adaptation are summarized in Table 2.

Table 2. Applications of precision agronomy technologies for climate adaptation

S. No	Applications	Benefits	Barriers	References
1	Soil Health Mnagement	Soil health improvements by 20%–30%; resource use efficiency up by 15%	Poor soil fertility; inefficient resource use	Ahmad and Dar 2020; Monteiro *et al.,* 2021
2	Water Management	Water usage reduction by 30%–50%; crop yield increase of 10–20%	Water scarcity; inefficient irrigation systems	Ademei et al., 2017; Zafar et al., 2020
3	Surveillance and Crop monitoring	Yield improvement by 10%–25%; reduction in input costs by 15%	Lack of real-time crop data; high input costs	Balafoutis et al., 2017; Shaf et al., 2019
4	Nutrient Mnagement	Nutrient use efficiency up by 20%; reduction in fertilizer costs by 25%	Overuse of fertilizers; high nutrient costs	Parihar et al., 2020; Liang et al., 2023
5	Pest and Disease management	Pest/disease reduction by 20%–40%; crop loss reduction by 15–25%	Pest and disease management challenges	Robert et al., 2020; Panda 2021
6	Precision farming (Precision Planting and Harvesting)	Yield increase by 15%–30%; fuel savings of 10–20%	Inefficient planting/harvesting; high fuel costs	Ahmad and Dar 2020; Monteiro *et al.,* 2021
7	Climate adaptation and Risk Mangement	Improved crop resilience by 20%; adaptation costs reduced by 10%	Climate change impacts; adaptation costs	Balafoutis, 2017; Roy, 2020

8	**Crop production through advanced data management and analysis techniques**	**Crop production increase by 15%–25%; data management efficiency up by 20%**	**Low productivity; inefficient data management**	**Saiz-Rubio and Rovira-Mas, 2020**
9	Sustainable Resource management	Reduction in land degradation by 20%; resource usage efficiency up by 15%	Land degradation; inefficient resource use	Ahmad and Dar, 2020; Monteiro et al., 2021
10	Carbon management and Energy management	Carbon emissions reduction by 15%–25%; energy use reduction by 10–20%	High carbon emissions; high energy costs	Balafoutis, 2017; Soto et al., 2021

Overall, precision agronomy significantly improves resource-use efficiency by optimizing the use of water, fertilizers, pesticides, energy, and labor. It also reduces production risks associated with climate variability through timely monitoring and predictive decision-making. By integrating advanced digital technologies with climate-smart farming practices, precision agronomy supports sustainable agricultural production, enhances resilience to climate change, and contributes to long-term food security.

Challenges

Precision farming faces several challenges in world wide despite its promising potential to increase agricultural productivity and sustainability. The initial investment required for implementing Precision Technologies is often prohibitive, particularly for smallholder farmers. The high cost of GPS guided machinery, sensors, drones and the expenses associated with data collection and analysis pose significant barriers to adoption (Cheema *et al.,* 2023). In addition, the lack of reliable internet connectivity and electricity in rural areas hampers the effective deployment and operation of precision agriculture systems (Nayak et al., 2020).

Conclusion

Climate change has emerged as one of the greatest challenges to global agricultural production, demanding innovative approaches to improve resilience and sustainability. Precision agronomy has become an essential strategy for climate adaptation by integrating advanced technologies such as sensors, Artificial Intelligence (AI), and Decision Support Systems (DSS) to support data-driven farm management. Sensors provide continuous monitoring of soil, crop, and environmental conditions, AI enables accurate prediction and analysis of complex agricultural data, and DSS transforms these data into practical management recommendations. The integration of these technologies enables efficient management of water, nutrients, pests, diseases, and other climate-related stresses while improving productivity and resource-use efficiency. Precision agronomy reduces production risks associated with droughts, floods, heat stress, and unpredictable weather conditions through timely monitoring and predictive decision-making. Furthermore, site-specific management minimizes input wastage, lowers environmental impacts, and promotes sustainable agricultural production. Despite considerable progress, challenges such as high technology costs, inadequate digital infrastructure, limited technical expertise, and low adoption among smallholder farmers continue to restrict widespread implementation. Future success will depend on developing affordable technologies, strengthening digital infrastructure, improving farmer awareness, and expanding mobile-based advisory services and AI-driven Decision

Support Systems. With continued technological advancement and supportive policies, the integration of sensors, AI, and DSS will play a vital role in building climate-resilient, productive, and sustainable agricultural systems capable of ensuring global food security under changing climatic conditions.

