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ADVANCES IN ROOTSTOCK BREEDING FOR ABIOTIC AND BIOTIC STRESS TOLERANCE IN FRUIT CROPS : A REVIEW

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ABSTRACT

Fruit crops are essential for the global human diet, food security, and rural livelihoods, but their production and sustainability are under growing threat from climate-induced abiotic stresses including drought, salinity, heat, and cold, and biotic stresses such as soil-borne pathogens, nematodes and insect pests. Due to the profound effects of rootstocks on uptake of water and nutrients, hormonal signaling, control of vigor, and the resistance to biotic constraints, rootstock breeding is considered as a promising and sustainable approach to improve stress tolerance of perennial fruit crops. In contrast with scion breeding, rootstock development allows fast introduction of stress tolerant traits into the market without changing the fruit or the features that the consumer expects from the product. There have been a number of recent developments in rootstock breeding that go beyond traditional selection and crossing, including the use of modern tools such as marker-assisted selection, QTL (quantitative trait locus) mapping, genomic selection and high-throughput phenotyping. Also, advances in transcriptomics, proteomics, and metabolomics have contributed to deciphering physiological and molecular mechanisms involved in rootstock-mediated stress tolerance. Novel biotechnological strategies, such as genome editing and rootstock–scion signaling research, will further enhance the prospects of producing multi-stress-tolerant rootstocks. Considerable improvement has been made in major fruit crops, including apple, citrus, grapevine, mango and stone fruits, for which rootstocks have been identified that conferred enhanced tolerance to drought, salinity and important pathogens. Here, we review recent progress in rootstock breeding for abiotic and biotic stresses, highlight the underlying mechanisms and breeding approaches, and discuss future perspectives for the development of climate-resilient and sustainable fruit production systems.

***Key words*: Rootstock breeding; Abiotic stress tolerance; Biotic stress resistance; Climate change; Fruit crops; Drought and salinity tolerance**

Introduction

Fruit crops are a cornerstone of world agriculture and are crucial for human nutrition and food security, providing source of employment and foreign revenues to many countries, as well as offering essential human health-promoting vitamins, minerals, dietary fiber, antioxidants, and other bioactive compounds (Narang and Shweta, 2025; Abobatta, 2021). The productivity and sustainability of fruit crops, however, are increasingly under threat from a range of abiotic and biotic stresses exacerbated by climate change despite mounting demand and expanding areas under fruit cultivation. Drought, salinity, high and low temperature, waterlogging and soil erosion are the major environmental constraints limiting fruit production worldwide, especially in arid and semi-arid regions, and these stresses are now being accompanied by increasing rainfall variability and recurring heat waves (Ren *et al.*, 2025; Nigussie, 2024). Perennial fruit crops are particularly at risk owing to their lengthy life cycle and minimal flexibility after establishment, and pathogenic stresses such as soil-borne pathogens, nematodes, insect pests and viruses led to significantly reduced yields and increased reliance on chemical substances, thereby generating severe environmental and food security concerns (Li and Wu, 2025). Traditional breeding for stress tolerance in fruit crops is hindered by long juvenile phases, high heterozygosity and complex inheritance of stress-associated traits (Jena and Pramanik, 2025). Advances in molecular breeding, omics technologies and genome editing have recently accelerated the improvement of rootstocks and have the potential to contribute to enhancing fruit production systems that are climate resilient and environmentally sustainable.

Importance of Fruit Production and Stress Challenges

Fruit crops play a significant role in global nutritional security and income generation, providing vitamin and mineral-rich foods and livelihood support to millions of farmers and consumers. Abiotic stress including drought, salinity, and extreme temperatures among others, which is intensified by climate change, lead to reduction in quantity and quality of fruits through interfering with plant physiological activities (Jyoti *et al.*, 2025; Dhanyasree *et al.*, 2025). Biotic stresses such as pathogens, insect pests and nematodes also pose a risk to orchard productivity on a global scale. These two stresses together increasingly limit high fruit production and result in big yield losses. As most fruit trees are perennial and vegetatively propagated, rootstock breeding has emerged as a prominent approach in enhancing tolerance against both abiotic and biotic constructs of stresses impacting fruit trees. The selection or development of stress tolerant rootstocks may increase the adaptation to unsuitable soil and climate conditions, contribute to a more efficient water and nutrient uptake, and maintain fruit yield and quality (Prasad *et al.*, 2024). The fusion of classical rootstock breeding with novel cultivation techniques offers a solution to anticipated fruit production competence reduction (Dhurve *et al.*, 2023).

