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Modern breeding techniques for biotic and abiotic stress in solanaceous vegetable crops

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Abstract

Solanaceous vegetable crops, such as tomatoes, peppers, eggplants, and potatoes, are among the most widely cultivated and economically significant crops globally. However, their productivity and quality are significantly affected by both biotic and abiotic stresses, which include pests, diseases, drought, salinity, and temperature extremes. Biotic stresses, such as infections caused by fungi, bacteria, and viruses, alongside pest infestations, lead to substantial yield losses. Concurrently, abiotic stresses like water scarcity, soil salinity, and temperature fluctuations exacerbate crop production challenges. Given the increasing impact of climate change and global food insecurity, breeding stress-resistant varieties has become a priority for ensuring the sustainability and productivity of Solanaceous crops. This review highlights the recent advances in breeding strategies aimed at enhancing biotic and abiotic stress resistance in these crops. Traditional breeding methods, such as hybridization and selection, have been combined with cutting-edge genomic tools like Marker-Assisted Selection (MAS), Genome-Wide Association Studies (GWAS), and CRISPR/Cas9-based genome editing to accelerate the development of stress-resistant varieties. Additionally, the integration of multi-omics approaches has provided new insights into the molecular mechanisms governing stress tolerance, allowing for more precise breeding strategies. Despite significant progress, challenges such as limited genetic diversity, complex polygenic inheritance, and environmental variability continue to hinder breeding efforts. This review discusses the progress, challenges, and future directions for breeding biotic and abiotic stress tolerance in Solanaceous crops, emphasizing the need for innovative, sustainable approaches to ensure food security in the face of changing environmental conditions.

Keywords: Solanaceous crops, stress, abiotic, biotic, breeding

1. Introduction

Solanaceous vegetable crops, including tomatoes (*Solanum lycopersicum*), peppers (*Capsicum spp.*), eggplants (*Solanum melongena*), and potatoes (*Solanum tuberosum*), are among the most widely cultivated and economically important crops worldwide. These crops play a critical role in global food security, providing essential nutrients, vitamins, and minerals. However, their productivity and quality are often severely impacted by both biotic and abiotic stresses. Biotic stresses are caused by various pests and pathogens, including fungi, bacteria, viruses, and nematodes, which can lead to significant crop losses and affect crop yield and quality (Cao *et al.*, 2023) [4]. Abiotic stresses, on the other hand, include environmental factors such as drought, salinity, temperature extremes (heat and cold), and nutrient deficiencies, which can significantly reduce plant growth and development (Ali *et al.*, 2022) [1].

The impact of biotic and abiotic stresses on Solanaceous crops is becoming increasingly pronounced due to the challenges posed by climate change, which exacerbates the severity and frequency of these stresses. As a result, the development of stress-resistant varieties has become a priority in breeding programs. Breeding for stress tolerance involves identifying and incorporating genetic traits that can help crops withstand the adverse effects of pests, diseases, and environmental stresses. Traditional breeding methods have been complemented by modern biotechnological tools such as molecular markers, genomic selection, and gene editing technologies like CRISPR/Cas9, which offer new possibilities for more efficient and precise breeding strategies (Yadav *et al.*, 2023; Chavez *et al.*, 2023) [5, 23]. In addition to these technical advancements, the understanding of the molecular and

Physiological mechanisms underlying stress tolerance has grown significantly in recent years. With the application of high-throughput genomics, transcriptomics, and other omics technologies, researchers have gained new insights into the genes, pathways, and networks involved in biotic and abiotic stress responses (Li *et al.*, 2022) ^[14]. This knowledge has paved the way for the development of Solanaceous crops with enhanced resistance to a wide range of environmental challenges, allowing breeders to incorporate multiple stress tolerance traits into crop varieties more efficiently (Ali *et al.*, 2022) ^[1].

Despite the progress made in breeding for stress tolerance, challenges remain, including limited genetic diversity in commercially cultivated varieties, the complexity of polygenic traits involved in stress tolerance, and the environmental variability that affects gene expression and phenotypic outcomes (Tobias *et al.*, 2023) ^[21]. Furthermore, the integration of stress resistance traits into high-yielding, market-preferred cultivars requires overcoming both scientific and practical breeding obstacles. Future breeding programs will need to focus on increasing genetic diversity, improving climate resilience, and ensuring that new varieties meet both the production needs of farmers and the quality preferences of consumers (Tiware *et al.*, 2022) ^[20].