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Popular Article

Traditional Knowledge for Sustainable Climate Justice and Adaptation

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Abstract

Climate change is a burgeoning issue wherein anthropogenic reasons is paving the way of climate change. Today, world is facing visible changes in increased temperature, change in precipitation pattern, frequent occurrences of climate shock etc. Unsustainable lifestyle coupled with policies that are governed by economic concerns and short-term priorities, often led to scenario where climate changes aggravated and prominent impacts were largely seen to be not followed equitable distribution. Indigenous people always tend to live a life that tries to maintain balance between humans and natural environment. Their low environmental footprint in one side causes less harm to climate and in other side, being the most vulnerable people are taken severe hit of climate change. Thereby climate justice needs to be at the forefront for making any climate policies. Intergenerational and community-based traditional knowledge coupled with scientific data in this regard can play a pivotal role to forefront equity and justice system. Here in this chapter author argues for possible framework for channelizing power of ITKs in climate change adaptation.

Keywords: Traditional knowledge, Climate change, climate justice

KEY HIGHLIGHT

- ⚖️ **Climate Justice:** Vulnerable smallholders face disproportionate impacts of climate change.
- 🌾 **Agroecology:** Diversified, ecological farming can strengthen resilience and reduce degradation.
- 👩‍🌾 **Indigenous Knowledge:** Traditional practices support biodiversity, soil health, and climate adaptation.
- 🌱 **Seed Conservation:** Seed festivals and community seed banks help preserve indigenous varieties.
- 🤝 **Community Benefits:** Benefit-sharing and ecosystem payments can support livelihoods and conservation.
- 🔬 **Science & Tradition:** Validating and integrating traditional knowledge with modern science can strengthen climate resilience.

Climate justice- a growing challenge for agriculture

Environmental issues possess a great threat to the sustainability across different section, process, activity of society. The unsustainable lifestyle of people is a major anthropogenic reason coupled with other biotic and abiotic factors that are causing aggravation of climate change. Climate change is causing concern for food security and poverty. Various effects have

been reported in agricultural sector, like shifting of cultivable areas, shifting of crops, change in preference of insect pest scenario, genetic erosion, loss of biodiversity, water scarcity, enhancing heat stress, feed scarcity, etc. The small holder farmers residing in vulnerable areas are mostly affected. Moreover, marginal resource less rain fed farmers who are possessing marginal plots with poor irrigation facilities, problematic soils etc. So, climate sensitive policies with ethical, inclusive, and context-sensitive responses approach driven by equity and justice value system is need of the hour. Making transition to a more climate sensitive food production system, policy recognition of the fact that resource less farmers needs to be heard, sensitized, supported to protect their lives and livelihoods and also to convert resistance of climate action to become advocating change is highly needed.

Agro-ecological approach

Agro-ecological approach is a holistic approach for production of food which has transformative effect to mitigate climate change. These agro-ecological practices include landscape management, resource management, biodiversity, crop rotation, soil health, and natural pest control etc. Promoting local diversified sustainable farming system following ecological principles, retards environmental degradation and promotes regenerative agriculture. Agro ecological principles focused on participatory process of co-creation of knowledge with direct connections building between producers and consumers, and reducing existing social inequities (Nicolétis et al. 2019).

Indigenous Technical knowledge system and communication network

Indigenous knowledge is local as it is rooted in a particular community and cultural traditions; it is dynamic in nature as ITKs are generated, reproduced, discovered as well as lost. This is tacit knowledge, experiential rather than theoretical as well as repetitive. Indigenous Technical knowledge system often comprises of time tested knowledge passes through word of mouth from one generation to other. Every society has this knowledge, specially the primitive society where developmental efforts were minimal possesses a great deal of traditional knowledge. In agriculture and allied sector, traditional knowledge exists and practiced in varying intensity. ITKs can be integrated in Biodiversity conservation, conserving traditional seeds, ecosystem integration, natural pest and disease management, soil health and fertility, cultural and spiritual significance, community engagement and decision, and climate resilience (Tripura et al., 2024). Ethnopedological knowledge helps to understand folk taxonomies as well as systematic classification and management of soils by indigenous folks (Nag et al., 2017). Strong local connection to their ecosystems, makes it possible to adapt diverse ecological niches through careful observation and experimentation. ITKs mostly follows oral communication network. However, documenting ITKs and validating them to integrate with modern science can help in achieving true potential of ITKs.