Role of Rootstocks in Fruit Crop Improvement

The rootstock is an important determinant of the growth habit and water relations of the scion in fruit trees. They have a definite impact on the efficiency of water and nutrient absorption, and as a consequence on the tree vigor, productivity and fruit quality (Habibi *et al.*, 2022). Rootstocks also provide tolerance to abiotic stressors including drought, salinity and extreme temperatures, which contribute to enhanced orchard sustainability (Santhi *et al.*, 2020). They also impart resistance or tolerance to soil-borne diseases, nematodes and pests, minimizing input use and consequent loss in yield (Fazio, 2021). Flowering behaviour, yield efficiency and tree longevity can be modulated by rootstock-scion relations (Flachowsky *et al.*, 2007; Knabel *et al.*, 2015; Davies *et al.*, 2011). Rootstocks also promote size control and the use of high density planting systems (Shivran *et al.*, 2022). Thus, they are the foundation of modern horticulture, particularly in fruit species with long juvenility and intricate genetics backgrounds.

Historical Overview of Rootstock Breeding

Early Use and Traditional Practices

The use of rootstock in fruiting plants has been practiced for a long time as early farmers naturally selected plants that performed well in their local conditions in terms of vigor, growth control, and survival. In apple, the introduction of dwarfing rootstocks (e.g., Malling and Malling–Merton series) led to a revolution in orchard systems, making early bearing, size control, and high density planting possible (Webster, 2002). Likewise, in citrus, rootstocks such as Rough lemon, Rangpur lime and Trifoliate orange contributed to increased adaptation to different soil types and imparted better tolerance to diseases (Hayat *et al.*, 2022). This early success showed that rootstocks could have dramatic effects on tree growth, production, and longevity. Such empirical selection informed the development of today's scientifically guided rootstock breeding programs. Using genetics and physiology, modern systems now leverage this traditional knowledge to grow climate-resilient orchards.

Transition to Scientific Breeding

The development of scientific breeding represented a change of the tide from the stumbling upon rootstocks to the conventionalization of rootstock breeding for fruit crops. Breeding methods such as introduction, clonal selection, hybridization and multilocation testing allowed focused enhancement of desirable traits (Ugur, 2025). In citrus, hybrid rootstocks such as Carrizo and Troyer citrange were raised for tristeza virus and soil salinity tolerance (Castle *et al.*, 2011). Apple rootstocks of the Malling and Malling-Merton series were developed for controlling vigour and resistance to woolly apple aphid

Table 1: Functional roles of rootstocks in mitigating abiotic and biotic stresses in fruit crops.

Stress Type	Major Constraints	Rootstock-Mediated Mechanisms	Physiological/ Molecular Effects	Outcome in Fruit Crops
Drought stress	Water deficit, reduced growth	Deep root system, improved water uptake	Enhanced ABA , signaling antioxidant activity, osmotic adjustment	Improved drought tolerance and yield stability
Salinity stress	Na^+ and Cl^- toxicity, osmotic stress	Ion exclusion and compartmentalization	Regulation of ion transporters, stress-responsive gene expression	Reduced salt injury and better plant growth
Heat stress	High temperature, photosynthetic damage	Enhanced transpiration and stress signaling	Activation of heat shock proteins (HSPs) and ROS scavenging systems	Improved thermal tolerance and survival
Cold stress	Low temperature, frost damage	Improved membrane stability and carbohydrate metabolism	Regulation of cold-responsive genes (CBF pathways)	Enhanced cold hardiness and scion survival
Soil-borne pathogens	Fungi, bacteria, nematodes	Disease-resistant rootstocks	Induction of defense-related genes and phytohormones	Reduced disease incidence and chemical inputs
Insect pests	Root and soil pests	Rootstock-based pest resistance	Altered root exudates and signaling pathways	Lower pest damage and improved orchard health
Combined stresses	Multiple abiotic and biotic stresses	Integrated stress signaling and adaptation	Crosstalk among stress pathways	Development of multi-stress tolerant orchards

(Lordan *et al.*, 2019). In grapevine, hybrid rootstocks (Dog Ridge and 110R) not only conferred resistance to nematodes but also to drought stress (Chen *et al.*, 2024; Mustapha *et al.*, 2025). Similarly for peach × almond hybrids to increase tolerance to calcareous and drought soils (Fallah *et al.*, 2025; Mestre *et al.*, 2015; Felipe, 2009). Therefore, scientific breeding further enhanced the significance of the rootstock in conferring stress tolerance, yield, and orchard sustainability (Roberto *et al.*, 2025).

