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RESEARCH ARTICLE

Exploring the role of grafting in abiotic stress management: Contemporary insights and automation trends

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Abstract

Grafting is a technique that involves attaching a rootstock to the aerial part of another genotype or species (scion), leading to improved crop performance and sustainable growth. The ability to tolerate abiotic stresses depends on cell membrane stability, a reduction in electrolyte leakage, and the species of scion and rootstock chosen. This external mechanism, grafting, serves as a beneficial tool in influencing crop performance by combining nutrient uptake and translocation to shoots, promoting sustainable plant growth, and enhancing the potential yield of both fruit and vegetable crops. Grafting helps to enhance crop production and improve the capacity of plants to utilize water when undergoing abiotic stress, particularly in genotypes that produce high yields upon rootstocks that are capable of decreasing the impact of drought stress on the shoot. The rootstock plays a pivotal role in establishing a grafted plant by forming a union between the graft and the rootstock. This process is characterized by its integrative, reciprocal nature, enabling plants to tolerate abiotic stress conditions. Grafting has been shown to alleviate the overproduction of lipid peroxidation and reactive oxygen species in the leaves and roots and enhance drought tolerance in plants by maintaining antioxidant enzyme activities and stress-responsive gene expression. Phytohormones, such as cytokinin, auxin, and gibberellin, play a critical role in maintaining rootstock-scion interactions. This review unveils the role of grafting in mitigating various environmental stressors, establishment of a robust graft junction, physiology of rootstock-scion communication, the mechanism underlying rootstock influence, hormonal regulations and the utilization of agri-bots in perfect healing and further cultivation of vegetable crops through grafting.

KEYWORDS
abiotic stress, automation, crop physiology, crop productivity, molecular physiology, plant grafting, stress management

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1 | INTRODUCTION

Over the past 5 years, the cultivable area and crop production of vegetables in India have increased drastically by 11.23% and 10.57% respectively, (Agricultural statistics at a glance, 2022). However, there is instability in production at national level (Bhuyan & Kotoky, 2023). Vegetable crops are extremely susceptible to climatic fluctuations. A shift in the solar cycle is the primary cause of crop failure or complete loss. The varieties of many agricultural products with higher yields have been developed or are now under development. Some cultivars, meanwhile, are unable to deliver this potential in fields despite having high yield values under controlled conditions (Dhar et al., 2023). It is of the utmost significance to raise the yield in addition to the production of high-quality vegetables so that demand can be fulfilled at both the level of production and the level of consumption. Increasing the production of quality products also increases the yield (Ngoune Liliane & Shelton Charles, 2020). However, significant diseases and infestation of insect pests, coupled with the challenges posed by the climate and the soil, are the most common factors that limit the yield and productivity of vegetable crops (Dhar et al., 2023; Kumar, 2023). Plants must sense, classify, and transmit various stress signals before activating downstream reactions and allocating resources. To address the great challenge of climate change, the response to various stress exposures must be researched (Tanaka et al., 2023). Drought, salinity, and extreme temperatures are the primary environmental factors limiting the sustainable production of agricultural and horticultural commodities. Heat stress refers to an increase in temperature that exceeds the threshold level for a period of time, causing harm to plant growth and development. Heat stress causes interference with the establishment of seedlings (Hu et al., 2020; Jyothsna, 2022; Zhao, Zhang, et al., 2020). The plant experiences desiccation, burning, and hindrance in growth due to disruptions in various physiological activities such as pollen formation, photosynthesis, total biomass, spikelet sterility, and disrupted maturation and quality of grains and fruits (Jyothsna, 2022; Zhao, Zhang, et al. 2020). Temperature changes can have a substantial effect on plant physiology because each species has an optimal temperature for growth. For example, Perdomo et al. (2017) reported that the activity of Rubisco (the central enzyme in photosynthesis) and its substrate, ribulose-1,5-bisphosphate (RuBP), decreased at high temperatures, resulting in a significant decrease in yield. Besides, temperature changes play an important role in plant physiological activities, from germination to reproduction, (Hu et al., 2020; Jyothsna, 2022; Zhao, Lu, et al. 2020).

Drought stress is a multi-dimensional abiotic stress that modifies the morphological, physiological, biochemical, and molecular characteristic of a crop (Kaur & Asthir, 2017). Moreover over, reduced seed germination, seedling development, poor vegetative and reproductive growth, decreased plant height and leaf area, and significant reductions in leaf weight, photosynthesis, stomatal conductance, and total dry matter are the essential effects of drought stress on vegetable crops (Salehi-Lisar & Bakhshayeshan-Agdam, 2016). Inhibition of shoot growth during drought reduces the plant's metabolic demands and mobilizes metabolites for the synthesis of protective compounds necessary for osmotic adjustment (Salehi-Lisar & Bakhshayeshan-Agdam, 2016; Tanaka et al., 2023).

Grafting, a vegetative propagation process, joins rootstock and scion from two plants of the same or different species (Bayoumi et al., 2022). Rootstock is the underground plant component that becomes the root system, whereas scion is the aboveground part that becomes the shoot system of the scion plant (Dhar et al., 2023). The agricultural practice of grafting, which involves attaching modern vegetable cultivars onto stress-resistant rootstocks in order to increase the plants' adaptability or resistance to a variety of environmental stresses, has recently gained in favor (Majhi et al., 2023). The method has mostly been used in two significant vegetable families, namely, Cucurbitaceae and Solanaceae (Dhar et al., 2023). Several improved characteristics of grafted crops have been linked to grafting's capability to enhance vegetable crop resistance to both abiotic and biotic stresses, involving (a) improved water relations; (b) boosted nutrient and water absorption; (c) stronger root system; (d) photosynthetic efficiency; (e) transmission of short RNAs, mRNAs, and proteins over long distances; (f) additional hormonal signaling; and (g) raised antioxidant security (Kumar, 2023). Grafting combines the benefits of "resistant plant material" with increased vigor from rootstocks. Grafting may help plants tolerate abiotic stresses including drought and low root-zone temperatures (Keatinge et al., 2014).

Rootstock characteristics determine the efficacy of grafting under stressful conditions. They also help to reduce fungal problems in the soil and the need for agrochemicals, they also make plants more resistant to abiotic stresses (Luna-Garcia et al., 2023). Rootstocks can also enhance scion tolerance via long-distance communication signals, including Ca^{2+} signals, plant hormones, reactive oxygen species (ROS), peptides, RNA, water, and nutrients (Wang et al., 2023). Therefore, the efficacy of grafted plants depends on the compatibility of the scion and rootstock (Coşkun, 2023). It was reported by Dhar et al. (2023) that rootstocks play a vital role in developing tolerance to environmental stress and improve quality, vigor and ultimate yield of the crop. For instances of low compatibility, in addition to the decline in quality and production of the resultant product, fatalities in plant organisms may occur. The success of grafting is influenced by various factors, including the suitable pairing of rootstock and scion, as well as the shared anatomical, physiological, and genetic traits between them. Additionally, the environmental conditions and the specific growth environment of the plant also play a role in determining compatibility. The presence of incompatibility results in a decline in the quality characteristics of the fruit, particularly its internal values such as sugar and fructose content, while the size of the fruit remains unaffected (Adigüzel et al., 2022; Pradeepkumara et al., 2022).

Despite the vast amount of research conducted on vegetables over the past several decades, there are still voids in our understanding of the responses of vegetables to abiotic stress as well as compatibility of grafts (Khalid et al., 2023). Modern genomics (mass spectrometry, genome-wide association studies, gene editing, genomic selection, and transgenic breeding), proteomics, transcriptomics, and the use of next-generation sequencing provide an array of novel, potent approaches for examining vegetable crops (Mangal et al., 2023). When grafted plants are employed as a method to improve abiotic stress tolerance, two primary issues still persist. The first step is to choose the appropriate blend of rootstock and scion so that it can withstand the real or anticipated abiotic stress factors. The second step is to extend the abiotic stress tolerance (robustness) of vegetable crops by improving our understanding of the underlying tolerance processes. This may help the breeding of rootstocks that broaden this tolerance (Rouphael et al., 2017). Traditional varieties exhibit susceptibility to various stressors in several places. Hence, taking into account the intricate nature of genetics and the influence of environmental factors, employing a more comprehensive and interdisciplinary approach presents a superior technique for enhancing stress tolerance in contemporary agricultural crops (Chaudhary et al., 2019). Biotechnological methodologies like plant genetic modification, genome editing technology, and large-scale gene expression analysis have expanded the understanding of plant stress response molecular regulatory networks. These methods confirm the efficacy of drought responsive genes and produce drought-resistant cultivars, as noted by Taheri et al. (2022) and Roychowdhury et al. (2023).

Moreover, grafting requires skill and precision to ensure a successful outcome; it has varied success rates. The limited availability of grafting tools is another major disadvantage (Dhar et al., 2023). To overcome these problems, it is essential to select compatible plant materials, follow proper grafting techniques, maintain ideal environmental conditions, and implement appropriate aftercare practices. The implementation of mechanized grafting was initiated with the objective of mitigating the potential occurrence of graft union failure (Dhar et al., 2023). The utilization of an automated grafting robot has demonstrated significant enhancements in both the efficiency and survival rate of grafted seedlings. This technological advancement has considerable importance in meeting the requirements for the commercialization and widespread adoption of vegetable cultivation practices (Pradeepkumara et al., 2022; Yan et al., 2022). In India, a grafting robot has been created as part of the NAHEP-CAAST-DFSRDA-VNMKV initiative, namely, within the Agri-bot division located in Parbhani. The robotic system is capable of doing various tasks like as clipping, moving, positioning, cutting, binding, and wrapping the rootstock and scion together. The success rate of grafting performed by the robot is 87.3%, whereas the success rate of binding achieved is 68.9%. The process has the capacity to successfully graft between 700 and 800 rootstocks during a single hour (Dhar et al., 2023). Therefore, research gaps and constraints like abiotic stress, grafting practices to use for abiotic stress tolerance, and compatibility of graft junctions and the robots used for grafting were taken into consideration for this review. The review highlights the most recent findings on the role of grafting in alleviating important abiotic stresses, the mechanism behind graft union formation, crop response, and healing to these stresses the potential approaches to maximizing graft compatibility and investigating the metabolite transferred during scion-rootstock interaction and robotics used for grafting. Additionally, glance at physiological and omics-based strategies for increasing vegetable resilience under abiotic stress conditions using grafting practice and graft mechanization is summarized in this review.