Various national level efforts taken for promotion of ITKs include collection, documentation and validation of indigenous technical knowledge under National Agricultural Technology Project (NATP) project was undertaken by ICAR wherein ICAR documented and validated a total of 4880 ITKs in 28 thematic areas were collected, validated and published in seven volumes. Through Protection of Plant Varieties and Farmers Rights Authority (PPVFRA) a total of 5262 plant varieties IP is protected under farmers (2005-2026). This

effective system for protection of plant varieties considered necessary to recognize and protect the rights of the farmers in respect of their contribution made at any time in conserving, improving and making available plant genetic resources for the development of the new plant varieties.

The process of recognizing and promoting ITKs involve following steps like Identification of ITK's being used by the Farmers through voluntary sharing of primary information. For this survey methods, critical incident techniques, agro-ecosystem analysis, case studies, FGDS etc are important strategy to identify ITKs. In next step, ITKs are validated, through literature validation, scientific validation through expert judgement or experimentation. In simplest form comparative results are ascertained with and without application of ITKs in on station as well as on farm trial. The process of validation of ITKs shall be always interpreted for rationality, value and belief system of the farmers holding ITKS. In next phase, validated ITKs are documented for readily accessibility. In next phase, upscaling and out scaling of ITKs are performed. During upscaling, institutional efforts are needed for integrating ITKs with modern science and in out scaling, Multi Locational trials (MLTs) are conducted.

Innovative approaches for maintaining and mainstreaming ITKs

Seed festival: Seed festivals celebrate and showcase indigenous seeds. At these events, farmers gather to display various traditional seed varieties, creating a vibrant forum for exchanging ideas and thoughts regarding native crops. For example, the **Bihan Mela** (seed festival) is celebrated among members of the Kondh tribe in Odisha's Nayagarh district.

Traditional Seed Bank: This is a community owned seed bank, where farmers voluntarily deposit and preserve their indigenous varieties. Farmer can take these varieties from the bank and next year they need to return double the quantity (or norm fixed by the community) of seeds or additional varieties for preserve and promotion through seed bank.

Rewarding farmers: Farmers who are engaged in germplasm saving are given awards for recognizing their efforts and to create a source of motivation for promotion of germplasm. One such award is Plant Genome Saviour Community Awards which is given to the tribal and rural communities engaged in conservation, improvement and preservation of genetic resources of economic plants and their wild relatives particularly in the areas identified as agro bio-diversity hotspots.

Biodiversity financing: Access and benefit sharing (ABS) is the core of biodiversity financing. ITKs held by communities for preserving biological resources can be accessed by private business houses and fair benefits are being shared with the communities. This mechanism is a Win-Win strategy for both communities and business houses. In one side, the voluntary certificate accessed by the business house is testament to the fact that it enhances the uptake of the ABS legislation and also bring back currently non-compliant bio-resource users into the ABS system; promotion of biodiversity-responsible businesses; enable consumers to support companies that contribute to local communities. And in other side, the local entities receive fair benefits which lead to generation of livelihood and community up-liftment.

Payment of Ecosystem Services: Indigenous farming systems like Apatani paddy-cum-fish cultivation system practiced in Ziro Valley of Lower Subansiri district, Arunachal Pradesh, demonstrates how indigenous knowledge and

locally adapted management practices can sustain agricultural production over long periods with role in resource conservation, food production, and the long-term sustainability of farming. The Zabo system is an indigenous farming system practiced in Phek district, Nagaland, India. It is an indigenous, gravity-fed resource management model that seamlessly integrates forestry, water harvesting, livestock rearing, and agriculture into a self-sustaining loop on steep hill slopes. These traditional practices excel at maximizing ecosystem services. While four broad types of ecosystem services exist (provisioning, regulating, cultural, and supporting), there is a pressing need to make them economically viable by formally embedding **Payment for Ecosystem Services (PES)** into regional policies. These policy mechanisms utilize financial instruments ranging from voluntary to non-voluntary compensation schemes.

