**Enhancing Vegetable Crop Breeding and Adaptation to Changing Climates**

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**ABSTRACT**

The ability of the world to feed itself is under danger due to the global loss in agricultural output caused by climate change. Given that it is anticipated that by 2020, there will be more than 10 billion people on the planet, stakeholders and governments are concerned about food security. Crop improvement combining modern breeding techniques, efficient agronomic methods, advancements in microbiome applications, and using the natural variety in underutilised crops is a great step in the correct path for meeting future food needs. The breeding objectives concerning fruit quality, yield, and resilience to environmental stresses will be discussed, with a particular focus on how climate change could influence these goals. Next, we will discuss the utilization of traditional and molecular breeding strategies.

**Keywords:** Breeding, Climate change, Biotic stress, Abiotic stress tolerance, Molecular breeding, Genomics.

**I. INTRODUCTION**

Due to their potential contribution to a healthy diet for humans, especially for vegetarians who rely on them as a rich supply of vitamins, minerals, and dietary fibres, vegetable crops are referred to as protective foods. These crops' growth, productivity, and quality are threatened by a variety of biotic and abiotic stressors. In terms of reproduction, these crops might be classified as annual, biennial, or perennial. It is difficult to improve economic agricultural qualities using traditional breeding techniques [1]. According to [2], producing crops with a high yield and superior quality while using little inputs will eventually be extremely difficult for modern agriculture. Vegetable crops provide abundant nutrients such as vitamins, minerals, dietary fiber, and phytochemicals, making them protective foods essential for fulfilling people's vital nutritional requirements [3].

To lower the risk of cardiovascular diseases, a person should consume more than 400 g of fruits and vegetables each day [4]. Vegetable crops, like all other food crops, are susceptible to a variety of biotic and abiotic challenges [5,6]. As a result, it is necessary to design crops of the next generation that can withstand severe environmental conditions [7]. To address the demands of a new era, turf vegetable breeding is continually evolving and developing new tactics. In recent years, the world has been primarily concerned with food quality to meet the demands of health-conscious consumers and food quantity to cater to the rapidly expanding global population. Additionally, challenges related to biotic and abiotic stresses have resulted in significant financial losses for farmers [8].

Due to climate change, we can expect a rise in global temperatures and CO2 levels, along with an increase in the frequency of unpredictable droughts, floods, and storms worldwide [9,10,11]. At the same time, the global population is rapidly expanding [12]. Crop yields are expected to be significantly impacted by rising temperatures [13], hence the rapid creation of novel resistant varieties is necessary to mitigate this [14, 15].

Increasing crop yields is crucial, but if we want to expand the areas where crops may be grown, we must create crop types that can withstand poor soils, more variable precipitation, and/or salt [16]. In the future, crops may face the challenge of combating new sets of pests and pathogens, while also adapting to the immediate abiotic pressures of climate change and unfavorable growth conditions. These biotic pressures are thought to affect crop yields by 20–40% [17], and it is anticipated that many diseases' native geographic ranges may change as a result of climate change [18]. Even if climate-tolerant varieties are created, this added (and currently somewhat unpredictable; [19] pressure, novel pests, and illnesses could cause a large decrease in production.

Climate prediction models forecast dramatic shifts in weather patterns that would lead to more frequent floods and droughts, a rise in global temperatures, and a reduction in the amount of fresh water available for agriculture. Therefore, preparing for future climates presents a significant difficulty. This chapter delves into the techniques used for breeding climate-resilient superior genotypes of vegetable crops, aiming to enhance agricultural productivity and address the challenges of future global food security.

**II. HOW DO CROPS RESPOND TO CLIMATE CHANGES?**

The most probable scenario requiring the establishment of plant breeding targets includes:

• Certain higher temperatures leading to reduced crop productivity.

• Certain increase in CO2 concentration with both direct and indirect effects.

• Highly probable increasing frequency of drought.

• Highly probable increase in the areas affected by salinity.

• Highly probable increasing frequency of biotic stress.