2 | GRAFT COMPATIBILITY AND INCOMPATIBILITY: CHALLENGES AND EXCEPTIONS

Grafting is a primitive asexual propagation technique through which two separate plants can be attached and developed into one. Graft compatibility depends on the specific family or families being utilized for grafting, as well as on the varieties, grafting tools used (Goldschmidt, 2014; Pina et al., 2017). For monocot plants, grafting is difficult because of their vascular bundle structural orientation, whereas in dicot plant species, it can be easier due to vascular bundle arrangements (Santa-Cruz et al., 2002). The survival of the grafted plant also depends on the nature and structure of vascular bundles (Goldschmidt, 2014; Lee et al., 2010). For proper graft structure formation, both rootstock and scion must have a compatible nature towards each other (Moore, 1984); hence, compatibility plays a major role in attaining a good graft junction (Melnyk et al., 2015). Trinchera et al. (2013) reported that for graft junction, a graft bridge between cambium structures from both rootstock and scion further develops to callus proliferation, and by the end of a marginal gap of grafting, there is differentiation between tissues among scion and rootstock. Initial graft union formation does not prove long term compatibility (Goldschmidt, 2014); for example, in Cucurbitaceae, it was observed that the successful graft junction failed after a month of grafting (Aloni et al., 2008; Edelstein et al., 2004). Incompatibility despite not being quantitative trait, it can be differentiated using specific morphological characters such as mortality of the stock, scion, or both (Goldschmidt, 2014). According to Moore (1984), enough evidence of a specific biochemical mechanism for graft compatibility/incompatibility is not documented. However, there are two kinds of graft incompatibility reported: (1) translocated and (2) localized (Zarrouk et al., 2010). Translocated incompatibility includes symptoms that can be found in the early stage of development, which include scion and rootstock growth termination at an early stage, reduction of carbohydrate translocation at graft union, shrinking of leaves, and leaf chlorosis leading to early dropping of leaves. In localized incompatibility, malformation at the union due to physiology and morphological variations takes place, which results in weakened graft union development at the junction (Errea, 1998).

Grafting is a practice where several combinations between rootstock and scion can be made such as by selecting rootstocks those are resistant towards abiotic stresses and selecting scions that have capability to provide more number of flowers and fruits. Similarly, one species can be taken as a rootstock and another species as a scion. However, graft combinations are not explored due to various compatibility barriers that includes (i) the genetic changes of adjacent cells of the graft junction (Hartmann, 2014; Tsaballa et al., 2021; Wulf et al., 2020); (ii) anatomical or physiological difficulties between scion and rootstock, position of vascular bundles (Melnyk, 2017; Melnyk & Meyerowitz, 2015); (iii) inadequate cell–cell recognition (Pina et al., 2012); (iv) the triggering of stress response at graft junction (Aloni et al., 2008; Baron et al., 2019; Irisarri et al., 2015; Pina et al., 2012); and (v) toxic compound transference (Goldschmidt, 2014; Moore, 1982). Therefore, exploring several combinations of graft unions such as species-species, homo-grafts, hetero-grafts, resilient rootstock, and resilient scion will bridge the gap for graft compatibility.

Precisely in horticulture, homo-grafts mean that both the rootstock and scion belong to the same species, which is considered to be always compatible in nature. In hetero-grafts, rootstock and scion belong to different species (Yeoman & Brown, 1976). In autograft, both rootstock and scion belongs to same plant and the same species (Wang, 2011); there is intraspecific graft where both genus and species are same and inter-specific graft where both scion and rootstock genus are same but species are different and are almost sa web compatible in nature (Mudge et al., 2009). Research by Schöning and Kollmann (1997) and Flaishman et al. (2008) confirmed that due to long-distance genetic and physiological rejection, the heterograft incompatibility increases. However, incompatibility may occur in a rather unpredictable way even between closely connected genera within the same family. In comparison to compatible tomato homograft, reciprocal grafts of tomato (*Solanum lycopersicum* L.) and pepper were considered severely incompatible within the Solanaceae, whereas tomato and eggplant (*Solanum melongena* L.) were only moderately so (Kawaguchi et al., 2008). In recent times, a new concept has been introduced called as "ultra-compatibility" (UC) , where the graft plant is considered as superior quality. In UC, the genetic exchange such as transfer of DNA and RNA will be easy and highly compatible between rootstock and scion such as exchange. The grafted plant species is considered to be beneficial in terms of genetic exchange and expression (Nesbitt & Gartler, 1971). Genes with non-autonomous functions impact cellular phenotypes outside of the cellular context of expression, suggesting the presence of an unstable signal, and genes with autonomous functions directly affect the phenotype of the cells in which they are expressed. Similar to this, non-autonomous UC traits are transferred across the graft junction and affect the reciprocal organ system, while autonomous UC traits are restricted to the tissues in which they emerge (Brandon et al., 2021). Grafting top scion cultivars onto wild rootstocks results in a dual plant system with better stress tolerance in the rootstock and superior fruit traits in the scion. For example various studies on grafting has proved, enhanced salinity tolerance (Asins et al., 2015; Di Gioia et al., 2013; Singh, Kumar et al., 2020), resistance to drought tolerance (Kumar et al., 2017; Liu et al., 2014; López-Serrano et al., 2019; Sánchez-Rodríguez et al., 2012; Yao et al., 2016) and withstand flooding (Peng et al., 2020). Besides abiotic stress, it also alleviates biotic stress, which includes soil-borne diseases caused by multiple pathogens (Louws et al., 2010) like bacterial wilt in tomato plants. Many of the autonomous traits are directly linked to rootstock, which may have advanced root architecture for having adaptiveness to both biotic and abiotic conditions (Williams et al., 2021). Moreover, rootstocks are directly in contact with soil microbiota (Liu et al., 2018; Marasco et al., 2018; Poudel et al., 2019) thus helps the grafted plant disease resistant and for better ion uptake based on the genotypes used for grafting (Baxter & Dilkes, 2012; Guan et al., 2012). The extent to which beneficial independent traits can be adapted across diverse grafted species is largely determined by whether these abiotic and biotic stress tolerance mechanisms are conserved across species (Williams et al., 2021).

On the other hand, non-autonomous traits are more difficult to monitor mechanistically because they suggest the possible existence of an underlying mobile signal at the graft junction, which involves the exchange of signals from gene active during the process of grafting. Also, similar to heterotic connections in hybrid breeding, specific genotypic rootstock-scion combinations frequently interact synergistically to create UC non-autonomous traits (Birchler et al., 2010). In addition to that, grafted genotypes are considered to be a single because of transfer of genetic materials from rootstocks to scions or vice versa (Williams et al., 2021).

The grafting techniques have been greatly improved over time, however, the compatibility between scion and rootstock is still not improved. The plants decide the graft compatibility based on their physiology and morphological traits as described in Figure 1. Rootstock-scion interactions have a complex and unclear role in fruit crop growth, reproductive potential recognition, fruit set, yield efficiency, and quality traits (Adıgüzel et al., 2023). Future rootstock selection and application could benefit from a better understanding of the interactions between rootstocks and scions.

The complexity of graft union compatibility is still unclear, as the finding takes several years for woody fruit crops, which ensure the aligned development of tissues in the scion and rootstock regions. Besides, it is also unclear for grafting what kind of genotypes can be considered for successful grafting. It is also unclear what lighting conditions, humidity, and so forth can be adapted for successful grafts.

3 | ROLE OF GRAFTING IN ABIOTIC STRESS TOLERANCE

Grafting works as a propitious tool (ancient time practice) that helps in controlling the crop improvement in performance of combining the nutrient uptake and translocation to shoot, sustainable plant growth and potential yield production of both vegetable and fruit crops (Rasool et al., 2020). As grafting is often known to be an integrative reciprocal and a highly promising process, which gives the capability to the plant to tolerate the abiotic stress conditions by making a graft junction having the rootstock genotype (tolerant); this helps the plants overcome or reduce the adverse effects of abiotic stresses (Rouphael et al., 2017; Yang et al., 2023).

Grafting has been used as a tool to decrease or avoid the loss in yield production, which is due to the effect of severe environmental conditions or abiotic stresses (such as salinity, heavy metals, drought, high amounts of trace elements, cold, heat, soil pH, and flooding) (Oyebamiji et al., 2024; Rouphael et al., 2017) in fruits and vegetable crops. Rootstock has the capability to reduce the effect of external stress on shoot region (Colla et al., 2013) and also enhance the robustness and root growth (Gaion et al., 2018) without being dependent on any mechanisms to tolerate an unfavorable abiotic stress condition (Nordey et al., 2020). Grafted plants have shown an increase in