Way forward

Climate-resilient agriculture cannot rely solely on technological innovations. Traditional knowledge systems, supported by strong communication networks, provide practical, location-specific solutions that have the potential to sustain farming communities for generations. Indigenous technical knowledge (ITK) has a long-lasting effect on agriculture, especially in the face of global warming and climate-change-related effects. Adaptation measures, as well as coping strategies followed by farmers and governed by their time-tested knowledge, not only have immediate benefits but also have immense potential for promotion on a wider scale. The approach should move from the mere collection and documentation of ITKs to their validation, intellectual property protection, and financial benefit-sharing, facilitating a sustainable transition by integrating them into modern scientific practices. A concerted effort to create synergy among different domains, including research, extension, and policy, would be beneficial to harness and streamline the ITKs possessed by the community.

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Popular Article

Impact of climate change on flowering and production of cut flowers

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Abstract

Climate change poses multidimensional challenges to the floriculture industry, impacting flowering pattern i.e. temperature, photoperiod and CO_2 level and precipitation changes; changes in flower quality and yield; shift in growth dynamics and resource allocation. Floriculture crops are highly sensitive to environmental changes. Therefore, suitable adoption measure needs to be taken to cope the climate change. Breeding of climate resilient varieties of floriculture crops, smart agricultural practices, protected cultivation will be helpful to mitigate the impact of climate change. Future research should focus on species specific responses, interaction of multiple stress factors, phenotypic changes in various climate, advance studies on genomics and biotechnological tools will cope the climate change situations.

Keywords: Climate change, heat stress, drought tolerant, precipitation, photoperiod, CO_2, flowering pattern.

KEY HIGHLIGHT

- **Flowering Shifts:** Rising temperatures, changing photoperiod and CO_2 levels alter flowering time and patterns.
- **Water Stress:** Drought, excessive rainfall and waterlogging reduce flowering, quality and yield.
- **Flower Quality:** Climate stress affects flower size, colour, shape, fragrance and post-harvest life.
- **Resilient Varieties:** Heat-, drought- and salinity-tolerant cultivars can strengthen climate resilience.
- **Smart Practices:** Precise irrigation, mulching, shading and protected cultivation help reduce climate impacts.
- **Future Solutions:** Phenological modelling, genomics and biotechnology can support climate-resilient floriculture.

Introduction

The Earth climate system constantly adjusts between the received energy from sun and the energy goes from Earth to space. The misbalance of energy causes the warming of the Earth. The global warming is changing the timing of important developmental and behavioral events. Warming of climate affect the species ranges and interaction with existing tropic range. The phenological changes occurred due to global climate change alter the population levels and have profound impact on ecosystem and evolution. The rise in temperature is attributed to alarming increase in the atmospheric concentration of greenhouse gases CO_2, CH_4, N_2O and chlorofluorocarbons mainly due to accelerated consumptions of fossil fuels in industry and transport. The average global temperature has increased by 0.8^oC in past 100 years and it projected to rise by 1.8 to 4.0^oC by the year 2100. The warming also associated with rainfall pattern, increased frequency of extreme events of drought, frost and flooding. Climate change interacts with habitat loss and fragmentation; introduced and

existing species and population growth, will bring the modification of many ecosystems. Floriculture is increasingly regarded as a viable diversification from the traditional field crops due to increase per unit returns. With the opening up of world market in the WTO regime, there is a free movement of floricultural products worldwide. In this context, each and every country has equal opportunity for trade in each other's territory. Globally, more than 140 countries are involved in cultivation of floricultural crops. The USA continues to be the highest consumer with more than $ 15 billion per annum, followed by Japan with more than $ 10 billion.