Abiotic Stress Tolerance in Rootstock Breeding

Drought and Water Stress

Drought and water stress tolerance is a key target in rootstock breeding for fruit crops to improve related physiology with such asdeep/efficient root system, high relative water content, or strong antioxidant defenses. Physiological screening in citrus rootstocks led to the identification of drought tolerant genotypes showing efficient water uptake, stable chlorophyll fluorescence and enhanced antioxidant enzyme activities in the water deficit environment and these constitute the main adaptive traits (Morade *et al.*, 2025). Transcriptomic studies in citrus revealed that rootstock-mediated drought tolerance is characterized by an altered expression of stress-responsive genes, some of which are related to cell wall, carbohydrate metabolism and ABA signalling pathways under water deficit (Goncalves *et al.*, 2019). In apple rootstocks, integrated physiological, metabolomic, and transcriptomic analyses have demonstrated that drought tolerant cultivars had higher leaf water content and greater antioxidant capacity and distinctive gene expression profiles compared to sensitive cultivars (Li *et al.*, 2024). In grapevine, grafted plants on drought tolerant rootstocks displayed induction of stress-related genes and enhancement of physiological responses under water stress, providing evidence for the molecular regulation of tolerance (Jiao *et al.*, 2023).

Salinity Stress

Salinity stress disturbs ion homeostasis and root water uptake in fruit crops, which results in ionic toxicity and osmotic stress, ultimately curtailing plant growth and productivity. Several investigations have demonstrated that tolerant rootstocks (1103-Paulsen and SO-4) in grapevine are capable of limiting toxic Naz and Cl^- accumulation in shoots and exhibiting superior physiological performance under saline irrigation, suggesting a more efficient ion compartmentalization and stress regulation mechanisms (Mustapha *et al.*, 2025). Physiological and proteomic comparison studies also reveal unique salt-stress adaptation mechanisms in 110R-grafted vines, such as altering growth- and stress

Table 2: Important rootstocks and their tolerance to abiotic and biotic stresses in major fruit crops.

Fruit crop	Rootstock	Abiotic stress tolerance	Biotic stress resistance
Apple (*Malus domestica*)	M.9, M.26	Moderate drought tolerance, cold tolerance	Fire blight, crown rot (partial)
	MM.106, MM.111	Drought tolerance, soil adaptability	Phytophthora resistance
Citrus	*Poncirus trifoliata*	Cold tolerance, tristeza virus tolerance	Phytophthora resistance
	Swingle citrumelo	Moderate salt tolerance, frost tolerance	Tristeza virus, Phytophthora
	Carrizo / Troyer citrange	Cold tolerance, moderate drought tolerance	Nematodes, tristeza virus
	Sour orange	Drought tolerance	Disease tolerance (limited)
Grapevine (*Vitis vinifera*)	110R, 140Ru	Drought tolerance, alkaline soil tolerance	Phylloxera resistance
	SO4, 5BB	Salinity tolerance, nutrient stress tolerance	Phylloxera resistance
Pistachio nut	*Pistacia atlantica, P. integerrima*	Drought and salinity tolerance	Soil-borne pathogens

metabolism-related proteins (Patil *et al*., 2019). In citrus, the rootstock genotypes screening has shown different levels of salinity tolerance with respect to ion retention and lesser leaf injury during salinity, indicating a rootstock-dependent physiological tolerance (Marathe *et al*., 2022). Transcriptome analysis of citrus rootstocks under salinity stress reveals differential expression of salt stress responsive genes exposing molecular aspects of adaptive mechanisms (Snoussi *et al*., 2022).