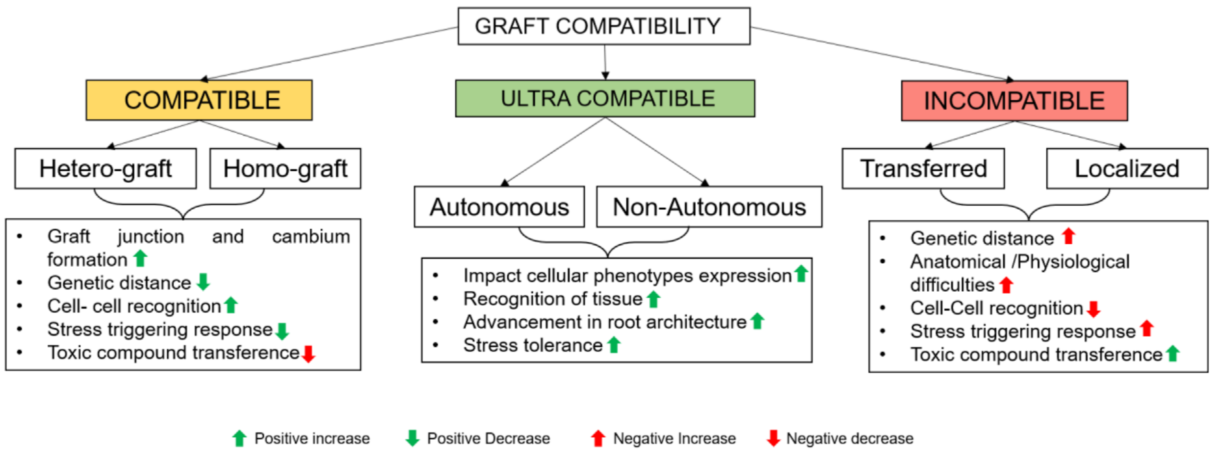

FIGURE 1 Schematic representation of graft compatibilities and changes in the physiology of grafted crops; compatible, ultra-compatible, and incompatible. The figure explains graft compatibility, incompatibility, and ultra-compatibility among hetero and homo-grafts. Arrows indicated with an upward green color indicate an increase in several metabolic activities such as cell-to cell recognition, stress response, cambium formation, root architecture, tissue recognition, and phenotypic expression (positive increase). Red arrows with downward direction indicates negative changes such as decrease in cell-to cell recognition, and toxic compound transferase (negative decrease). Similarly, red arrows with upward direction indicates increase in genetic distance, physiological difficulties, and stress triggering response (negative changes).

physiological, morphological (also, it can increase the leaf foliage), and photosynthetic parameters under various abiotic stress conditions, along with the decrease in cellular damage (Coşkun, 2023; Fullana-Pericàs et al., 2020; Singh, Sethi et al. 2020).

Grafting has become an efficient way for mitigating abiotic stresses such as drought, salinity, and temperature (Melnyk, 2017). It has become an essential process for improving plant development (Rouphael et al., 2018) and increasing the performance of plants under the environmental stresses or abiotic stresses (Rivero et al., 2003; Schwarz et al., 2010). Grafting has been in use (mostly in horticultural crops) to alter the growth habits of scion part in the grafted plants by changing its size, improving fruit quality and yield (Noor et al., 2019) and maintaining the growth vigor (Lee et al., 2010; Melnyk, 2017); also, it has the ability to alter the ionic accumulation in certain horticultural crops (Nawaz et al., 2016).

3.1 | Grafting and drought stress

Water is a resource that is rapidly evolving to be economically insufficient in many regions of the world, mainly semi-arid and arid areas. It has been noticed that there is a requirement of water to be used in different areas such as industries and agriculture for the continued irrigation in the production of commercial vegetables (Schwarz et al., 2010). Grafting is a better technique in helping crops to perform well under drought conditions, for high crop yield when tolerant to drought is grafted with susuptible genotypes (Yang et al., 2023).

It has been estimated that the root system architecture (RSA), root hydraulic conductivity, root-to-shoot ratio, and root biomass usually get reduced under drought stressed conditions (Yang et al., 2022). These effects can be mitigated by using the drought-resistant genotype/seedlings of plants to perform grafting. There are several studies conducted on grafting and drought stress, for example, cucumber grafted with pumpkin (Ashok Kumar & Sanket, 2017). The scion region of mini-watermelon was grafted onto the commercial rootstock PS1313 (*Cucurbita maxima* Duchesne × *Cucurbita moschata* Duchesne); it showed an increase of 60% (marketable range) in yield (more than 115% in total) under water stress conditions when compared to non-grafted watermelon plants (Rouphael et al., 2018). Similarly, grafting performed on kiwi-fruit (four species of Actinidia grafted with *Actinidia chinensis*) has proven to be resistant towards water stress by analyzing their hydraulic conductance (Clearwater et al., 2004). Similarly, it has been observed that grafting the sensitive okra genotypes onto the tolerant genotypes (Coşkun, 2023) helped in mitigating the adverse effects of drought stress with an improvement in physiochemical parameters and reduction in ROS (Razi & Muneer, 2021). The plants such as polyploid mulberry (*Morus alba* L.) (Hui et al., 2024) and young European pear (*Pyrus communis* L.) (Asayesh et al., 2023) were grown under drought stress, and grafting process was performed to develop the tolerance towards the drought stress.

The plants under drought stress produce different forms of ROS mainly hydrogen peroxide, which has the ability to damage various cellular components by the production of lipid peroxidation (LPO), membrane destruction, and protein damage (Das & Roychoudhury, 2014). Grafting has played an important role in alleviating the over production of LPO in several crops under drought stress such as in grapevines (Tandonnet et al., 2010) and tobacco (Kumar et al., 2017). In woody crops such as kiwi, it has been found that the variation in phenology such as hydraulic conductance and photosynthesis between the rootstock and scion combinations appears to be in control for the effect of rootstock on shoot growth (Clearwater et al., 2007). A tolerance towards abiotic stresses depends upon the cell membrane stability, reduction in electrolyte leakage, and the species of scion and rootstock chosen for the study

(Ranjbar & Imani, 2022). From previous studies (Serra et al., 2014; Soar et al., 2006), it is known that in heterografted grapevines minimized the effect of drought stress by maintaining the transpiration of plant via chemical signaling (Serra et al., 2014; Soar et al., 2006; Stoll, 2000) proving heterografted crops have greater tolerance towards abiotic stressors. Also, in another study (Liu et al., 2014), it has been found that grafting the tolerant rootstock genotypes helps the plants in enhancing the drought tolerance trait in tobacco. Furthermore, it has been observed that the resistance mechanism towards drought stress is through rootstock and scion interaction in almonds (Ranjbar & Imani, 2022).

It was also found that grafting the rapeseed (*Brassica rapa* subsp. *Rapa*) scion onto the turnip (*B. rapa* subsp. *Oleifera*) rootstock increases the rapeseed tolerance towards drought stress, as turnip has been noticed to be drought tolerant when compared to rapeseed. In another study, drought stress led to the changes in epigenetic modification on stress marker gene (proline)-P5CS1-2 (gene-homologue of P5CS1) and induced its transcript level during the drought stress (Luo et al., 2020). In another study conducted on tomatoes, it was reported that grafting improved drought tolerance by enhancing photosynthetic capacity and also reduced the ROS accumulation (Zhang et al., 2019).

3.2 | Grafting and salinity stress

Salinity is one of the major issues for the loss of crop productivity due to sources of irrigation used and alkaline soils. Initially, conventional breeding methods were used in order to improve the salt tolerance, but it resulted in limited success as their salt tolerance characteristics were genetically and physiologically complex in nature (Cuartero & Fernández-Muñoz, 1998; Flowers, 2004). Grafting has been employed due to its simplicity and affordability, mainly for the improvement of salt tolerance capacity in tomato plants; that study had commercial tomato "Jaguar," which was grafted onto the tomato rootstocks such as "Radja," "Pera," "Volgogradskij," and also with a hybrid tomato rootstock Volgogradskij × Pera under salt concentrations (0, 25, 50, 75 mM) (Colla et al., 2010; Estan et al., 2005). Tomato scion was grafted onto the tobacco (solanaceous species) rootstock, which has shown salt tolerance ability (Ruiz et al., 2006); thus, this combination of tomato and tobacco was coined to be "tomacco" in a previous study (Yasinok et al., 2009). Similarly, by grafting a salt sensitive tomato like "moneymaker" along with tolerant rootstocks such as "Pera" and "Radja" under 50 mM salt condition had the capability of mitigating the harmful effect of salinity which resulted in an increased fruit yield when compared to self-grafted tomato plants (Martínez-Rodríguez et al., 2008; Santa-Cruz et al., 2002). "Pera" has the potential to ameliorate the salt tolerance traits in plants when being cultivated under saline conditions. There was a significant difference in plant growth especially in case of stem growth rate in tomato plants under salt stress; "Charlotte" scion was grafted onto the "Cyndia" rootstock, which resulted in an increased stem growth rate and that remained dissimilar from the non-grafted tomato plants (Balliu et al., 2007). It has been noticed that the rootstock of "unifort" had an ability to reduce the transportation of Na^+ and Cl^- ions to the aboveground level parts when the scion region of tomato (cv. "Faridah") was grafted onto the rootstock "unifort," which showed diminished effect of salinity stress when compared with non-grafted tomato scion (Al-Harbi et al., 2017). A previous report has shown a significant increase in yield up to 80% with grafted plant when compared to self-grafted and non-grafted tomato plants under salt stress conditions. It was also observed that there was significant reduction in root dry mass in tomato plants under severe saline conditions (100 and 150 mM); however, the level of reduction was less in grafted when compared to non-grafted plants (He et al., 2009). The major reason behind the salinity stress tolerance in the studies is due to the root system and its root characteristics, which play a vital role in soil related salinity stress; the root system has the capability to alleviate the effect of salinity stress, especially on the growth of shoot and in overall yield. The plants or crops after being grafted obtain a capacity to develop the properties of salt tolerance with respect to the decrease in the Na^+ and Cl^- ions into the shoot region (Rouphael et al., 2017). Furthermore, it has been noticed by Colla et al. (2010) that there has been an improvement in nutrient uptake such as potassium and translocation to shoot in case of salt tolerant grafting conditions, which further resulted in the decrease in nutrient deficiencies and imbalances caused by salt stress. The exclusion of Na^+ and/or Cl^- in grafted vegetables under saline conditions has been linked with the reduced traits of the morphological root system, especially total root length, total root surface, root diameter, and number of root hairs and also their length (Colla et al., 2010).

Beside, tobacco plant roots have shown a better adaptive response to saline conditions when compared to tomato plants; the difference was well-identified with level of proline content and the antioxidant enzymes such as APX and CAT (Sun et al., 2020). Similarly, watermelon plant grafted on to their salt tolerant rootstocks has shown an increase in the yield about 81% when it was grown under the greenhouse conditions (Colla et al., 2010). In a previous study (Goreta et al., 2008), it was noticed that there was an increase in shoot weight and leaf area in spite of salinity stress when watermelon (cv. fantasy) was grafted onto the strong-tosa rootstock (*C. maxima* Duch × *C. moschata* Duch). The effect of grafting on the cucumber plants grown under salinity stress has shown an increase in the taste, flavor, and nutrient contents when compared to non-grafted cucumber plants (Zhou et al., 2007). In another study which is reported on grafted cucumber plants' scion onto the fig-leaf gourd which showed its capability to modulate the salt and water absorption and was avle to successively translocate to the scion region of the plant (Zhen et al., 2010).