Impact of climate change on flowering pattern

Temperature is a major environmental factor which regulates quality of flowering and timing in floriculture crops and even small changes can significantly shifts in phenology (Chandel et al. 2023). It was recorded that an increase of just 1^{o} C can advance the flowering time by 6 days in temperate region. Warming temperatures hasten early flowering in Tulip and Daffodils. Higher temperatures also affect quality of flowering and morphology in chrysanthemum and snapdragons, increased temperatures cause flower bud abortion, reduced petal size and discolouration of blooms. In some cases, heat stress reduces pollen viability and stigmatic receptivity in Petunia and Lilium, whereas, cold stress affects flower yield of Geranium.

In many floriculture crops, photoperiod is key determinant factor for transforming vegetative phase to reproductive phase. Regional climates may shift crop to new latitude and unfamiliar photoperiod regimes. Change in day length can disrupt flowering of Chrysanthemum and other short day loving flowers (Proietti et al.2022). In addition to photoperiod, the CO_2 level of atmosphere is expected to reach 550ppm by 2050 which will directly affect flowering phenology. Increased level of CO_2 will promote early flowering, flower size and numbers in many flowering species resulting improving market value. The interaction between elevated CO_2 and temperature can lead to unpredictable outcomes.

Climate change is expected to change global precipitation patterns, leading to increased frequency and intensity of droughts, heavy rainfall, and extreme weather events (Trenberth 2005). These changes have significant implications for the flowering patterns of floricultural species, particularly those sensitive to water availability. Drought stress can delay flowering, reduce flower size and quantity in many flowering crops like Marigold, Chrysanthemum and Zinnia. This is due to disruption of abscisic acid and gibberellins level. It was found that severe water stress period leads to abortion of flowers and bud formation in Balsam. Excessive rainfall as well as waterlogging are also detrimental like water stress affecting flowering and overall plant health**.** It was observed that water logged conditions severely increased bud drop, poor quality of flower, leaching of nutrients, increased diseases in many floriculture crops like Rose, Zinnia, Chrysanthemum, Marigold, Tuberose and Carnation in open field condition. Extreme weather events like hails, storms, frosts also pose thread to floriculture crops.

Flower quality is a major qualitative trait in floriculture business. The price of floriculture commodity is related with the freshness and appearance. Climate change affects size, shape, colour, fragrance and post- harvest life of flowers (Muchie and Assefa 2021). Heat sensitive flowers like Rose and Carnation are directly affected by elevated temperature during flowering time. Reduced flower size, petal number, petal scorching and altered pigmentation was observed in Rose. Elevated temperature during bud initiation induced premature bud differentiation which leads to deformed size in Chrysanthemum. High

temperature during early growth induces stem elongation, reduce flower size and weaker stem strength in Lilium. Also, higher temperature for prolong period induced tip burning, deformed bud, little leaf in Snapdragon and Poinsettia. Higher temperature induced shorter flower stem, deformed bud or unopen bud in Cymbidium. Extreme weather induced discolouration of petal in Phalaenopses, Cattleya and in Cymbidium. Chilling injuries like browning of throat, blackening of stem, water-soaked spot-on petals and sepals were observed in Cattleya, Cymbidium and Cypripedium and Vanda when growing below 15^{o}C, whereas temperature above 35^{o}C and below 15^{o}C induced shorter stem in Dendrobium.

Climate change also changes the resource allocation pattern in floriculture plants. Higher atmospheric CO_2 promotes increased biomass production due to enhanced photosynthesis and water use efficiency. In Petunia and Geraniums, elevated CO_2 increase vegetative growth at the expense of reproductive output, leading to poor flower yield. This reduces the aesthetic quality of cut flowers and potted plants. Similarly, increased levels also enhance stem length, thinner stems and more leaf area and lower bud formation of Carnation. Like CO_2, higher temperature also promotes excessive vegetative growth and a reduction in flower bud differentiation in heat sensitive flower crops. The productivity and market quality of floriculture species will be influenced by climate induced changes.

The climate change situation has a direct impact on floriculture industry as productivity, quality and time of flowering is related to profitability. This impact is more profound in high value low value flowers like Orchids and Roses. The mismatches between peak market demand and production for seasonal flowers like Chrysanthemum and Poinsettias disrupt the supply chains and reduced the profitability of growers. The floriculture industry is vulnerable to extreme weather events like hailstorms, floods and heat wave etc. causes severe damage to flower fields or structures resulting heavy loses to farmers.