Temperature Extremes

Heat and cold stress tolerance are among the important targets for rootstock breeding in perennial fruit crops under the current and predicted future climatic scenarios (Warschefsky *et al*., 2016). In citrus, rootstocks including Poncirus trifoliata and its hybrids (Carrizo, Troyer citrange) are believed to possess greater cold hardiness and scion survival in subtropical and temperate areas (Hasan, 2022). In apple, rootstocks of the Malling series have been shown to differ in response to low temperature stress affecting winter hardiness and spring growth (Fazio *et al*., 2015). Wild Vitis species based (e.g., *V. berlandieri* × *V. rupestris*) grapevine rootstocks have been extensively employed for heat and drought tolerance in warm viticultural areas (Keller, 2020). Similarly, wild relatives of peach (Prunus) and almond (Amygdalus) contributed genes for ultra temperature tolerance via interspecific hybrid rootstocks (Minas *et al*., 2023). These cases demonstrate the significance of wild germplasm and rootstock scion interaction in the thermal stress resilience of fruit crops.

Biotic Stress Tolerance Through Rootstocks

Disease Resistance

Rootstocks provide resistance to soil pathogens and pests, reducing the need for chemicals and enabling more sustainable production of fruit. In citrus, tolerant rootstocks (*Poncirus trifoliata*, Carrizo citrange, and Swingle citrumelo) are resistant or tolerant to *Phytophthora* spp. and (root rot/gummosis) and to citrus nematodes (*Tylenchulus semipenetrans*), and are associated with mitigated symptom expression of citrus tristeza virus (CTV) (Aparicio-Duran *et al*., 2021; Zoubi *et al*., 2024; Kunta *et al*., 2020). Apple rootstocks of the G, CG, and M (e.g. M9, G11, G935) series exhibit different levels of resistance against Phytophthora root rot, white root rot, southern blight and woolly apple aphid, revealing rootstock-specific responses to pathogens (Choi *et al*., 2021). Grapevine rootstocks, largely from wild Vitis species, have also been selected for resistance to root-knot nematodes (*Meloidogyne spp*.) and other soil pests and work is ongoing to identify nematode-resistance loci in species such as Vitis rotundifolia (Ferris *et al*., 2012).

Pest Tolerance

Rootstocks affect pest prevalence in perennial fruit crops by restricting pest population development and damage at the soil interface. In apple, the Malling-Merton (MM) rootstocks were developed to provide resistance to soil pest of apple, the woolly apple aphid, one of the most damaging root pest (Choi *et al*., 2021). Likewise, improved tolerance to soil pest and increased tree vigor

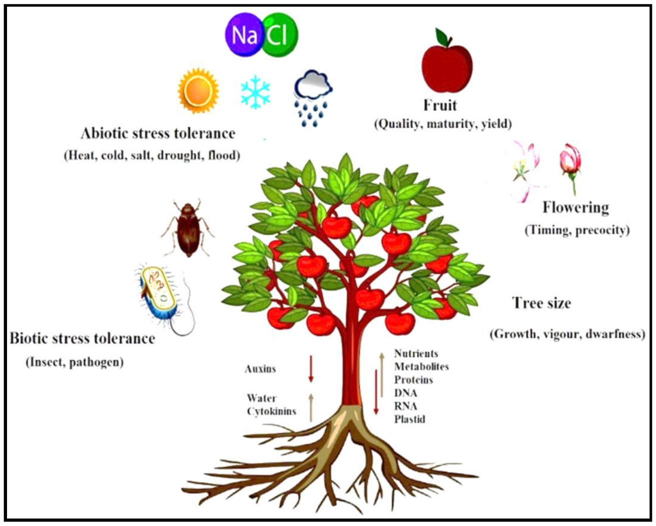

Fig. 1: Mechanisms of Rootstock Influence on Abiotic and Biotic Stress Tolerance and Productivity (Source-Shivran *et al*., 2022).

were also observed among Geneva (G) series apple rootstocks (Robinson *et al.*, 2002). In grapevine, wild Vitis-derived rootstocks (e.g., *V. riparia*, *V. rupestris*, and *V. berlandieri*) protect against root-knot and dagger nematodes and prevent vine decline (Ferris *et al.*, 2012; Esmenjaud *et al.*, 2023). Adoption of pest-resistant rootstocks helps to build resilience in orchards and decreases reliance on chemical pest control.