This review aims to provide an overview of the current state of breeding for biotic and abiotic stress resistance in Solanaceous crops. It highlights the latest advancements in breeding techniques, the role of molecular tools in identifying and introducing stress resistance traits, and the ongoing challenges and opportunities for improving stress resilience in these important vegetable crops. By examining the progress and challenges, we aim to provide insights into future strategies that can help ensure the sustainable production of Solanaceous crops in a changing global climate.

Breeding for biotic and abiotic stress in solanaceous vegetable crops is a critical area of research aimed at enhancing crop resilience and productivity. This involves the integration of molecular markers, grafting techniques, and advanced breeding methodologies to develop cultivars that can withstand various environmental challenges. The following sections outline key strategies employed in this breeding process.

2. Advanced breeding approaches

The integration of omics technologies (genomics, proteomics, etc.) has revolutionized breeding by providing insights into the genetic basis of stress tolerance ("Omics in vegetable crops under the family. Speed breeding and multi-omics approaches allow for rapid development and selection of stress-tolerant varieties, significantly reducing the time required for traditional breeding (Azeem *et al.*, 2025) ^[2]. While these strategies show promise, challenges remain in effectively implementing these techniques across diverse environments and ensuring that newly developed cultivars meet the nutritional and economic needs of farmers.

Breeding for biotic and abiotic stress resistance in

Solanaceous vegetable crops is a critical area of research aimed at enhancing crop resilience and productivity. Solanaceous crops, including tomatoes (*Solanum lycopersicum*), peppers (*Capsicum spp.*), eggplants (*Solanum melongena*), and potatoes (*Solanum tuberosum*), are vital for global food security, providing essential nutrients and vitamins. However, these crops face significant challenges due to various biotic stresses, such as pests and pathogens, and abiotic stresses, including drought, salinity, and temperature extremes. These stresses often result in substantial yield losses and reduced quality, exacerbated by the ongoing effects of climate change (Cao *et al.*, 2023; Ali *et al.*, 2022) ^[1, 4].

To address these challenges, breeding programs have shifted focus toward developing stress-resistant varieties. Molecular markers play a key role in identifying genetic traits associated with disease resistance and tolerance to environmental stresses. Specific markers linked to disease resistance and traits like anthocyanin regulation are crucial for accelerating targeted breeding efforts. Additionally, grafting has emerged as an effective technique for improving stress tolerance, particularly against soil-borne diseases and temperature extremes. The choice of rootstock significantly impacts the resilience, growth, and yield of grafted crops, particularly under challenging environmental conditions (Imandi & Bahadur, 2023) ^[8].

Advanced breeding methodologies, incorporating omics technologies such as genomics and proteomics, have revolutionized the process of developing stress-resistant cultivars. These technologies provide insights into the genetic underpinnings of stress tolerance, enabling breeders to select for specific traits more efficiently (Azeem *et al.*, 2025; ^[2] "Omics in vegetable crops under the family. Speed breeding and multi-omics approaches further expedite the development of resilient varieties, reducing the time traditionally required for breeding (Azeem *et al.*, 2025) ^[2]. Despite these advancements, challenges remain in the practical application of these techniques across diverse environments, and ensuring newly developed cultivars meet the nutritional and economic needs of farmers is an ongoing priority (Tiware *et al.*, 2022) ^[20].

2.1. Molecular markers and genetic resistance

Molecular markers are essential for identifying genetic traits associated with resistance to diseases and environmental stresses in crops like tomato and pepper (Zhang *et al.*, 2023) ^[24, 25]. Advances in marker technologies such as SSRs, SNPs, and QTL mapping have accelerated the identification of resistance loci. Marker-assisted selection (MAS) allows breeders to efficiently incorporate resistance genes into elite varieties. This is particularly important for combating diseases like bacterial wilt, late blight, and root-knot nematodes. Recent studies highlight the utility of markers like RsR6-5, RsR12-1, and ISAP in breeding programs (Wang *et al.*, 2023) ^[22]. Such innovations are key to ensuring food security and sustainable crop production in Table 1.