Given this situation and the fact that plant breeding has been successful in increasing yield [20], it is possible that Plant breeding has the potential to facilitate the development of new cultivars with enhanced traits, better suited to adapt to climate change conditions, by leveraging both conventional and genomic technologies [21]. These characteristics include resistance to salinity and water logging [22], pests and diseases that continue to result in crop losses [23], drought and temperature stress resistance, and pest and disease resistance. One of the most significant and typical goals of many breeding initiatives for all the major food crops in most countries has historically been breeding for drought resistance [24,25]. Changes in phenology or improved responses to increasing CO2 are potential opportunities for novel cultivars with increased drought resistance. In terms of water, some studies have shown that key crop species (such as maize and soybeans) have undergone genetic alterations that have boosted their water-deficit tolerance [26, 27, 28], while it's possible that not all crops have undergone these adaptations. In general, there is currently insufficient knowledge regarding how genetically modified characteristics work in actual farming and forestry applications [29].

**III. CHALLENGES, PRIORITIES, AND BREEDING OBJECTIVES**

Vegetable crops have a range of challenges that influence their breeding objectives. In line with the diverse range of growth conditions, breeders will concentrate on their key breeding objectives and use them either as-is or after processing. These objectives can be broken down into two groups: (1) adaptation to growth conditions in terms of reaction to biotic and abiotic challenges; and (2) vegetable quality on both a sensory and dietary level. (3) Cold tolerance.

**IV. APPROACHES TO DEVELOP CLIMATE-RESILIENT VEGETABLE CROP**

**A. Abiotic stress**

Vegetable crops face numerous abiotic stresses, such as temperature, drought, salinity, and heat, which adversely affect their crop yield. Traditional breeding methods can mitigate pressures to some extent, but new cutting-edge technologies, like as CRISPR-Cas 9, have the potential to produce more resilient genotypes that can handle these stresses [30]. A significant stressor that slows the growth and yield of vegetable crops is high temperatures.

**a. Drought Tolerance**

The majority of potato types have thin, shallow roots that are susceptible to a variety of abiotic challenges, such as excessive salt and dryness, which lowers tuber output and quality. Even brief bouts of drought stress have the potential to inflict significant harm and a sharp decline in tuber yield. Since drought was not seen as a significant yield-limiting factor for potatoes for a very long time, research on drought tolerance in potatoes did not begin until the 1960s to 1980s. Over the past few years, the situation regarding drought in potato production has undergone a radical change, with a growing recognition of its significance and a notable interest in developing potato cultivars that can thrive in drought-prone areas [31].

Many scientists have tested the drought tolerance of different potato landraces. In Andean landraces, particularly in the species *S. curtilobum* (Juz. and *Bukasov*) in the cultivar families *Stenotomum, Andigenum,* and *Chaucha*, a high number of accessions combining drought tolerance with high irrigated production were discovered. *S. chillonanum, S. jamesii*, and *S. okadae* were discovered by [32] through the screening of 44 accessions of wild species chosen based on their drought habitats derived from geographic information system (GIS).

Due to the constitutive and plastic nature of roots, they are typically implicated in both drought avoidance and tolerance during water shortages. Because of its tremendous plasticity, RSA can adapt quickly to environmental changes like a water shortage. According to [33], potato plants have significantly higher ABA concentrations in their xylem when water content in the substrate decreases.

[34] described the 83 tomato WRKY genes and showed how each one behaved differently to pathogen infection, drought, salt, heat, and cold stimuli. Some genes (SlWRKY3, SlWRKY3, and SlWRKY33) were shown to be impacted by a variety of conditions, including salinity and drought stress, and they were recognised as possible study candidates. For a group of genes belonging to the ERFs family [35] and the Hsp20 gene family [36], the expression profiles of additional tomato stress-response genes were also studied. Single genes that are crucial for tomato tolerance to abiotic stress include SlJUB1, which enhances tolerance to drought, and ShDHN, MYB49, and SlWRKY39, which promote tolerance to a variety of stress conditions [37, 38, 39].

