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CLIMATE-SMART STRATEGIES FOR RESILIENT VEGETABLE PRODUCTION SYSTEMS

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Abstract

Vegetable crops become significant risks to global nutritional security due to their high-water content and genetic susceptibility to environmental changes, making them especially vulnerable to the detrimental effects of climate change. This study focuses on how the primary abiotic hazard such as drought, flooding, heat, and salinity affect the growth, yield, and quality of vegetable crops physiologically. The study evaluates climate-smart adaptation strategies, including as grafting techniques, precision irrigation technologies, climate-resilient varieties, and biotechnology interventions. System-based approaches that combine smart technologies with sustainable resource management are the main focus in order to increase resilience and productivity.

Keywords: Abiotic stress, climate resilience, grafting, resilient varieties, sustainable horticulture, vegetable production

1. Introduction:

Vitamins, minerals, dietary fibre, and a variety of bioactive substances that help prevent chronic diseases are all abundant in vegetables, which are an important part of human nutrition (Slavin & Lloyd, 2012). Vegetables are extremely sensitive to changes in their environment and have limited ecological potential because of their succulent nature, with water content frequently exceeding 90% (Bhardwaj *et al.*, 2025). In particular, during important phases of development like flowering and fruiting, abiotic stresses like flooding, high temperatures, erratic precipitation, and soil salinity—all of which are made more frequent and intense by climate change—disturb plant morpho-physiology and metabolic processes, negatively impacting vegetable growth, yield, and quality (Laxman *et al.*, 2024; Gruda, 2005). These pressures threaten crop revenue and supply chain stability, which especially impacts smallholder farmers, in addition to threatening public health through nutritional insecurity (Bose & Pal, 2023). To protect vegetable production systems in the context of changing climate circumstances, sturdy, scientifically verified resilience methods are desperately needed.

2. Physiological Impacts of Major Abiotic Stresses

2.1 High Temperature

In thermosensitive vegetable crops, thermal stress significantly reduces productivity, particularly during reproductive development. According to Laxman *et al.* (2024), male gametogenesis is inhibited by day/night temperatures above 34/18°C. This leads to decreased pollen viability, disturbed anther dehiscence, and impaired ovule function, all of which result in poor fruit set. For instance, pollen viability in tomatoes drops significantly beyond 37°C, and similarly in chili peppers over 40°C (Dahal *et al*., 2006; Mazzeo *et al*., 2018). Heat stress affects photosynthesis at the cellular level by causing oxidative stress through the formation of reactive oxygen species (ROS), compromising membrane integrity, and decreasing photosystem II efficiency (Kruk *et al*., 2005).

2.2 Drought and Waterlogging

Reproductive stages are significantly impacted by drought stress, which results in osmotic imbalance, stomatal closure, and photosynthetic reductions. When transpiration occurs during flowering or fruiting, tomato yield decreases of more than 50% have been documented (Manjusree *et al*., 2012). Low soil moisture additionally interferes with crop establishment since it reduces okra and onion germination rates (Arora *et al*., 2010). On the other hand, waterlogging creates hypoxic soil conditions that limit roots' ability to breathe aerobically. Under saturated conditions, ethylene buildup causes wilting, flower and fruit abscission, and leaf epinasty. After merely a few days of soil saturation, tomato plants suffer permanent damages (Bhatt *et al*., 2015), and after a week of flooding, onions can exhibit a reduction in photosynthesis of up to 86% (Srinivasa Rao *et al*., 2010). In vulnerable crops, like tomato and chillies waterlogged soils additionally result in changes in nutrient intake, such as deficiencies in calcium and nitrogen, which can lead to physiological problems like blossom end rot.