Table 1: Molecular Markers and Resistance Breeding in Solanaceous Crops

Crop	Pathogen/Disease	Resistance Gene(s)/QTL(s)	Molecular Marker(s) Used	Marker Type	Citation
Tomato	Tomato Spotted Wilt Virus (TSWV)	Sw-5b	Gene-specific markers distinguishing resistant and susceptible alleles	PCR-based, Codominant	(Zhang <i>et al.</i> , 2023) ^[24, 25]
	Early Blight (<i>Alternaria solani</i>)	QTLs on chromosomes 2, 5, 11	SSR and SNP markers via QTL mapping	Codominant	(Zhang <i>et al.</i> , 2023) ^[24, 25]
	Root-knot Nematode (<i>Meloidogyne</i> spp.)	Mi-1.2	CAPS marker Mi1713	Codominant	(Rodriguez <i>et al.</i> , 2023) ^[16]
	Tomato Leaf Curl Virus & Late Blight	Ty-2, Ty-3, Ph-2, Ph-3	Marker-assisted pyramiding using gene-specific markers	Multiple PCR-based markers	(Li <i>et al.</i> , 2024) ^[15]
Potato	Late Blight (<i>Phytophthora infestans</i>)	Rpi2 from <i>Solanum pinnatisectum</i>	RFLP and AFLP markers flanking the resistance gene	Codominant	(Barlow <i>et al.</i> , 2017) ^[3]
	Bacterial Wilt (<i>Ralstonia solanacearum</i>)	PBWR-6b	Allele-specific markers Rbw6-1 and Rbw6-2	Codominant	(Gupta <i>et al.</i> , 2023) ^[7]
	Late Blight & Potato Cyst Nematodes	Multiple resistance loci	SSR markers and phenotypic screening	Codominant	(Sharma <i>et al.</i> , 2023) ^[17]
Pepper	Powdery Mildew (<i>Leveillula taurica</i>)	QTL on chromosome 5 (Capana05g000392)	InDel and KSAP markers developed from QTL region	Codominant	(Lee <i>et al.</i> , 2024) ^[13]

2.2. Grafting techniques

Grafting has emerged as a valuable technique to improve stress tolerance in solanaceous vegetables, particularly against soil-borne diseases and temperature extremes (Imandi & Bahadur, 2023) ^[8]. The choice of rootstock significantly influences the growth, yield, and quality of grafted crops, enhancing their resilience to abiotic stresses. Thus, the integration of molecular markers, grafting techniques, and advanced breeding strategies offers promising avenues for developing Solanaceous crops that can withstand both biotic and abiotic stresses. However, to ensure these crops meet the demands of food security and climate resilience, future breeding programs will need to overcome several challenges, including environmental variability, limited genetic diversity, and the need for high-quality, market-preferred cultivars (Tobias *et al.*, 2023; Yadav *et al.*, 2023) ^[21, 23].

3. Breeding for biotic stress resistance in solanaceous crops

Breeding for biotic stress resistance in Solanaceous crops such as tomato, eggplant, and potato has significantly advanced with the integration of conventional breeding,

Molecular Marker-Assisted Selection (MAS), and genome editing techniques. For instance, recent efforts in tomato have incorporated resistance genes like *Ty2* from *Solanum habrochaites* To Combat Tomato Leaf Curl Virus (ToLCV), leading to high-yielding resistant hybrids (Jeevan Kumar *et al.*, 2023) ^[9]. In eggplant, progress has been made through QTL mapping and the use of PCR-based markers for resistance against *Phomopsis vexans* (Kashyap *et al.*, 2024) ^[10]. Potato breeding has benefited from transcriptomic studies revealing key defense-related genes and transcription factors such as WRKY and MYB involved in resistance to late blight and bacterial wilt (Singh *et al.*, 2024) ^[18]. Moreover, CRISPR/Cas9 gene-editing has emerged as a precise tool to develop disease-resistant cultivars without transgene integration, making it a promising strategy for sustainable crop improvement (Zhang *et al.*, 2023) ^[24, 25]. These innovations collectively enhance the resilience of Solanaceous crops to biotic stress, contributing to food security in the face of climate change and evolving pathogens. Breeding Approaches for biotic Stress Resistance in Solanaceous Crops is included in Table 2 (Singh *et al.*, 2023) ^[19].