3.3 | Grafting and thermal stress (heat and cold)

Thermal stress (heat/cold) is another abiotic stress that has effect on plant productivity by changingthe plants' metabolic activities. Several methods have been deployed to practice in field to reduce the effects of thermal stress including grafting. The mechanism underlying grafting and thermal stress mechanism are not known; however, few studies have been carried out. For example, grafting of cucurbits has taken place with cucumber scion having *Cucurbita ficifolia* and *Sicos angulatus* L. in a previous study (Zhou et al., 2007), which has shown an improvement in vegetative growth and yield against low temperature stress condition. In another study (Shibuya et al., 2007), it is stated that there was a tolerance towards low temperature stress under sub-optimal temperature, when the cucumber scion was grafted onto the squash rootstock (*C. moschata* Duch). The watermelon plant was used as a scion to perform grafting with the inter-specific squash hybrid (*C. maxima* × *C. moschata*); this has resulted in improvement of propagating duration by cold period (Davis et al., 2008). The scion region of tomato (*S. lycopersicum*) plant was grafted onto the rootstock of *Solanum habrochaites* (hairy tomato), which has shown an effect of higher yields even at 10–13°C (Okimura et al., 1986). In Khah et al. (2006), the scion part tomato cv. Big Red was grafted onto the tomato cv. Heman (*S. lycopersicum* L. × *Solanum hirsutum* [Vahl Dunal]) and also with cv. Primavera (*S. lycopersicum* L.) where the authors have noticed that there were higher fruits produced when compared to the control group of plants. The brinjal scion was taken to graft onto the whole-leaf rosin-wood rootstock region (*Solanum integrifolium* × *S. melongena*), which has shown an increased yield production at 18–21°C (Okimura et al., 1986).

In a previous report (Abdelmageed & Gruda, 2009), tomato was taken as a scion part, which was grafted with rootstock of brinjal where they have noticed an enhancement in vegetative growth at the temperature of about 28°C, a decrease in number of total fruit, and a reduction in dry weight. Brinjal scion was grafted along with heat tolerant rootstock (cv. nianmaoquie) where the prolonged period of growth stage and increase in yield up to 10% was observed (Wang et al., 2006). The highest yield was observed in the grafted plant where chili was taken as scion region and *Capsicum annuum* cv. Toom-1 and 9852-54 (AVRDC) (Palada & Wu, 2009). The scion region of chili plant was grafted onto the rootstocks of sweet pepper, which has shown a highest yield when grown under the high temperature stress (Palada & Wu, 2009).

3.4 | Grafting and heavy metal, metalloid and nutrient stress

The usage of heavy metals such as mercury, lead, cadmium, and arsenic has been observed in many crops, and sources are mainly either from industries, waste water, or soil alteration (Alengebawy et al., 2021). There are certain heavy metals like arsenic and mercury, which are toxic even when it is used in the range of lower concentrations (Alengebawy et al., 2021). Several studies on metal toxicities in plants have been carried out, but very limited studies are reported on grafting and toxic metals. In few studies, researchers observed reduction in accumulation of copper in leaf and fruits (Rouphael et al. 2008) when grafted on to the Shintoza type rootstock of the same (*C. maxima* Duchesne × *C. moschata* Duchesne). Similarly, cadmium concentrations in the eggplant (*S. melongena*) were grafted onto *Solanum torvum*; the leaves and stem have shown a reduced level of Cd concentrations (67%–73%) (Arao et al., 2008).

In another study (Edelstein & Ben-Hur, 2007), it was noticed that when the melon plants (cv. arava-galia type) were grafted on to the rootstock of cucurbita plant (TZ-148), there was a reduction in boron (B), zinc (Zn), strontium (Sr), manganese (Mn), copper (Cu), titanium (Ti), chromium (Cr), nickel (Ni), and cadmium (Cd) compared to the non-grafted plants. Grafting has shown a reduction in concentrations of cadmium in brinjal fruits when it was grafted onto the *S. torvum* (Arao et al., 2008). The trace elements' tolerance was studied with the cucumber "Akito" scion that was grafted on to the commercial squash rootstock "Shintoza," which controlled the uptake and translocation of Cu to shoot, therewith alleviating an unfavorable effect of enormous Cu supply on yield of fruits and plant biomass (Rouphael et al. 2008). Grafting influences the absorption and translocation of nutrients such as nitrogen, calcium, magnesium, and phosphorus. For example, from a previous study, it was observed that grafting will improve the uptake of nutrients and plant photosynthetic rate (mainly during winter season) (Davis et al., 2008; Hu et al., 2006; Neocleous & Savvas, 2015).

3.5 | Grafting and flood stress

Flooding stress can negatively impact plant growth and development, but plants have a number of ways to adapt it, and several agricultural practices are also followed to tackle it, and one practice among them is grafting. The mechanism of grafting and flooding stress is not well-known; limited studies are reported. For example, the scion region of watermelon was grafted with the rootstock of bottle gourd in loam soil, which has the capacity to enhance the flood tolerance (Maurya et al., 2019). The grafting of cucumber scion part with the squash rootstock region has shown an increase in the chlorophyll content against flooding stress in a previous study (Kato et al., 2001); whereas in another report (Yetışır et al., 2003), the watermelon cv. Crimson Tide scion plant was grafted with the rootstock of *Lagenaria siceraria* SKP (Landrace), and it has shown a decrease in chlorophyll content, which is noticed in rare conditions. The scion part of tomato plant was used to graft with the brinjal accessions EG195 and E203, which has further resulted in the flood tolerance in a previous study. The scion region of the pepper plant was grafted with chili accessions "PP0237-7502," "PP0242-62," and "Lee B," which has resulted in flooding tolerance (Ashok Kumar & Sanket, 2017).

3.6 | Grafting and alkalinity (soil pH) stress

Extreme levels of soil acidity will lead to harmful circumstances for the vegetable crops in several areas of this world (Savvas et al., 2010). Plants or crops exposed to alkaline soil conditions have the increased amount of chemical present within can result in different physiological and biochemical disorders, it could end up in the reduction in growth and loss of yield (Alengebawy et al., 2021). In a previous study, it was reported that there were considerable changes in the biochemical and physiological parameters such as photosynthesis and nutrients when alkalinity is high in the grafted watermelon (*Citrullus lanatus* grafted with cucurbita species) (Colla et al., 2010). In another study, the authors have reported about the effects of five rootstocks such as "Long purple" (eggplant), *Datura patula* (datura), *Solanum luteum* Mill. (orange nightshade), *Nicotiana tabacum* L. (tobacco), and "Cal.jn3"-*S. lycopersicum* L. (field tomato); these were grown under different alkaline conditions like as 0, 5, and 10 mM of $NaHCO_3$ (Mohsenian et al., 2012). Thus, the study stated that there were high total soluble solids (TSS) content, maximal quantum yield of PS-II photochemistry (Fv/Fm), performance index (PI) values, and photosynthetic pigment content in the plants that had *Datura* as their rootstock and rest remained vice versa. So, it was concluded that the datura rootstock has been a beneficial tool to enhance the alkaline tolerance in tomato plants, which are grown under (sodium bicarbonate) $NaHCO_3$ stress (Mohsenian & Roosta, 2015) conditions.

4 | GRAFT UNION FORMATION: A DEEPER LOOK INTO THE ROOTSTOCK-SCION RELATIONSHIP

The successful establishment of a graft union is dependent on the careful selection of both rootstock and scion (Habibi et al., 2022; Rasool et al., 2020). The process of grafting involves the disruption of the plant's vascular system, which must be reconnected in order to facilitate water uptake and nutrient transport to the graft junction. This reconnection occurs through molecular, biochemical, and physiological pathways that resemble the tissue healing process following a wound (Habibi et al., 2022). Additionally, vascular reconstruction allows for the transport of macromolecules across the graft union (Rasool et al., 2020). The relationship between rootstock and scion can significantly impact the growth patterns, precocity in flowering and fruiting, fruit set and yield, quality and size, nutrient status, and disease resistance of the grafted plant (Kumar et al., 2022). For example, a scion may exhibit dwarfing characteristics only when grafted onto a dwarf rootstock, like var. M.9. apple. Conversely, the same scion may grow vigorously when grafted onto a particularly robust rootstock, like the M26 cultivar. However, it is important to note that vigorous rootstocks have a slower rate of fruiting than dwarfing rootstocks (Kumar et al., 2022). The choice of rootstock can also impact the plant's resistance to environmental stressors, such as high salt levels or winter damage. For instance, mandarin grafted onto *Citrus jambhiri* rootstock is more precocious than when grafted onto sweet orange, orange, or acid lime rootstocks. Overall, the careful selection of rootstock and scion is crucial for the successful establishment and growth of a grafted plant (Kumar et al., 2022; Mauro et al., 2022). The study on physiological aspects, movement of proteins, hormones, mRNA, and short RNA across the graft junction (Mauro et al., 2022) may greatly assist to understand the mechanism and communications between rootstock and scion (Figure 2).