2.3 Soil Salinity

Both osmotic pressure and ionic toxicity are triggered by soil salinity stress, which is frequently made severe by improper irrigation techniques or coastal incursion. Excess sodium (Na^+) and chloride (Cl^-) ions impede the growth and development of plants by interfering with the absorption of vital minerals like calcium and potassium (Singh *et al*., 2012). When exposed to salt, tomato and chilies exhibited decreased germination, delayed reproductive development, and less and smaller fruits (Mustafa *et al*., 2014). Electrical conductivity (EC) levels of 6.7 dS m^{-1} could result in a 50% reduction in okra yields (Minhas & Gupta, 1993). Salinity also affects agricultural productivity by decreasing chlorophyll content and oxidatively damaging stomatal conductance and photosynthetic activity (Shao *et al*., 2023).

3. Adaptation and Mitigation Strategies

3.1 Climate-Resilient Varieties

Vegetable varieties with improved resistance to particular abiotic stresses have been developed effectively by breeding programs, and their use is a key component of climate adaptation (Table 1). By using both traditional as well as modern breeding techniques, such as marker-assisted selection and gene editing, these climate-resilient plants frequently integrate characteristics including resilience to heat, drought, and salinity (Mohapatra *et al*., 2025). For smallholder farmers dealing with climate constraints, speed breeding facilities have sped the breeding cycle, allowing for up to 4–6 generations per year for features like disease resistance and thermotolerance in tomatoes and peppers. The resilience base is further strengthened by using the genetic diversity present in landraces and wild relatives, which allows steady yield in a variety of circumstances (Upadhyay *et al*., 2025).

3.2 Grafting Technology

Grafting combines strong, stress-tolerant rootstocks with superior scions to improve tolerance to abiotic stresses. As a case study, tomato grafted onto brinjal rootstocks (IC-111056, IC-354557) show exceptional recovery and resilience during prolonged waterlogging (Rai *et al*., 2023; Bhatt *et al*., 2015). Melons grown on hybrid squash rootstocks also exhibit improved resistance to drought and salinity (Rouphael *et al*., 2010; Romero *et al*., 1997). According to estimates, this strategy can reduce the effects of abiotic stress in agricultural environments by up to 70%, which will improve crop survival along with yield stability (Bhardwaj *et al*., 2025).

3.3 Precision Irrigation and Agronomic Management

Water-smart irrigation methods, notably drip irrigation, optimize soil moisture availability while reducing water use by 30–40% and increasing yields by up to 50% (Bhardwaj *et al*., 2025). Mulching with organic materials or polyethylene helps moderate soil temperature and conserve moisture, and enhances soil structure and resilience through organic matter enrichment. These practices collectively support adaptive water management crucial in climates prone to drought or erratic rainfall.

3.4 Biotechnological Innovations

Physiological supplements such as foliar sprays of salicylic acid (250 μM) or sodium nitroprusside (25 μM) have been shown to enhance reproductive resilience under stress by modulating antioxidant systems and hormonal balance (Rai *et al*., 2023). Transgenic approaches have multiple stress-responsive genes such as *AIDREB1A* (*Arabidopsis thaliana* Dehydration-Responsive Element Binding 1A) and *BcZAT12* (*Brassica campestris* Zinc-finger protein 12) into tomatoes, resulting in improved water-use efficiency, photosynthetic stability, and antioxidant defense mechanisms under combined abiotic stresses. These advances translate into sustained productivity in adverse environments and promise future potential for multi-trait climate resilience (Mohapatra *et al*., 2025).

Table 1. Examples of climate-resilient vegetable varieties

Crop	Variety/Hybrid	Tolerance Trait
Tomato	Kashi Adbhut (>38°C), Kashi Tapas (>38°C), Thar Anant, Pusa Sadabahar (8°C and 28°C)	Heat tolerance
	Arka Vikas, Arka Meghali	Drought tolerance
	Pusa Sheetal	Low temperature fruit set (8°C)
Brinjal	Pragati, Pusa Bindu	Salinity tolerance
Okra	Pusa Sawani	Salinity tolerance
Radish	Kashi Rituraj	Heat tolerance (up to 43°C)
Onion	Arka Kalyan	Waterlogging tolerance
Bottle Gourd	Pusa Santushti	Dual heat and cold tolerance
Cowpea	Arka Garima, Arka Suman	Water-limited conditions tolerance
Water Spinach	Kashi Mannu	Drought, cold and water logging conditions