Numerous investigations have concentrated on locating the genes in pepper that can withstand heat stress and testing them in transgenic model systems. For instance, CaHSL1, a protein kinase involved in shielding plants from high temperature stress under high humidity, was described by [40]. [41] discovered a gene called BAX inhibitor-1 that confers transgenic plants with increased tolerance to a variety of stress stimuli and is linked to the regulation of programmed cell death. Despite the acknowledgment of genetic diversity for heat stress tolerance [4,43] and particular molecular investigations on the activity of heat shock proteins [44,45], research on the quantitative inheritance of heat tolerance in pepper is still lacking. Future plant breeding initiatives are required to create cultivars that are better able to withstand the stress of high temperatures.

New cultivars with excellent root characteristics, capable of absorbing water from deeper regions of the soil and under lower soil water potential, are being bred to enhance the utilization of soil water and contribute to the efficient use of water in vegetable production, whether from precipitation or irrigation.

**b. Salinity Tolerance**

Salinity-sensitive potato leaves are severely harmed by overhead watering with salinity-rich water. Toxic effects from chlorine and salt uptake by leaves can manifest as leaf burn around the edges. According to [46], salt stress had a deleterious impact on the cultivar Desiree's relative water content, leaf stomata/conductance, and transpiration rate.

The pH is raised by sodium carbonate, which is formed when the amount of exchangeable sodium ions in the soil solution increases due to saline water. These alkaline circumstances make it harder for plants to get nutrients like phosphate, iron, zinc, and manganese. This destructive process is stopped in soils high in calcium carbonate, a fact that has been demonstrated in vitro where extra calcium prevented salinity-induced nuclear deterioration in root meristematic cells [47]. In a study cited as [48], it was found that adding 2% gypsum to salty soil enhanced the potato production in pots, increased their protein, potassium, and calcium content, and reduced their glycoalkaloid levels.

The in vitro system was utilised to show that exogenously given proline offered some level of protection against salt stress and was deemed appropriate for testing salt tolerance [49]. [50] showed that salt-tolerant and sensitive potato cultivars had different antioxidant enzyme activities, indicating that the salt-tolerant cultivars may be better protected against reactive oxygen species due to their capacity to increase antioxidant enzyme activity under salt stress.

Using an in vitro microtuberization system, [51] discovered differences in salt sensitivity between two potato cultivars. According to [52], the effects of 5-aminolevulinic acid (ALA), a crucial precursor in the manufacture of porphyrins like chlorophyll and heine, encouraged potato microtuber formation and growth as well as improved protective activities against oxidative stressors.

ShDHN, MYB49, and SlWRKY39 are single genes for tolerance to multi-stress factors, and DREB1A and VP1.1 are single genes for salinity tolerance [43,38].

The characterisation of a few chosen tomato cultivars served as the basis for setting the threshold for saline tolerance described above. [53] observed a considerable genotypic heterogeneity in fresh-market tomato cultivars' responses to salinity. This demonstrates the potential for the crop to produce salt-tolerant cultivars.

In *Capsicum*, there is a significant genotypic heterogeneity for tolerance to salt [53]. The sensitive types in the study accumulated noticeably more sodium ions in their shoot than the resistant varieties. According to [54], salt-tolerant cultivars had higher levels of enzymatic antioxidants and less relative water content loss.

It has been discovered that a few mitigating strategies for dealing with high salinity are relatively helpful in the production of peppers. These cultural techniques include better nutrient management, the use of protectants like glycine betaine or catechin, and better watering techniques. For example, calcium nutrition can be improved to lessen harm from sodium or chloride. Saline-tolerant grafted plants can be produced using rootstocks that have been found [55].

**B. Biotic stresses**

Environmental circumstances are constantly changing, and by 2050, maintaining food production to feed growing populations will be difficult due to a lack of arable land [56]. A key strategy for addressing this problem is the creation of robust crops with high stress tolerance.

New pests and pathogens should enter production areas as a result of global climate change. Climate prediction models forecast abrupt changes in weather patterns that would lead to more frequent floods and droughts, a rise in global temperatures, and a reduction in the amount of fresh water available for agriculture. Therefore, strengthening plant resistance and tolerance to pests is a major task [57].