5 | GRAFT UNION FORMATION AND GENES INVOLVED

Graft union formation in rootstock-scion combinations involves a series of histological stages. The first stage is characterized by the formation and orientation of a necrotic layer (Melnyk et al., 2015; Rasool et al., 2020). In the second stage, callus cell proliferation occurs, leading to the growth of new tissue (Rasool et al., 2020). The third stage is marked by the formation of a callus bridge at the graft interface, connecting the rootstock and scion. This bridge plays a crucial role in the successful union of the two tissues (Fan et al., 2015). The fourth stage

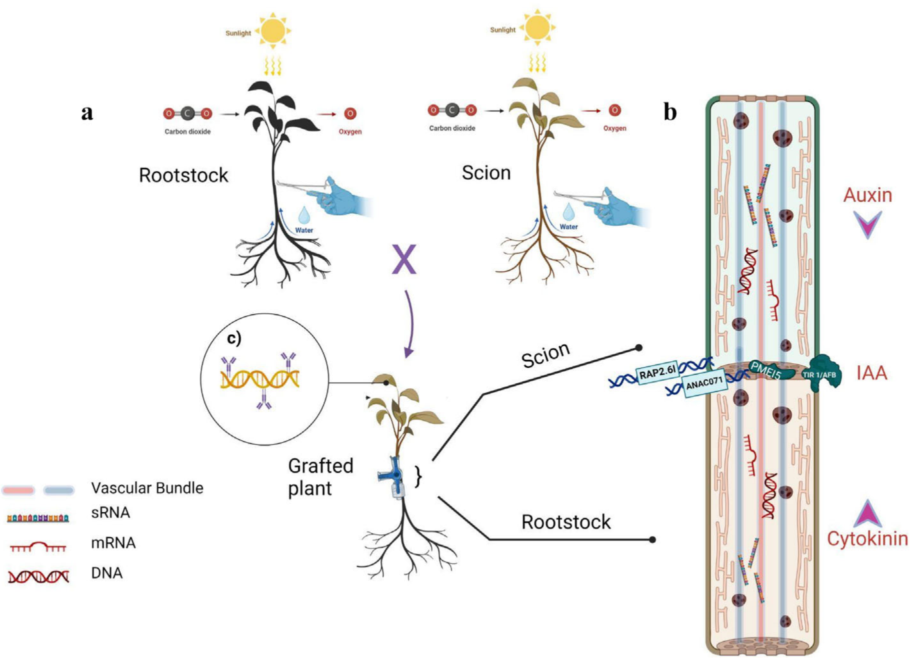

FIGURE 2 Representation of grafting (a) represents grafting and junction formation, (b) represents the signaling process between rootstock and scion such as transfer of mRNA, DNA, and sRNA movement across the graft union formation, (c) represents DNA methylation (created with Biorender.com, license provided). IAA, indole-3-acetic acid.

TABLE 1 Overview of genes/metabolites involved in mitigation of various abiotic stressors through grafting technique in vegetable crops.

S. no	Crop used for study	Stress	Gene/metabolite type	Gene/metabolite identified	Location	Major function	Expression level	Findings	Authors and year
1	Cucumber	Heat stress	Graft healing gene	*HSP70*	Cambium	Facilitates protein folding during heat stress	Upregulated	HSP70 expression led to better survival rates in grafted cucumbers under heat stress.	Li et al. (2014)
2	Eggplant	Salinity stress	Abiotic stressor gene	Na^+/K^+ transporter	Root	Maintains ion balance under salt stress	Upregulated	Na^+/K^+ homeostasis was better maintained in salinized grafted eggplants.	Park et al. (2023)
3	Soybean	Waterlogging stress	Abiotic stressor gene	ERF	Roots	Activates anaerobic metabolism pathways	Upregulated	ERF gene expression improved waterlogging tolerance in grafted soybeans.	Huang et al. (2023)
4	Wheat	Heat stress	Graft healing gene	ROS scavenging enzymes	Leaves/stem	Reduces oxidative damage under heat conditions	Upregulated	Enhanced ROS scavenging improved heat tolerance in grafted wheat.	Reddy et al. (2023)
5	Tomato	Waterlogging stress	Abiotic stressor gene	ERF-VII	Roots	Controls oxygen sensing and triggers anaerobic survival pathways	Upregulated	ERF-VII enhanced root functioning in grafted tomatoes under flooded conditions.	Zhang and Huang (2022)
6	Cucumber	Drought stress	Abiotic stressor metabolite	Proline	Root/leaves	Acts as an osmoprotectant to maintain cell turgor	Upregulated	Drought upregulated proline metabolism genes in grafted cucumber.	Wang and Ren (2024)
7	Citrus	Drought stress	Abiotic stressor gene	ABA signaling genes	Leaves/roots	Regulates osmotic balance during water deficit	Upregulated	ABA pathways were activated synergistically in grafted citrus plants under drought.	Lin et al. (2022)
8	Grapevine	Salinity stress	Abiotic stressor gene	Ion transporters	Root/leaves	Balances ion concentration during salt stress	Upregulated	Grafted grapevines demonstrated improved salt tolerance via ion transport control.	Zhang et al. (2022)
9	Tomato	Drought stress	Abiotic stressor gene	*DREB1A*	Roots/leaves	Enhances drought tolerance by regulating water loss	Upregulated	DREB1A expression improved water retention in grafted tomato plants.	Krishna et al. (2021))
10	Tomato	Salinity stress	Abiotic stressor gene	*SOD, CAT*	Root/leaves	Detoxifies reactive oxygen species (ROS)	Upregulated	Increased SOD and CAT expression resulted in increased salt tolerance in grafted tomatoes.	Singh et al. (2021)
11	Melon	Cold stress	Graft healing gene	Antioxidants	Leaves	Scavenges ROS under cold conditions	Upregulated	Under cold stress, grafted melon exhibited increased antioxidant activity.	Rodriguez et al. (2021)
12	Cucumber	Cold stress	Graft healing gene	*HSP60*	Leaves	Promotes protein stability and stress recovery	Upregulated	HSP60 expression improved chilling tolerance in grafted cucumbers.	Zhu et al. (2021)
13	Rice	Salinity stress	Abiotic stressor gene	*NHX1*	Root/leaf cells	Maintains ion homeostasis in	Upregulated	The NHX1 gene helped grafted rice regulate ions in salty conditions.	Kumar and Patel (2020)
14	Watermelon	Drought stress	Abiotic stressor metabolite	ABA	Leaves	Regulates stomatal closure and water retention	Upregulated	ABA signaling was increased in grafted watermelon during drought conditions.	Li et al. (2020)
15	Tomato	Drought stress	Abiotic stressor gene	ABA signaling components	Leaves	Modulates stomatal behavior and drought responses	Upregulated	Grafted tomatoes' ABA pathways were modified for improved drought tolerance.	Gao et al. (2020)
16	Rice	Salinity stress	Abiotic stressor gene	Antioxidative enzymes	Roots	Reduces oxidative stress	Upregulated	Increased antioxidant enzyme activity in grafted rice exposed to salt.	Nguyen et al. (2020)

(Continues)

TABLE 1 (Continued)

S. no	Crop used for study	Stress	Gene/metabolite type	Gene/metabolite identified	Location	Major function	Expression level	Findings	Authors and year
17	Cucumber	Heat stress	Graft healing gene	*HSF-A2*	Leaves	Controls heat shock response pathways	Upregulated	HSF-A2 overexpression increased heat tolerance in grafted cucumbers.	Wang and Ren (2024)
18	Eggplant	Cold stress	Graft healing gene	*LIP1*	Stem	Enhances structural stability by promoting lignin biosynthesis	Downregulated	Reduced LIP1 expression resulted in flexible grafted eggplants under cold stress conditions.	Wang et al. (2019)
19	Pepper	Heat stress	Graft healing gene	*HSP90*	Stem/leaves	Protects proteins from heat denaturation	Upregulated	HSP90 expression enhanced heat stress tolerance in grafted pepper plants.	Ahmed and Ali (2019)
20	Tomato	Cold stress	Graft healing metabolite	Proline	Stem/leaves	Acts as an osmoprotectant in low temperatures	Upregulated	Grafted tomato proline levels increased, indicating greater cold stress resilience.	Wang et al. (2019)

involves the formation of vascular cambium, which is responsible for the production of new vascular tissue (Melnyk et al., 2015). Finally, in the fifth stage, vascular tissue reconstruction takes place, completing the process of graft union formation. During this process, necrotic layers disappear, except in the outer cortex, where they usually become bark (Fan et al., 2015; Rasool et al., 2020). This disappearance is attributed to the activity of callus cells, which contribute to the regeneration of healthy tissue (Fan et al., 2015; Melnyk et al., 2015).

Several mechanisms are involved in regulating rootstock and scion interactions during graft healing (Liu et al., 2023) (Table 1). One such mechanism is differential gene expression (Figure 1), specific genes, such as *ANAC071* and *RAP2.6L*, have been expressed at the scion and rootstock cut surfaces in Arabidopsis inflorescence stems, respectively (Nie & Wen, 2023). The *ANAC071* gene encodes a transcription factor that contains the NAC domain (no apical meristem [NAM], Arabidopsis transcription activation factor [ATAF], cup-shaped cotyledon [CUC]). NAC transcription factors play a role in various kinds of plant activities, including environmental stress response, organ formation, and vascular development. *ANAC071* is particularly involved with modulating cell differentiation and stress responses, which are critical for effective grafting since they can affect the development and stability of the graft interface. *RAP2.6L* transcription factor is found in the lower region of the wound site and is controlled by jasmonic acid (JA) and low auxin levels. It also enhances the cell division required for wound healing and graft stability. Both *ANAC071* and *RAP2.6L* collaborate, with their expression being spatially controlled by the distribution of auxin, ethylene, and JA, all of which are required for optimal tissue regeneration after grafting. The expression of these genes is promoted by ethylene and JA. Additionally, the accumulation of indole-3-acetic acid (IAA) is observed at the scion cut surface, while its concentration declines at the rootstock cut surface. These gene expressions and IAA accumulation are essential for tissue reunion at graft formation in *Arabidopsis thaliana* (Asahina et al., 2011; Nie & Wen, 2023).