Interaction with Microbiome

Growing evidence indicates that rootstock genetics may modify root microbial community composition and functionality in fruit crops. In grapevine, rootstock genotype has been reported to modulate rhizosphere and endosphere microbial community composition linked to plant health and susceptibility to biotic stress (Lailheugue *et al.*, 2024; Marasco *et al.*, 2022). Similar observations for apple and citrus demonstrate that microbial diversity/ composition and density is influenced by rootstock genotype in the rhizosphere possibly conferring resistance to soil-borne pathogens (Trivedi *et al.*, 2020; Castellano-Hinojosa *et al.*, 2023; Liu *et al.*, 2018). Specific rootstocks associated with beneficial microbes may enhance nutrient uptake and antagonize pathogens (Berendsen *et al.*, 2012).

Breeding Strategies and Modern Tools

Conventional Breeding

Traditional breeding still forms the basis of rootstock enhancement for fruit crops, and it depends on crossing, selection, and multiyear field evaluation in a variety of locations (Roberto *et al.*, 2025). This method has seen wide application in improving vigor control, stress tolerance, and adaptability in such crops as apple, citrus and grapevine (Castle, 2010; Rahemi *et al.*, 2022). Field evaluation under drought, salinity and disease allows the selection of stable and resilient rootstocks (Ling *et al.*, 2025; Raghavan *et al.*, 2025). Physiological traits including water-use efficiency, root morphology, and nutrient acquisition and biochemical markers such as antioxidant activity are among the most widely adopted selection criteria (Mustapha *et al.*, 2025). These methods yielded the broadly used rootstocks, e.g. Malling and Geneva (apple), Carrizo and Troyer citrange (citrus) (Morade *et al.*, 2025), and 110R and Dog Ridge (grapevine) (Krishankumar *et al.*, 2025).

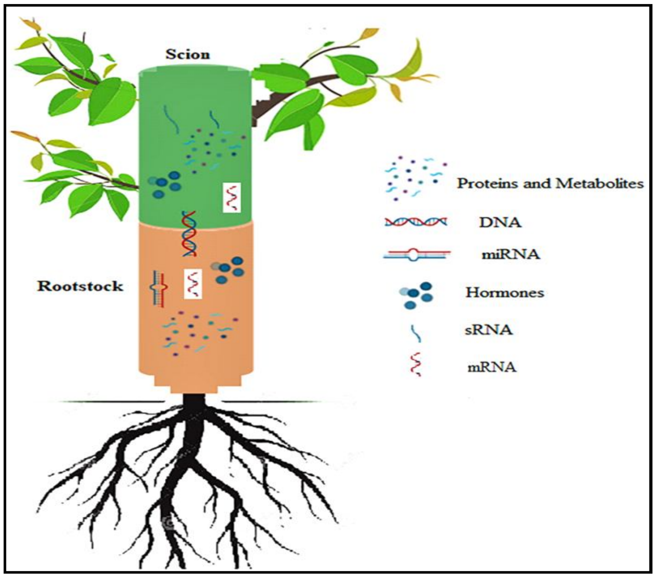

Fig. 2: Rootstock-Scion Molecular Crosstalk in Grafted Fruit Crops (Source- Rasool *et al.*, 2020).

Marker-Assisted and Genomic Selection

Marker-assisted selection (MAS), QTL mapping and genomic selection have made rootstock breeding more efficient by allowing indirect selection for traits of high complexity such as abiotic and biotic stress tolerance, vigor control, and resistance to disease (Varshney *et al.*, 2014). In apple, molecular markers associated with resistance to woolly apple aphid and fire blight have been incorporated in rootstock breeding programs such as the Geneva series (Bus *et al.*, 2019; Fazio *et al.*, 2015). In grapevine, QTLs for drought tolerance, root architecture and nematode resistance (Brault *et al.*, 2022) have been identified in wild Vitis spp. and used for rootstock breeding. Genomic tools make possible the screening of seedlings at an early stage, limiting breeding time with respect to traditional field evaluation (Lee *et al.*, 2024; De Mori and Cipriani, 2023). These approaches are additive to classical selection and facilitate the selection of polygenic traits that are otherwise difficult to enhance (Rane *et al.*, 2025).