**a. Disease Resistance**

At different stages of crop growth, crop plants are affected by many and distinct forms of diseases, which severely reduce production. There are several ways to avoid crop losses brought on by these dangerous diseases. Many diseases harm the pepper crop. Therefore, it's crucial to apply fungicides, miticides, and insecticides responsibly in order to effectively manage infections and pests, as well as to achieve the best possible production and fruit quality. However, incorporating the usage of resistant types is a pest management strategy that is good for the environment. Every crop breeding programme now places a high priority on finding and using key genes for disease resistance in the crop. Breeders trying to create resistant types have a significant challenge as the disease races continuously evolve at various speeds to overcome host resistance. Pyramiding various resistance genes with various mechanisms of action together in one line is one solution to this issue. In pepper, polygenic resistance to Potato virus Y outperformed monogenic resistance, according to research by [58]. There is information available on pepper germplasm's high or moderate susceptibility to several of the major diseases, as well as the way the resistance trait is inherited.

Contrary to disease resistance features, little is known about the genetics of various pest resistance. Leaf position and ontogeny have an impact on thrips resistance, according to studies on the subject [59], and QTLs for this characteristic have been found in particular mapping populations [60]. Diterpenes and flavonoids may aid in thrips resistance, according to more recent metabolomic studies [61].

**Table 1: Disease resistance in various vegetable crops**

|  |  |  |
| --- | --- | --- |
| **Crop** | **Wild Species** | **Character transferred** |
| Okra | *Abelmoschus caillei* | Resistance to (YVMV) |
| Brinjal | *S. stenototum* | Resistance to bacterial wilt |
| Tomato | *Solanum hirsutum* | Resistance to Fusarium wilt |
| Chilli | *Capsicum chinense* | Resistance to fruit rot |
| Onion | *Allium fistulosum* | Resistance to Purple blotch |
| Potato | *Solanum demissum* | Resistance to late blight and leaf roll |
| French bean | *P. flavescens* | Rust resistance |
| Cucumber | *Cucumis Hardwiiki* | Resistance to green- mottle mosaic |

**b. Pest Resistance**

The global temperature is expected to rise, there will be more frequent droughts and floods, there will be less fresh water available for agriculture, and there will be dramatic changes in weather patterns. Therefore, strengthening plant resistance to pests and tolerance to them is a significant challenge.

In wild species, a variety of pest resistances have been found. According to several research [62], insect resistance is attributed to glycoalkaloids, glandular trichomes, and other unidentified mechanisms. [63] tested 100 species of wild potatoes for insect resistance and found that the glycoalkaloid tomatine, thick hairs, and glandular trichomes were all associated with resistance. According to Jansky et al. [64], species with abundant glandular trichomes (*S. polyadenium* and *S. tarijense*) or high amounts of glycoalkaloids (*S. chacoense*) have proven resistance to the Colorado potato beetle. *S. hougasii* exhibited high levels of resistance to the Columbia root-knot nematode. Additionally, the Argentinian wild species *S. vernei* and *S. acaule* were found to possess resistance to cyst nematodes [65].

Hypersensitive resistance and extreme resistance are two popular subtypes of single-gene viral resistance in potato. It's common for viral strains to have unique hypersensitive resistance genes. When plants with these genes are exposed to viruses, they typically exhibit systemic necrosis or local necrotic lesions in the infected tissue. In potatoes, a number of genes have been identified that code for hypersensitive resistance to potato viruses A, S, X, and Y [31]. The Solanaceae family exhibits a conserved location of genes imparting resistance to various other diseases in addition to resistance to Phytophthora. The resistance gene hotspot on the long arm of chromosome 11 is home to three potato genes that code for resistance to PVY (Ryadg and Rysto) and PVA Naadg [66].

Attacking plants, the onion thrips (Thrips *tabaci* L.) decreases photosynthetic activity, acts as a disease entry point, and spreads the IYSV [67]. To manage thrips, some onion growers employ biological and cultural measures, while the majority resort to insecticides. However, this practice may lead to the development of insecticide-resistant thrips and result in significant environmental problems. To address these concerns, efforts are underway to develop onion cultivars with inherent resistance to thrips. After analysing the germplasm from various countries, a few tolerant sources that can be exploited in breeding programmes have been identified [68]. It has been shown that onion plants with glossy or semi-glossy foliage are not more susceptible to thrips feeding damage [69]. It would be preferable to apply family-based selection to increase genetic gain because genetic studies reveal that thrips resistance is not extremely heritable [70].