Table 2: Breeding Approaches for biotic Stress Resistance in Solanaceous Crops

Crop	Major Biotic Stress	Resistance Source	Breeding Approaches	Recent Advances
Tomato	TYLCV, Fusarium wilt, Nematodes	<i>S. chilense</i> , <i>S. peruvianum</i> , <i>S. pimpinellifolium</i>	MAS, gene pyramiding, CRISPR/Cas9	Deployment of Ty1-Ty5 genes for TYLCV; CRISPR knockout of SIMlo1 for powdery mildew
Potato	Late blight (<i>Phytophthora infestans</i>)	<i>S. bulbocastanum</i> , <i>S. demissum</i>	Introgression, transgenic breeding, MAS	Use of Rpi-vnt1, Rpi-blb1 genes; genome editing applications
Eggplant	Fusarium wilt, Bacterial wilt	<i>S. torvum</i> , <i>S. aethiopicum</i>	Interspecific hybridization, MAS	Transcriptomic identification of resistance-related pathways
Chili	CMV, TMV, Anthracnose, Thrips	Landraces and Capsicum chinense	Conventional selection, gene pyramiding, MAS	Marker-based selection for L gene complex (TMV resistance)
Bell Pepper	Powdery mildew, Bacterial spot	Landraces, wild species	Wide crossing, transgenic approaches	Genome-wide SNP analysis for QTLs linked to bacterial spot resistance

4. Breeding for abiotic stress resistance in solanaceous crops

Abiotic stress, particularly drought, salinity, and extreme

Temperature variations, has become increasingly problematic for crop production due to climate change. Solanaceous crops are particularly susceptible to these stress

factors, which can reduce their growth, yield, and quality. For example, drought stress significantly limits the availability of water, thereby affecting physiological processes such as photosynthesis and nutrient uptake in crops like tomato and eggplant. Breeding efforts for drought resistance have increasingly focused on enhancing traits like root architecture, osmotic regulation, and water-use efficiency (Ali *et al.*, 2022) ^[1]. In recent years, new genetic resources from wild *Solanum* species, such as *Solanum pennellii*, have been explored for their ability to tolerate water stress, leading to the identification of key genes associated with drought tolerance. Moreover, the advent of

CRISPR/Cas9 technology has enabled precise gene editing to improve water-use efficiency in these crops (Chavez *et al.*, 2023) ^[5]. Similarly, salinity is a growing issue, particularly in irrigated regions where salt accumulation impacts crop performance. Genetic studies have identified genes involved in ion transport and osmotic regulation, which are crucial for breeding salt-tolerant varieties (Kaur *et al.*, 2022) ^[11]. These breeding strategies hold significant promise for developing Solanaceous crops that can thrive in increasingly saline and water-scarce environments. Breeding Approaches for Abiotic Stress Resistance in Solanaceous Crops is included in Table 3 (Kumar *et al.*, 2023) ^[12].

Table 3: Breeding Approaches for Abiotic Stress Resistance in Solanaceous Crops

Crop	Abiotic Stress	Key Traits for Resistance	Breeding Approaches	Recent Advances
Tomato (<i>Solanum lycopersicum</i>)	Drought, Heat	Deep root system, osmotic adjustment, stay-green, heat-tolerant flowering	Conventional breeding, QTL mapping, marker-assisted selection (MAS), genomic selection	Heat-tolerant lines developed (e.g., EC 620421); CRISPR targeting SIAGL6 for drought tolerance
Potato (<i>Solanum tuberosum</i>)	Drought, Heat, Salinity	Canopy temperature depression, high WUE, osmolyte accumulation	Hybridization with wild species (<i>S. chacoense</i> , <i>S. commersonii</i>), gene editing	Identification of StMYB44 and CBF1 genes for salinity and drought resilience
Eggplant (<i>Solanum melongena</i>)	Salinity, Heat, Drought	Ion homeostasis (Na ⁺ /K ⁺), antioxidant enzyme activity	Introgression from wild relatives (<i>S. torvum</i> , <i>S. incanum</i>), MAS	Use of <i>S. incanum</i> for introgression of salt-tolerant loci; transcriptomic studies under stress
Chili Pepper (<i>Capsicum annuum</i>)	Drought, Heat, Salinity	Leaf water retention, stomatal regulation, root architecture	Hybrid breeding, <i>in vitro</i> selection, mutagenesis	Development of heat-tolerant genotypes with improved pollen viability under stress
Bell Pepper (<i>Capsicum</i> spp.)	High temperature, Drought	Flower retention, fruit set under heat, high RWC	Wide hybridization, use of thermotolerant landraces	Identification of QTLs related to drought tolerance using GBS (Genotyping by Sequencing)