Biotechnological Approaches

The latest development in CRISPR/Cas genome editing technique is now opening up new possibilities for the precision tailoring of rootstocks in pome fruit species (Bhatta and Malla, 2020; Bortesi and Fischer, 2015). Genes associated with drought tolerance, disease resistance and nutrient-use efficiency can be precisely edited without modifying the traits of the scion. In perennial orchards crops such as apple, citrus and grapevine, genome editing offers great promise as a breeding technique for overcoming the long breeding cycles (Bodelot *et al.*, 2025; Nishitani *et al.*, 2016). Recent work in stone fruits, banana, papaya, pear and cherry suggest that the promise of edited rootstocks for improving stress tolerance and managing vigor. Yet CRISPR methods, even though they are at the experimental stage, hold promise to be used alongside conventional and molecular mediated breeding for generation of climate resilient rootstocks (Chen *et al*., 2019).

Transcriptomics and Omics Tools

Including transcriptomics, proteomics, metabolomics, high-throughout omics approaches have been increasingly exploited to study stress responses in fruit crops (Cao *et al*., 2024; Pacheco-Ruiz *et al*., 2025). Transcriptome analysis in apple, citrus, and grapevine identified a number of key genes and regulatory cascades associated with drought, salinity, and pathogen resistance (Yu *et al*., 2023; Serrano *et al*., 2017). Proteomics and metabolomics are also known to provide complementary information to transcriptomics by unveiling stress-related proteins and metabolites associated with root activity and nutrient acquisition (Yadav *et al*., 2024). These combined omics might promote novel candidate genes/biomarkers for rootstock breeding. Generally speaking the omics tools facilitate the dissection of intricate stress-response systems and enable precision breeding of stres resilient fruit crop rootstocks (Kajrolkar, 2025; Li *et al*., 2019).

Rootstock-Scion Interactions and Functional Mechanisms

Physiological Mechanisms

Rootstock genotypes conferring abiotic stress tolerance in fruit crops are known to modulate water and nutrient uptake, hormonal homeostasis (such as ABA, auxin), carbohydrate and antioxidant metabolism. Under drought, tolerant rootstocks (citrus: X639, RLC 4) (Morade *et al*., 2025), grapevine (Ramsey, 110R) (Krishankumar *et al*., 2025) preserve water status, photosynthesis, gas exchange and nutrient uptake while in apple (Hezema *et al*., 2021) ABA mediated stomatal control enhances water use efficiency. These combined physiological processes drive osmotic homeostasis, stress signaling and growth, informing precision rootstock breeding for climate-resilient orchards.

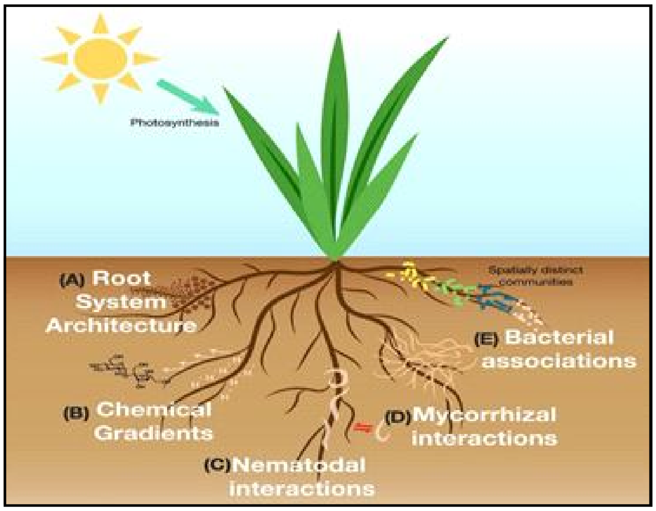

Fig. 3: Rhizosphere Interactions and Root System Architecture Shaping Plant–Microbe Dynamics Challenges and Future Prospects.

Molecular Regulation

Rootstocks also regulate stress tolerance at the molecular level through the modulation of the expression of genes related to important signaling pathways such as those of ABA, ethylene and reactive oxygen species (ROS) signaling (Devireddy *et al*., 2021; Wang *et al*., 2025). In drought tolerant rootstocks, ABA responsive genes and transcription factors such as DREB and NAC are induced to regulate the stomatal closure and osmotic adjustment in grapevine (Zhao *et al*., 2022; Zhang *et al*., 2016). In citrus, rootstocks promote the expression of ethylene and stress-related genes and enhance antioxidant protection and nutrient signaling under salinity and water deficit (Goncalves *et al*., 2019; Santos *et al*., 2021). These molecular changes, combined with physiological ones, allow grafted fruit crops to acclimate to abiotic stress and may provide guidance for rootstock breeding.

