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Breeding Climate-Resilient Vegetable Crops For National Food Security

Augusty Libang[1]* and Ajaz Ahmed Malik[2]
[1]Ph.D. Scholar, Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, India, email id: libangaugusty45@gmail.com
[2]Associate Professor, Senior Scientist, Head KVK, Ganderbal, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, India, email id: **ajazmalikskuast@gmail.com**
*Corresponding email address: libangaugusty45@gmail.com
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Abstract

Climate change is already reshaping the conditions under which vegetables are grown, bringing more frequent heat waves, erratic rainfall, and new pest and disease pressures that threaten yield stability and nutritional supply. Because vegetables are highly perishable, shallow-rooted, and often grown on marginal land by smallholders, they are especially vulnerable to climatic shocks, yet they remain central to dietary diversity and micronutrient security. Breeding climate-resilient vegetable crops, tolerant of heat, drought, flooding, salinity, and shifting pest complexes, is therefore a strategic priority for national food security. This article reviews the physiological and genetic basis of climate resilience in vegetable crops, examines modern breeding tools including genomic selection, marker-assisted breeding, and genome editing, and discusses institutional and policy measures needed to deliver resilient varieties to farmers at scale. Aligning breeding programmes, seed systems, and extension services around climate resilience offers a practical pathway to safeguard vegetable production and national nutrition security in an increasingly volatile climate.

Keywords: climate resilience, vegetable breeding, genomic selection, food security, abiotic stress, crop wild relatives

Introduction

Vegetables occupy a small share of cultivated land globally but supply a disproportionately large share of dietary vitamins, minerals, and fibre. This makes their continued productivity essential not just for farm income but for national nutrition security. However, vegetable crops are often more climate-sensitive than staple cereals. Many widely grown vegetables, including tomato, cabbage, pea, and okra, show sharp yield and quality declines when temperatures exceed narrow physiological thresholds during flowering and fruit set. Rising minimum night temperatures, prolonged dry spells punctuated by intense rainfall events, and expanding ranges of insect pests and pathogens are converging to threaten vegetable production systems across tropical, subtropical, and even temperate regions.

National food security strategies have traditionally focused on cereal self-sufficiency, but the growing burden of micronutrient deficiencies, sometimes called hidden hunger, has shifted attention toward the resilience of horticultural crops as well, particularly as global assessments continue to flag persistent food insecurity and malnutrition even where staple grain supply is stable (FAO, 2023). Breeding climate-resilient vegetable varieties, capable of maintaining yield and nutritional quality under heat, drought, waterlogging, and salinity stress, is now recognized as an essential complement to cereal-focused food security policy. The stakes are particularly high for countries where vegetables form a major share of both farm income and dietary micronutrient intake, since a single poor season can simultaneously depress rural earnings and worsen child and maternal nutrition outcomes. This article examines the scientific basis for climate resilience breeding in vegetables, surveys the tools available to breeders, reviews illustrative examples across major vegetable groups, and outlines the institutional changes needed to move resilient varieties from research stations into farmers' fields at national scale.

Why Vegetable Crops Are Climate-Vulnerable

Several biological and structural features make vegetable crops particularly exposed to climate stress, and understanding them is the starting point for any breeding programme aiming to build lasting resilience:

- **Narrow thermal windows for reproduction:** Many vegetables set fruit only within a specific temperature range, and even short heat spikes during flowering can cause pollen sterility, flower drop, and reduced fruit set in crops such as tomato, pepper, and bean.
- **Shallow root systems:** Leafy vegetables and many cucurbits have comparatively shallow roots, leaving them more sensitive to short dry spells than deep-rooted cereals or legume staples.
- **High water content and perishability:** The high moisture content of most vegetable produce means that heat and water stress affect not only yield but also postharvest shelf life and nutritional quality.
- **Concentrated production zones:** Vegetable production is often concentrated in peri-urban belts or specific agro-ecological niches, so a single climatic shock, such as an unseasonal flood, can disproportionately affect national supply and prices.
- **Pest and disease range shifts:** Warmer winters and altered humidity patterns are expanding the geographic range and generation cycles of many vegetable pests and pathogens, exposing crops to threats for which existing varieties carry little resistance.
- **Input and market sensitivity:** Vegetable cultivation is typically more input-intensive per hectare than cereal farming, so climate-driven disruptions to irrigation water, fertilizer access, or transport can compound directly into yield losses and price spikes, with knock-on effects for both producers and urban consumers who depend on affordable vegetables for a balanced diet.