5. Advanced breeding techniques and biotechnology for stress resistance

In recent years, the field of breeding for stress resistance in Solanaceous crops has made significant strides due to advances in molecular biology and biotechnology. Traditional breeding approaches have been enhanced with the integration of Marker-Assisted Selection (MAS), genomic selection, and gene editing technologies such as CRISPR/Cas9. These modern tools enable breeders to develop crops with multiple stress-resistant traits more efficiently and accurately. Genomic selection, for instance, has shown promise in selecting desirable traits related to both abiotic and biotic stress tolerance, providing a way to predict the breeding value of individuals based on their genetic profile (Tobias *et al.*, 2023) ^[21]. Additionally, the use of multi-omics technologies (including genomics, transcriptomics, proteomics, and metabolomics) allows for a more comprehensive understanding of the molecular mechanisms behind stress tolerance, enabling breeders to identify novel genes associated with specific stress responses (Li *et al.*, 2022) ^[17]. Furthermore, CRISPR/Cas9 gene editing technology has revolutionized breeding by enabling precise modifications to genes associated with stress resistance. This technology has been successfully applied to improve resistance to diseases such as tomato mosaic virus and enhance drought tolerance in tomatoes and eggplants (Chavez *et al.*, 2023) ^[5].

6. Challenges and future directions in stress resistance breeding

While significant progress has been made in breeding for stress resistance in Solanaceous crops, several challenges remain. One of the major obstacles is the limited genetic

diversity available in commercial cultivars, which restricts the potential for developing new stress-resistant varieties (Tiware *et al.*, 2022) ^[20]. Many Solanaceous crops are grown from a narrow genetic pool, which can reduce their ability to adapt to new environmental stresses. Moreover, polygenic traits like drought and disease resistance are controlled by multiple genes, each with small effects, making it difficult to achieve high levels of resistance in a single breeding cycle (Yadav *et al.*, 2023) ^[23]. Additionally, the environmental interactions that influence the expression of stress resistance traits pose another challenge, as the same variety may exhibit different resistance levels depending on environmental conditions. Future research in stress resistance breeding should focus on increasing genetic diversity through the use of wild relatives, developing climate-resilient varieties, and integrating omics technologies to better understand the complex genetic and physiological mechanisms underlying stress tolerance (Tobias *et al.*, 2023) ^[21]. The use of gene editing technologies such as CRISPR will also continue to play a key role in overcoming these challenges by providing a more targeted approach to improving stress resistance in Solanaceous crops.

7. Conclusion

Breeding for biotic and abiotic stress tolerance in Solanaceous vegetable crops is crucial for ensuring sustainable agricultural productivity, especially as global challenges such as climate change and increased pest and disease pressures continue to threaten food security. Over the past few decades, significant progress has been made in developing Solanaceous crops that can withstand a range of biotic stresses, including fungal, bacterial, and viral

diseases, as well as various abiotic stresses such as drought, salinity, and extreme temperatures. Advances in genomic tools such as marker-assisted selection (MAS), genomic selection, and gene editing techniques like CRISPR/Cas9 have revolutionized the ability to identify and introduce stress tolerance traits in these crops with greater precision and efficiency.

However, several challenges remain. Limited genetic diversity in commercial cultivars, the polygenic nature of stress tolerance traits, and the complex interactions between genes and the environment continue to pose obstacles. Moreover, while the molecular mechanisms of stress tolerance are becoming better understood through multi-omics approaches, translating this knowledge into practical breeding solutions for farmers remains a work in progress. Future research should focus on expanding genetic resources by exploring wild relatives and less-utilized *Solanum* species, improving breeding strategies for complex traits, and ensuring that new varieties are both resilient and high-yielding.

The integration of biotechnological advancements with traditional breeding methods offers promising avenues for developing more climate-resilient, pest-resistant, and high-quality Solanaceous crops. Ultimately, sustainable breeding efforts that focus on improving stress tolerance in these crops are vital for mitigating the adverse effects of environmental changes and ensuring food security in the face of growing global demands. The continued development of stress-tolerant Solanaceous varieties will be a key factor in future agricultural success, and further interdisciplinary collaboration between breeders, molecular biologists, and climate scientists will be essential in addressing these ongoing challenges.

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