French Bean	Kashi Sampann, Kashi Rajhans	Heat tolerance (up to 38°C)
Indian Bean	Kashi Bouni Sem-3, Kashi Bouni Sem-9	Heat tolerance (up to 35°C).
Garden pea	Arka Sampoorna, Oregon Sugar, Magadi local, Arka Uttam, Arka Apoorva, IIHR 680, PMR 37, and Swarna Mukti	Heat tolerance

(Source: Laxman *et al*., 2024; Rai *et al*., 2023 Susmita *et al*., 2020; Mohapatra *et al*., 2020; Verma *et al*., 2019)

3. Adaptation and Mitigation Strategies

3.1 Climate-Resilient Varieties

Breeding programs have successfully developed vegetable cultivars with enhanced tolerance to specific abiotic stresses, making the deployment of such varieties a cornerstone of climate adaptation (Table 1). These climate-resilient varieties often incorporate traits such as heat tolerance, drought resistance, and salinity tolerance through conventional and modern breeding technologies including marker-assisted selection and gene editing (Mohapatra *et al*., 2025). Speed breeding facilities have accelerated the breeding cycle, enabling up to 4–6 generations annually for traits such as thermotolerance and disease resistance in tomato and pepper, critical for smallholder farmers facing climate pressures (World Vegetable Center, 2025). Utilizing the genetic diversity found in wild relatives and landraces further broadens the resilience base, enabling stable yield under diverse environments (Upadhyay *et al*., 2025).

3.2 Grafting Technology

Grafting facilitates improved tolerance to abiotic stresses by combining elite scions with robust, stress-tolerant rootstocks. For example, tomato grafted onto brinjal rootstocks (IC-111056, IC-354557) exhibits remarkable resilience to prolonged waterlogging and superior recovery (Rai *et al*., 2023; Bhatt *et al*., 2015). Similarly, melons grafted onto hybrid squash rootstocks show enhanced tolerance to both saline and drought conditions (Rouphael *et al*., 2010; Romero *et al*., 1997). This approach has been estimated to mitigate up to 70% of abiotic stress impacts in field conditions, significantly improving crop survival and yield stability (Bhardwaj *et al*., 2025).

3.3 Precision Irrigation and Agronomic Management

Water-smart irrigation techniques, like as drip irrigation, maximize soil moisture availability while minimizing water use by 30–40% and enhancing yields by as substantially as 50% (Bhardwaj *et al*., 2025). By replenishing the soil with organic matter, mulching with polyethylene or organic materials improves soil structure and resilience while regulating soil temperature and preserving moisture. When combined, these techniques promote adaptive water management, which is essential in regions that are vulnerable to drought or unpredictable rainfall.

3.4 Biotechnological Innovations

It has been demonstrated that physiological supplements that alter antioxidant systems and hormonal balance, such as foliar sprays of sodium nitroprusside (25 μM) or salicylic acid (250 μM), improve reproductive resilience under stress (Rai *et al*., 2023). AIDREB1A and BcZAT12 are two examples of the numerous stress-responsive genes that transgenic techniques have incorporated into tomatoes, improving their water-use efficiency, photosynthetic stability, and antioxidant defence mechanisms under a variety of abiotic stressors. According to Mohapatra *et al*. (2025), these developments offer the possibility of multi-trait climate resilience in the future and translate into prolonged productivity in challenging situations.

4. Conclusion

In light of the information mentioned above, systemic agronomic, physiological, and genetic techniques is necessary to make vegetable production systems climate change resilient. Abiotic hazards can be considerably mitigated by producing and making use of climate-resilient varieties that can withstand various stresses, grafting techniques, and precise water management. In addition to conventional breeding efforts, biotechnological advancements offer instruments to improve plant adaptation mechanisms at the molecular level. Implementing effective approaches requires combining these scientific advancements with farmer-focused extension services along with supportive policy frameworks. In increasingly unpredictable and intense climatic conditions, such holistic approaches are crucial to maintaining vegetable production, nutritional quality, and food security.

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