**c. Root-Knot Nematodes Resistance**

High temperatures (over 30 °C) impair plant defence mechanisms, frequently rendering important resistance genes useless. For instance, high temperatures inactivate the tomato Mi-1.2 resistance gene to the root knot nematode and the Cf-4/Cf-9 genes to Cladosporium fulvum.

Another intriguing strategy that requires little effort throughout the growing season and is good for the environment is the use of root-knot nematode-resistant cultivars [71]. The study of pepper genetic resources against diseases, nematodes, and arthropods [72] lists more than 40 accessions as tolerant or very resistant to several root-knot nematode species. In the Solanaceae family, resistance to root-knot nematodes is primarily dominant and regulated by a small number of crucial genes. Nine different dominant genes have been found to confer resistance to root-knot nematodes in several populations of peppers. Out of these, the resistance of *M. incognita*, *M. javanica*, *M. arenaria*, and *M. haplanaria* to N, Me1, and Me3 (= Me7) was evaluated [73].

**Table 2: Insect resistance in various vegetable crops**

|  |  |  |
| --- | --- | --- |
| **Crop** | **Wild Species** | **Character transferred** |
| Potato | *Solanum verni* | Resistance to Nematode |
| Brinjal | *S. incanum* | Resistance to Shoot & fruit borer |
| Cucumbits | *Cucumis trigonus* | Resistance to Fruit fly |
| Okra | *Abelmoschus manihot* | Resistance to Shoot & fruit borer |
| Tomato | *Solanum hirsutum* | Resistance to White fly |

**C. Vegetable quality improvement**

Advanced post-harvest technologies are required for fruit and vegetable (F&V) storage stability and extended shelf life because they are highly perishable food products [74]. T1 homozygous plants with long shelf lives were produced in tomato by replacing the allele of ALC with the alc gene via the homology directed repair (HDR) mechanism. In many food applications, potato starch purity is crucial. In potatoes, full knockouts of the genes for the starch-branching enzymes (SBEs) SBE1 and SBE2 as well as the starch synthase gene (SS6) have been reported to improve starch quality [75, 76].

Similar to this, enzymatic browning in brinjal was associated with the three-polyphenol oxidase (PPO) genes SmelPPO4, SmelPPO5, and SmelPPO6. These three target PPO genes have been disabled utilising CRISPR-Cas9-based mutagenesis to prevent the browning of fruit flesh.  [77].

In particular, beta-carotene, which is a precursor to retinol (vitamin A), and lutein and zeaxanthin, which are significant antioxidants for eye health, are nutritionally valuable pepper carotenoids. Numerous research has examined total carotenoid levels and composition in various pepper cultivars due to the nutritional importance of carotenoids. According to Brewster [78] and [79], the first-class of onion cultivars is determined by the bulb colour (anthocyanin and flavonoid content), firmness, number of scales, number of developing points, neck thickness, Total soluble solids (TSS), pungency, and antioxidants.

**Table 3: Quality improvement in various vegetable crops**

|  |  |  |
| --- | --- | --- |
| **Crop** | **Wild Species** | **Character transferred** |
| Tomato | *Solanum hirsutum* | Carotenoid content |
| Chilli | *Capsicum frutescence* | High capsaicin |
| Onion | *Allium kurrat* | Leaf flavour |
| Potato | *Solanum acule* | Starch content |
| Melons | *Cucumis melo* var. cantaloupensis | Thick rind and good keeping quality |

**D. Cold Tolerance**

Cold is a major abiotic stress affecting agricultural productivity globally, impacting the growth and development of agronomic species. Given that approximately 64% of the earth's land area experiences an average minimum temperature below 0 °C and about 48% below 10 °C, comprehending the mechanism of frost damage and developing cold-tolerant varieties becomes highly essential. To boost output and stability in cold conditions that are getting worse with climate change, potato crops must adapt. In order to defend themselves from harm caused by below-freezing temperatures, plants have evolved two strategies. First, acclimated xylem parenchyma cells of moderately resistant woody plants are typically linked to supercooling, a low-temperature tolerance mechanism. Acclimatization is the second and most typical low-temperature response mechanism. According to [80], acclimation is a slow process that causes changes in almost every quantifiable morphological, physiological, and biochemical characteristic of the plant. The complicated interactions between genetics and environment are what cause these alterations.