Genetic and Physiological Basis of Climate Resilience

Climate resilience in vegetable crops rests on a combination of traits, including heat- and drought-tolerant photosynthetic and reproductive physiology, deep or efficient root architecture, cuticular and stomatal traits that reduce water loss, and tolerance to soil salinity that often accompanies drought and irrigation with marginal water. Crop wild relatives of major vegetables, growing in stressful natural habitats, harbour genetic variation for many of these traits that has been lost during domestication and modern breeding for uniformity and yield (Zhang et al., 2017), underscoring the importance of maintaining and characterizing these genetic resources within national and international collections (FAO, 2019; Ebert, 2020). Screening germplasm collections and wild relatives for stress-tolerant traits, followed by their introgression into elite backgrounds, is therefore a foundational step in climate resilience breeding programmes. Understanding the physiological basis of tolerance, whether through osmotic adjustment under drought, membrane stability under heat, or ion exclusion under salinity, allows breeders to select complementary traits rather than relying on a single mechanism that may fail under compound or unpredictable stress events.

Modern Tools for Breeding Climate-Resilient Vegetables

1. **Genomic Selection and Marker-Assisted Breeding:** High-throughput genotyping and genomic selection allow breeders to predict the performance of breeding lines under stress conditions before extensive field testing, substantially shortening the time needed to develop resilient varieties (Varshney et al., 2021). In legumes and other vegetable groups, genotyping-by-sequencing approaches have already been used to link genome-wide variation in wild populations to divergent adaptation along environmental gradients such as drought, offering a template for identifying resilience loci in other crops (Cortés & Blair, 2018). Marker-assisted backcrossing enables specific stress-tolerance genes identified in landraces or wild relatives to be introduced into locally adapted, high-yielding cultivars with minimal disruption to other desirable traits.
2. **Genome Editing:** Precision genome-editing tools, particularly CRISPR/Cas systems, are increasingly used to fine-tune genes controlling stomatal density, flowering time, and stress-signalling pathways, offering a faster route to climate resilience than conventional breeding alone (Scheben et al., 2017). Because these edits can be targeted to native genes without introducing foreign DNA, they may also face a more favourable regulatory pathway in some countries compared with earlier transgenic approaches.
3. **Phenomics and Controlled-Environment Screening:** Automated phenotyping platforms and controlled-environment facilities allow large breeding populations to be screened rapidly for heat, drought, and salinity tolerance under standardized conditions, improving the reliability of trait selection compared with variable field trials alone.
4. **Participatory and On-Farm Breeding:** Because climate stress varies enormously by micro-region, participatory breeding approaches that involve farmers in selecting and testing candidate lines under real field conditions help ensure that resilient varieties also match local agronomic and culinary preferences, improving the odds of adoption.
5. **Use of Crop Wild Relatives and Landraces:** Systematic collection, characterization, and pre-breeding of crop wild relatives and traditional landraces expands the genetic base available to breeders and provides a buffer against the erosion of resilience traits caused by decades of selection for uniformity (Bailey-Serres et al., 2019).

Case Examples Across Vegetable Groups

Across the world, national and regional vegetable breeding programmes are already demonstrating what climate resilience breeding can achieve in practice. Heat-tolerant tomato lines carrying pollen viability traits under high night temperatures have been developed through both conventional and marker-assisted breeding, helping stabilize yields in tropical lowland production zones. Drought-tolerant okra and indigenous leafy vegetables, drawing on landrace diversity, have shown promise for marginal rainfed systems where irrigation is unreliable, echoing the broader case for revisiting neglected and orphan vegetable crops as a source of climate resilience traits (Mabhaudhi et al., 2019). Flood- and waterlogging-tolerant cucurbit rootstocks used in grafting systems allow otherwise sensitive scion varieties to be cultivated in flood-prone lowland areas. Salinity-tolerant vegetable lines, developed by screening germplasm from coastal and arid production regions, are gradually being released for cultivation in areas affected by seawater intrusion and saline groundwater. These examples illustrate that climate resilience breeding is not a single technology but a portfolio of complementary approaches tailored to specific stresses and cropping systems. In many cases, the most durable gains come from combining two or more resilience traits, for example pairing heat-tolerant fruit set with moderate drought tolerance, so that varieties remain productive across the range of conditions a single growing season may bring rather than being optimized for only one type of stress.