Adoption and mitigation strategies

Climate change poses serious thread to floriculture industry impacting production and productivity. To address the issues suitable strategies, need to adopt to mitigate the challenges for sustainability of floriculture industry. Development of climate resilient cultivars is the long-term strategy to mitigate the climate change. Both conventional and molecular breeding technologies are employed to develop heat, drought salinity tolerant varieties. In Roses, breeding for heat tolerance has focused on selected genotype for maintain qualitative traits like flower size, colour and aroma. Transgenic approach has been adopted for developing heat tolerant varieties in Chrysanthemum. Water scarcity becoming a serious climatic thread in some floriculture growing area. Conventional breeding method is employed to develop drought tolerant variety of Chrysantemum and Geranium. Strategies are taken to develop salinity tolerant varieties of Lilium and Gladiolus.

Timely adopting agronomic practices such as sowing, site-specific irrigation, nutrient management and stress management are the key indicator for mitigate the climate challenge. Adoption of sprinkler irrigation or misting in Orchids, drip irrigation in Carnation, Rose, Gerbera and Chrysanthemum improve yield and quality and reduce cost of production. Mulching and shading during hotter season are another agronomic practice to cope the moisture stress and improve quality flowers of Chrysanthemum and Carnation. Controlled climatic condition now a days used to grow high value flowers like Orchids and Chrysanthemum (Chandel et al. 2024).



Figure: Automation of green house for timely planting to harvesting of market driven crops

Climate models which include temperature, precipitation and Carbon-di-oxide are using in scheduling planting time and date and adjusting production times in floriculture crops. Phenological models are used to predict flowering times of different commercial flowers where precise flowering time is critical for market supply. In green house production of Orchids and Chrysanthemum, Decision Support System is an effective tool for predicting crop growth and flowering. Zhao et al. (2013) reported that use of regional climate projection and risk assessment models can help policy makers and stake holders for adopting effective strategies for development of sustainable floriculture sector.

Future Strategy

Climate change poses unprecedented challenge to the floriculture sector. Future research needs to address on species specific and long-term research, multi-stressed impact and genetic and phenotypic mechanism**.** Species specific studies should include details phenotypic observations under controlled and field conditions to understand how many species are responding to variation of temperature, photoperiod and CO_2 levels and rainfall pattern. Long term studies on phenological observations of Roses and Chrysanthemum could be helpful in predicting flowering time that impact crop scheduling and marketing. Establishment of long-term field trial and phenotypical databases is the need of the day for the anticipation of climate change impact. Multi-stress impact assessments should address the simultaneous changes in temperature, water availability and CO_2 affect the photosynthesis, nutrient uptake and hormone regulation which impact on flowering and biomass production (Roy and Mathur2021). Phenotypic plasticity, genetic adaptation, genomics and biotechnology are tools for addressing the climate change in floriculture.

Conclusion

Climate change will have impact on floriculture crops due to erratic rainfall; more demand on water and enhanced biotic and abiotic stresses. Measures to adopt to this climate changed induced changes are critical for sustainable production of flowers. Increased temperature

will have more effect on reproductive biology. Reduced water may affect productivity, however, suitable adoptive mechanism like time of adjustment of sowing or planting precise use of water shall reduce negative effect of impact in flowering crops. The strategies must have to identify the gene tolerant to high temperature, flooding and drought, nutrient efficient cultivars and production system to efficient use of inputs. Strategies have to address the enhanced water use efficiency, cultural practices that conserve water and promote crop. Development of climate resilient cultivars that are tolerant to high temperature, moisture stress, salinity and validation through genomics and biotechnological tools would be essential requirement.

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IN THIS ISSUE

- Climate Change and Crop Health
- Precision Agronomy: Integrating Sensors, AI and Drones
- Climate Change Impacts on Tea Biochemistry and Quality
- Climate-Smart Agriculture and Extension Strategies
- Emerging Livestock Diseases and Climate Risk
- Climate-Change Impact on Darjeeling Tea
- Integrated Pest Management for Changing Climate
- Climate-Smart Villages for Resilient Future
- Nature-Based Solutions for a Sustainable Future
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