The induction of *ANAC071* expression is facilitated by the presence of auxin, upon binding to the promoters of *XTH19* and *XTH20*; *ANAC071* triggers their expression and promotes cell proliferation during tissue interaction, which can be marked as the end of the first stage (Nie & Wen, 2023). The *XTH19* and *XTH20* genes encode xyloglucan endotransglucosylase/hydrolases (XTHs), enzymes that play an important role in altering the plant cell wall by remodeling xyloglucan, a fundamental component of the wall matrix. In plant grafting, the *ANAC071* transcription factor regulates *XTH19* and *XTH20*, which are necessary for pith cell proliferation and tissue reunion in grafted plants. The *XTH19* and *XTH20* genes encode XTHs, enzymes that play an important role in altering the plant cell wall by remodeling xyloglucan, a fundamental component of the wall matrix. In plant grafting, the *ANAC071* transcription factor regulates *XTH19* and *XTH20*, which are necessary for pith cell proliferation and tissue reunion in grafted plants (Hyodo et al., 2003). DOF transcription factors are rapidly activated at wounding and regulate callus formation (Zhang et al., 2022). The callus proliferation accompanies with *GH9B3* expression that facilitates cell–cell adhesion (Notaguchi et al., 2020). The *GH9B3* gene encodes a glycosyl hydrolase that plays an important role in cell wall remodeling and is especially active during graft union formation. *GH9B3* expression can be driven by the wound-inducible promoter *RAP2.6*, indicating its participation in graft healing via cell wall remodeling (Notaguchi & Tsutsui, 2020). In the second stage, the cambium and parenchyma cells located at the cut surface of both the stock and scion undergo a robust division in response to the injury, resulting in the formation of callus (Aloni, 2021). This callus serves as a bridge, connecting the rootstock and scion (Aloni, 2021). Concurrently, the cells situated between the rootstock and scion initiate the transfer and exchange of water and nutrients through the plasmodesmata. In the third stage, as the callus between the rootstock and scion proliferates, the contact layer gradually disappears. Consequently, the callus between the rootstock and scion transitions from a state of close connection to being fused into a single entity. This transformation can pose challenges in terms of identification (Nie & Wen, 2023). The process of "cambialization" is redundantly influenced by *ANAC071* and *ANAC096*, as per a recent report by Matsuoka et al. (2021). During the fourth stage of this process, new vascular bundles are formed in the callus at the rootstock/scion junction, leading to the formation of a complete plant body. The PIN-formed proteins (PIN), auxin response factor 6 (*ARF6*), and *ARF8* modulate the role of IAA in grafting. The differentiation of the xylem is controlled by monopteros (MP), which is influenced by these factors through the Arabidopsis Histidine Phosphotransferase Protein 6 (*AHP6*) gene. The MP gene encodes an auxin response factor (ARF) that is pivotal in regulating embryogenesis and vascular development. It is involved in orchestrating cell differentiation and division at wound sites, making it essential for tissue regeneration during grafting (Goda et al., 2004).

Similarly, the differentiation of protophloem is regulated by the brevis radix (BRX) gene, while the *ALF4* gene manages cell division and the xylem pole pericycle. *BRX* (BREVIS RADIX) gene produces a protein that influences root growth and development through cell division and elongation. It also controls auxin-mediated growth responses, which are critical in rootstock-scion interactions in grafted plants (Goda et al., 2004). The pre-procambial cell specification is governed by the *Arabidopsis thaliana* homeobox 8 (*ATHB8*) gene (Smit et al., 2020). The *ATHB8* gene encodes a transcription factor from the HOMEODOMAIN-LEUCINE ZIPPER III (HD-ZIP III) family. This gene is essential for the formation of vascular tissues in plants. *ATHB8* is largely expressed in procambial cells, which are precursor cells that develop into vascular tissues. The gene is auxin-inducible and plays a specialized role in increasing vascular strand differentiation and formation, including xylem development, in response to environmental and developmental signals (Baima et al., 2001).

6 | METABOLITE EXCHANGE AT GRAFT INTERFACE

Grafting is a technique that can be employed to regulate the compositional characteristics of horticultural produce, encompassing the concentrations of primary and secondary metabolites. This intricate interdependence necessitates a multifaceted, two-way communication network between the two plant partners, which involves the transfer of water, nutrients, hormones, peptides, nucleic acids, and other metabolites. The physiology and determinism of these mechanisms remain largely unexplored (Mauro et al., 2022). There are certain phytohormones that are involved in abiotic stress mitigation through grafting techniques (Sharma & Zheng, 2019). There are few studies reporting that the phytohormones such as cytokinin, auxin, and gibberellin play a vital role in maintaining the rootstock-scion interactions (Aloni et al., 2010; Rasool et al., 2020).

Plant hormones play a crucial role in the rootstock-scion interaction during grafting, particularly in callus formation. It was also observed that cytokinins, auxins, abscisic acid (ABA), gibberellins, JA, and ethylene are involved in this process (Nanda & Melnyk, 2018). Notably, compounds such as IAA and 6-benzyl adenine (6-BA) can enhance xylem and phloem transport efficiency. These hormones also have a coordinating effect at the rootstock/scion contact area, stimulating cell differentiation and promoting callus formation. IAA synthesized in the scion leaves can be transferred to the rootstock, promoting the growth and development of lateral roots. By balancing the concentrations of cytokinins and ABA, the vigor of the scion can be increased, leading to improved vigor of grafted plants. Additionally, cytokinins and gibberellins transported through the xylem can promote branch growth and internode elongation of the scion partner (Jain et al., 2022; Nanda & Melnyk, 2018).

In other studies, it has been found that ABA plays a crucial role in regulating stomatal closure in plant leaves. When plants experience drought stress, ABA can be transported from the rootstock to the scion, effectively controlling stomatal closure in leaves and enhancing the drought tolerance of grafted plants (Aloni, 2021; Jain et al., 2022; Melnyk et al.,2018). Additionally, JA, an oxidized lipid, is responsible for regulating the expression of defense genes in plants when they undergo cell damage. It has been also shown that under osmotic stress conditions, scion plant leaves can synthesize a higher amount of JA and transport it to the roots of the rootstock, helping to alleviate the damage caused by abiotic stress in the plant. Furthermore, melatonin has been found to contribute to the enhanced cold tolerance of grafted watermelon plants in conjunction with JA (Liu et al., 2021). Melatonin helps to reconstruct the cell wall near the graft interface that is secreted into the extracellular region. Apart from melatonin, sugar metabolism plays a crucial role in the formation of graft unions (Nie & Wen, 2023). In a recent study, Loupit et al. (2022) predicted graft compatibility and identified certain marker metabolites, such as asparagine, trans-resveratrol, trans-piceatannol, and α-viniferin that were exchanged between rootstock and scion. The different metabolic markers between rootstock and scion can be analyzed using various omics technologies (Dong et al., 2022; Jain et al., 2022).

Despite the current findings, the understanding of the link between stock and scion, the integration of vascular tissues, the use of plasmodesmata in union formation, and the exchange of material at the graft interface remain unknown. Extensive research is required to address these fundamental concerns. To further investigate these areas, the use of fluorescent markers and correlative light-electron microscopy is recommended (Rasool et al., 2020). However, the roles of rootstock and scion, as well as the mechanism underlying rootstock influence, are still insufficiently understood. Exciting areas of future research include exploring the effect of rootstock diversity and molecular signaling during scion modulation. By exchanging rootstock in tomato grafts, leaf endophytic microbes of the scion cultivar were partially changed indicating bacteria and fungi could be preferentially associated with rootstock genotypes (Toju et al., 2019). The field of rootstock biology is still in its early stages, with important aspects such as long-distance molecular signaling and the capacity of rootstocks to modulate the interaction between plants and soil (Warschefsky et al., 2016). Further research is needed to uncover the molecular signals underlying graft-transmissible phenotypes, the extent to which large portions of DNA can traverse the graft junction, the impact of the soil on rootstock function and scion phenotype, and whether grafting induces heritable epigenetic changes that alter important agronomic traits.

7 | CRISPR TOOLS APPLICATION IN GRAFTING

CRISPR (clustered regularly interspaced short palindromic repeats) tools are a new genetic engineering method that enables precise DNA editing in live organisms. The CRISPR-Cas9 system, the most well-known CRISPR tool, is based on a natural defense mechanism utilized by bacteria to guard against viruses. The method employs a guide RNA (gRNA) to target certain DNA sequences, and the Cas9 enzyme functions as molecular scissors, cutting the DNA at a precise position. After the DNA is cut, researchers can deactivate a gene or implant a new piece of DNA (Jinek et al., 2012). CRISPR tools are widely used in a variety of applications, including gene therapy, agricultural biotechnology, and fundamental biological research, due to their versatility and precision. CRISPR offers the ability to fix genetic abnormalities, treat and prevent diseases, and increase crop resistance. However, ethical problems and potential off-target effects remain issues that must be addressed (Adli, 2018; Doudna & Charpentier, 2014; Hsu et al., 2014).

CRISPR-Cas12a (also known as Cpf1) is an advanced gene-editing technology that has gained popularity for its unique qualities, such as the capacity to generate staggered cuts in DNA, high specificity, and flexibility in targeting sequences that CRISPR-Cas9 cannot. Cas12a's characteristics make it especially effective for fine-tuning complicated traits such as nutrient intake and stress resistance, both of which are important in vegetable grafting. When used in grafting plants, Cas12a can improve rootstock characteristics, leading in higher nutrient absorption and resistance to various abiotic stresses like as salt, drought, and nutrient deficits. For example, in crops like tomato and cucumber, to improve nitrogen assimilation, CRISPR-Cas12a was used to target the *NRT1.1B* and *NRT2.1* genes that govern nitrate uptake. When these altered rootstocks are utilized in grafting, the scion has higher nutrient availability, which leads to increased growth and yield even in nutrient-limited situations (Zhao et al., 2020). CRISPR-Cas12a can also be utilized to change rootstock genes involved in ion transport and compartmentalization, such as *HKT1* (which regulates sodium transport) and NHX1 (which controls vacuolar sodium sequestration). Researchers fine-tuned these genes to create rootstocks that are better able to handle high salinity levels, minimizing the harmful consequences of excess sodium. For example, in cucumbers, altered rootstocks with better sodium exclusion ability have been demonstrated to flourish in saline soils. When grafted onto non-edited scions, these rootstocks improve the plant's overall salt tolerance (Erdoğan et al., 2023). Likewise, heavy metal contamination in soil, such as excess cadmium (Cd) and arsenic (As), is a significant abiotic stress that can limit plant growth and endanger food safety. CRISPR-Cas12a has been used to improve rootstocks' sequestration and detoxification capabilities by targeting metal transporter genes such as HMA3 and NRAMP. A study on rice found that rootstocks altered with CRISPR-Cas12a for *OsHMA3* (knocked out) reduced cadmium accumulation in shoots while improving the root's ability to retain heavy metals. When grafted, these rootstocks considerably reduced heavy metal uptake in edible plant portions, resulting in safer food harvests.