Peppers grown in tropical climates are vulnerable to frost. Numerous studies have examined how chilling stress negatively affects the various metabolic systems in peppers [81]. The plants grown at the lower night temperature showed superior chilling tolerance after being exposed for 4 nights at 6 °C [82]. Low nighttime temperatures (14 °C or lower) have a detrimental effect on the flower's female reproductive system, pollen viability, and pollen production [83]. The work by [84] demonstrated the function of reactive oxygen species in the harm caused by cold stress. Low temperature tolerance has a known genetic component [85], although no selections for this feature have been documented. Peppers are susceptible to cold damage when the harvested fruit is left in the cold (7 °C) for an extended period of time. A sign of cooling harm is surface pitting. It is possible to improve the cold storability of food by combining low temperature conditioning with the use of methyl jasmonate and UV-C treatments [86, 87]. A proteomic investigation found that the stress of freezing caused bell peppers to create more ethylene, modify the composition of their sugars and organic acids, and drastically alter the proteins involved in the regulation of redox homeostasis and the breakdown of carbohydrates.

**E. Herbicide resistance**

Selective herbicides are commonly employed during cultivation to control weed growth and development, as weeds are a significant stress factor impacting vegetable yield and quality. To confer herbicide resistance in plants, the herbicide target gene acetolactate synthase (ALS) has been modified using CRISPR-Cas9 technology in crops such as tomato, watermelon, and potato [88,89].

**F. Nutrient Use Efficiency**

When it comes to boosting crop yields in the face of escalating climate change and global warming, nutrient-efficient plants are crucial. At least 60% of the arable land on the planet has mineral or elemental toxicity issues. "The plant growth, physiological activity, yield, or harvested yield per unit of nutrient" is how the term "nutrient use efficiency" (NUE) is defined. The balance of nutrients and biological activity are the two main factors that affect a plant's productivity [31].

**V. FUTURE PROSPECTS**

To ensure global food security amid the ongoing and projected climate change, which includes rising temperatures and unpredictable climate events across large regions of the world, it is crucial to breed crop plants with enhanced yield potential and improved tolerance to such conditions. The goal of climate resilient agriculture can only be accomplished with improved plant types that can tolerate diseases and pests while effectively using fewer resources and demonstrating steady yields in stressful conditions in the near future. Research focus is essential for currently underutilised crop species if they are to contribute to climatic resilience. To address crop plants' sensitivity to climate change, smart breeding relies heavily on creating huge breeding populations, effective high throughput phenotyping, big data management technologies, and downstream molecular approaches.

To prepare for the challenges of a warmer climate, characterized by increased vulnerability to droughts, floods, and potential threats from novel pests and viruses, it is crucial for current research to identify crop varieties and Crop Wild Relatives exhibiting adaptive tolerance to these stresses. Despite these efforts being carried out for vegetable crops, it seems that progress has been slow and, until recently, lagged behind developments in other crops.

**VI. CONCLUSION**

The continuing development of innovative crops and new kinds of plant-based foods will be essential for future food production. To help with climate adaptation, research will need to be focused on crop species that are now underutilised. One of the major and difficult areas of agriculture is vegetable breeding. Breeding in agricultural crops benefits from both traditional and molecular approaches. In order to prepare for a warmer world that will be more vulnerable to droughts and floods as well as the prospect of novel pests and viruses becoming a threat, it is imperative that current research find cultivars of crops with adaptive resilience to these stresses. Even if this is being done for the vegetable crop, it seems like progress is being made slowly and has lagged behind other crops up until very recently. Despite not being among the most essential vegetables internationally, many nations and cultures rely heavily on vegetables in their diets, therefore any reduction in production could have a negative impact on these populations. In this chapter, I've emphasised what is already known about vegetable crop tolerances that might be useful in a future climate, as well as several crucial research directions that ought to be given top priority.

Plant breeders can potentially design and produce the appropriate genotype by selecting the best allele for each gene, enabling enhanced performance in the target environment. The path to this approach is swiftly being defined by functional genomics.

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