Institutional and Policy Requirements

Breeding alone cannot deliver climate resilience without supporting institutional structures. National vegetable improvement programmes need sustained funding that matches the scale of investment traditionally reserved for cereal breeding, given the outsized nutritional returns vegetables provide. Seed systems must be strengthened so that climate-resilient varieties, once released, can reach smallholders quickly and affordably, rather than remaining confined to research stations or high-input commercial farms. Extension services require updated training and communication materials so that farmers understand how to manage new stress-tolerant varieties, which may need different irrigation, spacing, or input schedules than familiar cultivars. Finally, coordinated policy linking agriculture, environment, and nutrition ministries can ensure that climate resilience breeding is embedded within broader national food security and climate adaptation strategies, rather than treated as an isolated technical exercise. Public-private partnerships can also play a useful role, particularly in multiplying and distributing seed of newly released resilient varieties, provided that safeguards are in place to keep such varieties affordable and accessible to smallholder farmers rather than restricted to larger commercial operations. Regular monitoring and evaluation of released varieties under real farm conditions, rather than research-station trials alone, will also help policymakers understand which resilience traits are delivering genuine benefits and where further breeding investment is most needed.

Vegetable Breeding, Climate Resilience, and National Food Security

Because vegetables deliver essential micronutrients that staple grains cannot supply in sufficient quantity, safeguarding their productivity under climate stress is inseparable from national food and nutrition security. A national food security strategy that stabilizes cereal supply but allows vegetable production to collapse under climate shocks would still leave populations vulnerable to micronutrient deficiencies and diet-related disease. Investing in climate-resilient vegetable breeding therefore complements, rather than competes with, cereal-focused food security programmes, and offers governments a cost-effective route to strengthen the resilience of the entire food system, in line with the broader case for diversifying food production toward more sustainable and resilient systems (Dwivedi et al., 2017). Because vegetable crop cycles are typically shorter than those of cereals, resilience gains from improved varieties can also translate into food and income security benefits more quickly, making vegetable breeding a valuable near-term complement to longer-term cereal improvement efforts.

Future Prospects

Advances in genomics, phenomics, and genome editing are accelerating the pace at which climate-resilient traits can be identified and incorporated into vegetable breeding pipelines, while digital tools and predictive climate modelling are helping breeders anticipate future stress patterns rather than simply responding to past ones. Expanding international collaboration on germplasm exchange, alongside stronger national gene banks, will be essential to keep the genetic base for resilience breeding as wide as possible. As climate variability intensifies, the pace of releasing, multiplying, and distributing resilient vegetable varieties will need to keep up with the pace of climatic change itself, requiring sustained investment across research, seed systems, and extension. Training the next generation of vegetable breeders in genomics, phenomics, and participatory methods will be equally important, ensuring that national programmes have the human capacity to sustain resilience breeding well beyond any single funding cycle or crisis-driven initiative.

Conclusion

Breeding climate-resilient vegetable crops is a strategic and cost-effective investment in national food security. Vegetable crops, despite their outsized nutritional importance, remain particularly vulnerable to heat, drought, flooding, salinity, and shifting pest pressures. Modern breeding tools, including genomic selection, genome editing, and participatory on-farm breeding, combined with systematic use of crop wild relatives and landraces, offer practical pathways to develop varieties that maintain yield and nutritional quality under climatic stress. Realizing this potential requires not only scientific advances but also sustained investment in seed systems, extension services, and coordinated policy. By prioritizing climate resilience in vegetable breeding alongside cereal crops, nations can build food systems that remain nutritious, productive, and stable even as the climate continues to change.

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