The effectiveness of CRISPR-Cas12a in mitigating abiotic stresses in grafted vegetables is based on its precise and flexible editing capabilities, such as follows: (a) staggered DNA cuts for precise edits, which is especially useful when editing complex traits involved in stress responses, ensuring minimal off-target effects while achieving the desired genetic change; (b) high targeting specificity as Cas12a recognizes T-rich PAM sequences, which are distinct from those targeted by Cas9. This broadens the spectrum of genes that can be altered, allowing for more precise improvements in stress resistance pathways including as nutrient transporters, osmotic regulation, and root growth; and (c) flexible editing of polygenic traits, because abiotic stress responses frequently involve several genes. Cas12a's capacity to target many gene sites at once (multiplex editing) makes it an ideal tool for enhancing the polygenic characteristics that determine stress tolerance in rootstocks. This characteristic ensures that rootstocks in vegetable grafting can be developed to operate well under varied stress situations, allowing for robust plant development in a variety of environments (Erdoğan et al., 2023; Uga et al., 2018; Zhao et al. 2020). Another tool, CRISPR-Cas13 is a unique RNA-targeting technique that differs from the more well-known DNA-editing CRISPR systems, Cas9 and Cas12a. By targeting mRNA or non-coding RNAs involved in stress responses, CRISPR-Cas13 can assist control stress-responsive pathways without permanently altering the plant's genome. This characteristic helps manage complicated and dynamic stress responses, such as those caused by various abiotic stressors (Abudayyeh et al., 2017; Liu et al., 2021; Mahas et al., 2021; Wessels et al., 2020).

CRISPR-Cas9 technology has helped to improves drought and salinity tolerance by developing rootstocks that are more resistant to drought and salinity. For example, Wang et al. (2020) employed CRISPR-Cas9 to knock out the *SlMAPK3* gene in tomato plants, which resulted in better drought tolerance when these modified rootstocks were grafted with wild-type scions (Wang et al., 2020). The study found that grafted plants retained more water and experienced less oxidative stress during drought conditions. The mechanism involved in mitigation is that the beneficial genes (like *DREB1* and *AREB*—genes help to tolerate stress particularly drought) are upregulated to preserve water and manage the osmotic pressure thus boosting the plant's resilience. Additionally, it is found that CRISPR-Cas9 has been utilized in rice to edit genes that affect root depth and angle, such as *OsNAC10* and *OsDRO1*. Plants with deeper and more spread-out root systems have better access to water and nutrients during droughts. Enhancing these rootstock features in grafted plants using CRISPR-Cas9 makes the entire grafted plant more resistant to water scarcity (Jeong et al., 2010; Uga et al., 2013). High salt levels cause an overabundance of sodium (Na^+) ions in plant cells, disrupting their functioning. CRISPR-Cas9 can target genes such as *HKT1* and *NHX1*, which control salt transport and sequestration in plants. CRISPR-Cas9 modifies these genes, allowing the plant to better manage ion balance and reduce the harmful consequences of salt. During grafting, rootstocks modified for better ion control improve the plant's overall salt tolerance (Munns et al., 2016; Zhao et al., 2016). CRISPR-Cas 9 can also aid in mitigating temperature stress by modifying heat shock proteins (HSPs) and cold-responsive genes (e.g., *CBF* and *ICE1*). For example, in tomato plants, CRISPR-Cas9 was utilized to eliminate the *SlHEAT1* gene in rootstocks, resulting in increased tolerance to both high and low temperatures. Grafted plants with these rootstocks had higher photosynthetic efficiency and less oxidative stress during temperature extremes (Zhang et al., 2019).

CRISPR-Cas13 was used to transiently reduce stress-responsive RNA transcripts in cucumber rootstocks. When grafted with non-edited scions, the changed rootstocks showed increased resistance to drought, heat, and oxidative stress (combined abiotic stress) (Liu et al., 2021). Drought and heat stress in cucumbers frequently result in increased ROS production, which can cause cellular damage. CRISPR-Cas13 was also used to reduce expression of NADPH oxidases and increase expression of SOD1, which had the combined effect of promoting cellular homeostasis and upregulating antioxidant defenses (e.g., *SOD1*). As a result, plants have superior tolerance to the combined impacts of heat and drought, as seen by increased water retention, reduced leaf withering, and increased photosynthetic efficiency. The rootstock can buffer oxidative damage by reducing the expression of stress-sensitive RNA transcripts related to ROS generation using CRISPR-Cas13. When these rootstocks are grafted with non-edited scions, the scion benefits from the changed rootstock's increased antioxidant capacity, which increases the overall robustness of the grafted plant (Liu et al., 2021).

CRISPR tools such as Cas9, Cas12a, and Cas13 are revolutionizing the generation of grafted plants that are more resistant to diverse abiotic challenges such as temperature fluctuations, heavy metal toxicity, and oxidative stress. By targeting specific genes in rootstocks, these technologies provide accuracy in boosting plant resistance, resulting in grafted plants that perform better in harsh environments. Such applications hold significant promise for sustainable agriculture, especially in areas with high abiotic stress levels.

8 | TARGETED MUTAGENESIS AND GRAFTING

Water and mineral nutrients absorbed by the roots of the rootstock can be transported to support the growth of the scion through the transport tissue. Induction of tracheary element formation by XYLEM CYSTEINE PROTEASE (XCP) facilitated water transport resulting in scion growth enhancement (Huang et al. 2023). Similarly, the scion can transport photosynthetic products to the root through the transport tissue (Melnyk, 2017; Nie & Wen, 2023). In a study conducted by Mo et al. (2023), it was found that the expression pattern analysis demonstrated the upregulation of seven CiARFs at specific time points during graft union formation. Among these, CiARF5 and CiARF2e were consistently upregulated and were also induced by drought stress and embryo development, respectively (Mo et al., 2023). Furthermore, a heterograft study by Miao et al. (2021) revealed that the correct sugar content is essential for graft union formation and plays a positive role in this process (Melnyk, 2017; Miao et al., 2021).

The establishment of a vascular connection between the scion and the rootstock is crucial for the successful resumption of growth in the scion. Similarly, the re-establishment of the vascular connection, facilitated by the formation of new xylem and phloem, is a critical stage in the process of new shoot growth from buds located on the scion (Habibi et al., 2022). Recent research by Yang et al. (2023) has revealed a transgene-free and heritable approach for incorporating targeted mutagenesis in plants through grafting. Their study demonstrates the mobility of Cas9 and single guide RNA (sgRNA) transcripts when fused with tRNA-like sequence (TLS) motifs across the grafted junction from transgenic rootstock to wild-type scion. This technique has the potential to be applied in various breeding programs and crop plants (Awan et al., 2023; Yang et al., 2023). The analysis of gene expression to identify genes involved in different aspects of graft union formation poses challenges due to the heterogeneous and complex nature of the graft interface. This interface consists of different cell types with varying responses, making it difficult to pinpoint the specific cells involved in vascular reconnection. For instance, cells involved in vascular reconnection may be sparsely distributed among other tissues present at the graft interface. To overcome these challenges, new techniques can be employed to study grafting and elucidate the roles of each tissue. One such technique is in vitro callus grafting, which allows for the examination of plasmodesmata formation at the callus graft interface. Additionally, single-cell transcript profiling can provide valuable insights into the gene expression patterns of individual cells at the graft interface (Loupit et al., 2023).

9 | MECHANIZED GRAFTING AND COMMERCIAL APPLICATION

Grafting is used as an easy approach for mitigating abiotic stresses (Pérez-Alfocea, 2019; Singh et al., 2017) but is a tedious process. Thus, the use of automated machines or robots (Kubota et al., 2008;

Xie et al., 2020) for grafting is being developed (Oyebamiji et al., 2024; Rivero et al., 2003). A vegetable grafting robot is a device that can be specifically programmed by a computer and is capable of performing an intricate sequence of tasks autonomously. These robots are steered by an internal control system or by an external control device. The majority of crop robotics research now focuses on horticultural or industrial crops (Singh, Sethi et al. 2020). Figure 3 illustrates the schematic diagram emphasizing on the importance of mechanized grafting in vegetable farming.

Grafting automation has been recognized as a key to success in the large-scale production of grafted seedlings. The high cost of grafted seedlings is due to intensive labor inputs for propagation using traditional grafting methods, longer production periods, and additional costs of rootstock seed (Singh, Sethi et al. 2020). Vegetable grafting robots rely heavily on machine vision technology since it increases grafting operations' efficiency and success rate (Devi et al., 2020). The introduction of automation and mechanization technology can help to address large-scale production needs. Semi and fully automated grafting robots have been presented from different agricultural machine industries (Devi et al., 2020; Yan et al., 2022). It assists with joint surface deviation detection, gap detection between rootstock and scion, and diameter matching and identification of seedlings. Intelligent grafting robots that improve accuracy and efficiency can be produced by combining machine vision technology with artificial intelligence and large data analysis (Jiang et al., 2022; Zhang et al., 2017). To determine surface parameters and cutting angles for precise cutting and grafting, it examines the morphology and structure of seedlings. Classification algorithms and statistical techniques aid in the accurate measurement of seedling size (Lee et al., 2010; Liang et al., 2023).