Microbiome and Root Environment

Rootstock genotype has a significant impact on the structure, diversity and predicted functional potential of rhizosphere microbial community, thereby determining which bacterial and fungal taxa are assembled around roots (Labarga *et al*., 2025; Dries *et al*., 2021). Similar results have been reported in crops including grapevine, citrus, peanut, and tomato where selected rootstocks enrich for specific microbial communities and metabolic pathways in the rhizosphere as well as the root endosphere (Poudel *et al*., 2019; Ren *et al*., 2024). These genotype dependent microbiotas may affect nutrient cycling and also affect interactions with other microbes in the soil that influence plant growth or resilience. Notably, rootstock-specific microbiome alterations have been correlated to enhanced plant performance under drought and soil-borne diseases (Castellano-Hinojosa *et al*., 2023). Hence, the rootsoil and its microbiome are determinative for host genetics-based stress resilience (Lailheugue *et al*., 2024).

Long Life Cycles and Evaluation

Perennial fruit crops have long juvenile phases and long- generation time, making traditional breeding laborious and time- consuming since evaluation of traits such as fruit quality is at the end of the life cycle of the plant (Campa *et al*., 2024; Song *et al*., 2026). Genomic prediction and genomic selection (GS) can predict breeding values based on genomic estimated breeding values (GEBVs) at the seedling stage, which means early selection can be performed without waiting for complete phenotypic information and this shortens breeding cycle in tree fruits such as apple and citrus (Kostick *et al.*, 2023; Muranty *et al.*, 2022). The combination of GS with high throughput genotyping and the prediction models derived from them will dramatically compress the time for the discovery of elite genotypes and the release of cultivars compared to classical phenotypic selection. These genomic strategies are being acknowledged as tools that will address the time lag associated with the breeding of perennial crops effectively (Lee *et al.*, 2024; Seyum *et al.*, 2022).

Integrating Traits

Simultaneous improvement of multiple stresses such as drought and disease is complicated as these attributes are regulated by complex polygenic gene networks instead of single major gene (Pasala *et al.*, 2025). Responses to dual stress are known to be associated with unique regulatory networks and gene interactions that are different from single stress responses. Interaction of Abiotic and Biotic Stress Signaling signaling crosstalk between abiotic and biotic stress signaling poses additional complexity in simultaneous enhancement of traits (Zandalinas and Casal, 2024; Elkelish and Abu-Elsaoud, 2024). Therefore, traditional breeding cannot pyramid the multi-stress tolerance and requires integrative genomics and systems-approach (Mandal and Prasad, 2025).

Climate Change Adaptation

Future rootstock breeding must apply climate and predictive tools to anticipate potential stress (e.g. higher drought, heat, rain timing, intensity) scenarios so that selections are appropriate for future environments. Taking wild genetic diversity from crop wild relatives into breeding pools adds greater percentages of adaptive alleles for abiotic and biotic stress resilience, enabling rootstocks to sustain scions under climate ambiguity (Kapazoglou *et al.*, 2023; Martínez *et al.*, 2024). Research on wild Vitis species indicates that wild relatives possess genetic diversity for drought, heat, and other stress tolerance that can strengthen the resilience of cultivated rootstock as climates shift (Zhang *et al.*, 2025). Predictive distribution models and genomic tools can inform the selection of wild germplasm that will best thrive in future environments, thereby supporting adaptation in the long term.

Conclusion

Rootstock selection is essential to improve fruit crop tolerance to abiotic and biotic stress, and hence establishment and yield, in stressful environments. Conventional breeding strategies, in combination with modern molecular tools including genomics, marker assisted selection and omics technologies have substantially expedited rootstock breeding. These advances allow the precise location of stress-adaptive alleles and introduction of these without severe linkage drag in scion quality. Climate-resilient rootstocks contribute to better water and nutrient use efficiency, disease resistance, and the sustainability of worldwide orchards. Further advancement in rootstock breeding is necessary to enhance the situational awareness of the orchard and its future stability with regard to sustainable fruit production in a changing climate.

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