One of the mechanized grafting technique is full-tray grafting that is achieved by plug seedlings clamping and positioning devices. Fu et al. (2022) showed that the average grafting success rate achieved by the full-tray grafting device was around 67%. Moreover, the success rate of rootstock cutting was 100%, while that of scion seedling cutting was over 88%. These findings of Fu et al. (2022) suggest that although the full-tray grafting device exhibited stable performance, there is still scope for enhancing the grafting success rate, especially for seedlings with thin stems and curved growth. The research carried out by Jiang et al. (2020) addresses the need for a cutting mechanism to guarantee the standard and rate of survival of grafting seedlings and offers a reliable procedure for grafting robots. The rootstock and scion cutting surfaces' fitting rates reached 99.04%, indicating the critical cutting angles for *C. moschata* and calabash gourd seedlings. Cutting *C. moschata* seedlings had a success rate of 98%, and pressing their cotyledons (embryonic leaf and critical to handle during grafting) had a 96.67% success rate. The rootstock and scion's cutting precision and fitting rate complied with the splice grafting method's requirements. Hence, these research outcomes serve as supportive shreds of evidence for switching grafting automation over conventional or human-intervened grafting practices. Table 2 lists the most recently developed grafting machines or research related to mechanized grafting and type of grafting that can be achieved.

From the "One Cotyledon Splice Grafting" device developed by Iam Brain in Japan in the 1980s to the sophisticated research in agribots (Singh et al., 2023), a number of factors influence the success rate, one of which is the seedlings' uniform and homogeneous growth in the vertical direction. Adoption of automated grafting is hindered by the high initial cost of grafting equipment, the stringent requirement for consistency of rootstock seedlings, and the intricacy of the cutting angle when utilizing the one-cotyledon grafting method (Devi et al., 2020). Current problems include high production costs, limited grafting speed, and a lack of supplementary grafting equipment. In the future, these limitations in the recent study can be further examined.

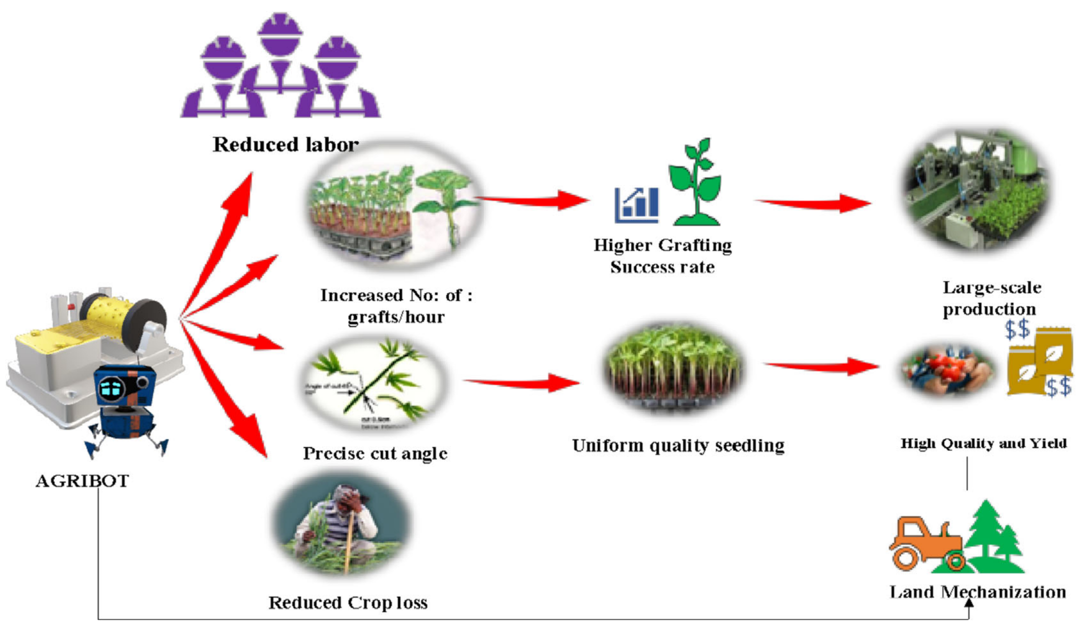

FIGURE 3 Schematic diagram of mechanization of grafting, depicting several benefits of using agri-bot for grafting.

TABLE 2 A summary on the designs and optimization researches carried out on the automatic grafting robots.

S. no	Model type/study on	Type of grafting	Target crop	Grafting rate (plants/hour)	Success rate	Developed by	Country	Year	Reference
1	Automatic; 2TJGQ-800	One-cotyledon grafting	Watermelon	774	90.07	Not specified	China	2023	Liang et al. (2023)
2	Semi-automatic machine	Splice grafting	Melon	2134	67	Not specified	China	2022	Fu et al. (2022)
3	Automatic; clip – Feeding mechanism	Not specified	Not specified	Not specified	98.67	Research Center of Intelligent Equipment, Beijing Academy of Agriculture and Forestry Sciences, and NERCITA	Beijing, China.	2022	Jiang et al. (2022)
4	Cutting mechanical properties	Not specified	Pumpkin	30,000	95	Institute of Agricultural Facilities and Equipment	China	2022	Lu et al. (2022)
5	Automatic; HAU-22	Splice grafting	Melon	2134	67	Huazhong Agricultural University	China	2022	Yan et al. (2022)
6	Semi-automatic machine	Not specified	Solanaceae, Cucurbitaceae	800	87.3	NAHEP-CAAST-DFSRDA-VNMKV	Parbhani, India	2021	Liang et al. (2023)
7	Semi-automatic; JFT-A1500T	Not specified	Melon and Solanaceae	1500	98	Hefei Jiafute Robot Technology Co., Ltd	China	2021	Yan et al. (2022)
8	Cutting mechanism	Splice grafting	Cucurbits	Not specified	98	Beijing Research Center of Intelligent Equipment for Agriculture and the Beijing Research Center of Information Technology for Agriculture	China	2020	Jiang et al. (2020)
9	Rootstock cutting mechanism	Splice grafting	*Cucurbita moschata* and calabash gourd	Not specified	Cutting success rate: 98% Cutting accuracy: 96.8%	Beijing Research Center of Intelligent Equipment for Agriculture	China	2020	Jiang et al. (2020)
10	High-productivity grafting robot (HPR)—two operator mode	Simultaneous multi-plant grafting	Solanaceae	2250	93.6	South China Agricultural University, Guangzhou	China	2020	Xie et al. (2020)
11	High-productivity grafting robot (HPR)—one operator mode	Simultaneous multi-plant	Solanaceae	1542	90.8	South China Agricultural University, Guangzhou	China	2020	Xie et al. (2020)
12	Agilus model R6 900—seedling handling	Splice grafting	Tomato	Not specified	99	KUKA Roboter	Spain	2020	Pardo-Alonso et al. (2020)
13	Semi-automatic; R6 900	Splice grafting	Tomato	80–300	90	University of Almería, Research Center CIMEDES	Italy	2019	Pardo-Alonso et al. (2019)
14	2TJGQ-800 semi-automatic grafting machine	Splice grafting	Melon	800	95	Intelligent Equipment Technology Research Center of Beijing Academy of Agricultural and Forestry Sciences, China	China	2018	Chen et al. (2024)

(Continues)

TABLE 2 (Continued)

S. no	Model type/study on	Type of grafting	Target crop	Grafting rate (plants/hour)	Success rate	Developed by	Country	Year	Reference
15	Automatic; JS-6	Cleft grafting	Solanaceae	720	96	Qingdao Agricultural University and Shandong Zhongtianshengke Automation Equipment Co., Ltd.	China	2018	Yan et al. (2022)
16	Fully automatic; image recognition technique	Splice grafting	Cucumber	Not specified	96	National Institute of Agricultural Sciences, Wanju	Korea	2017	Kang et al. (2019)
17	Fully automatic; image recognition technique	Splice grafting	Tomato	Not specified	95	National Institute of Agricultural Sciences, Wanju	Korea	2017	Kang et al. (2019)
18	Semi-automatic; cutting angle	Splice grafting	Tomato	Not specified	85	Tenova Technological Center: Foundation for Auxiliary Technologies for Agriculture in Almería	Spain	2017	Pardo-Alonso et al. (2018)
19	AFGR-800CS; semi-automatic	Splice grafting	Melon	800	95	Helper Robotech Co., Ltd., South Korea	South Korea	2016	Chen et al. (2024)
20	Automatic; fruit grafting machine	Cleft grafting	Passion fruit	200	>90	Chiayi University, TCDARES	Taiwan	2016	Lin et al. (2016)
21	Automatic; prototype	Splice grafting	Solanaceae/ Cucurbitaceae	840	>90	Israel Virentes	Israel	2016	Lin et al. (2016)
22	Automatic; GR600C-S	Splice grafting	Solanaceae/ Cucurbitaceae	Not specified	>90	Korea Helper Robotech	Korea	2016	Lin et al. (2016)
23	Automatic; 2JC-600B	Top plug-in/ insertion grafting	Cucurbitaceae	600	>90	Northeast Agricultural University	China	2016	Lin et al. (2016)
24	Automatic; 2JC-1000B	Top plug-in/ insertion grafting	Cucurbitaceae	1125	>90	South China Agricultural University	China	2016	Lin et al. (2016)
25	Semi-automatic; ISO-Graft 1100	Vertical cut/tube grafting	Melon/Solanaceae	1000	98	Netherlands ISO-Group	Netherland	2014	Lin et al. (2016)
26	Automatic; AFGR-800CS	Approach grafting	Solanaceae	800	95	Helper Robotech	Korea	2013	Yan et al. (2022)
27	Automatic; GRF800-U	Splice grafting	Cucurbitaceae	800	95	ISEKI, Japan	Japan	2011	Lin et al. (2016)
28	GR803-U	Splice grafting	Melon	800	95	ISEKI Co., Ltd., Japan	Japan	2010	Chen et al. (2024)
29	Automatic; tubing-grafting robotic system	Splice grafting	Tomato (S) Eggplant (R)	327	92–97	National Ilan, Taiwan University, and TNDARES	Taiwan	2010	Lin et al. (2016)
30	Semi-automatic; ISO-Graft 1200	Vertical cut/tube grafting	Melon/Solanaceae	1050	99	Netherlands ISO-Group	Netherland	2010	Lin et al. (2016)
31	Semi-automatic; ISO-Graft 1000	Vertical cut/tube grafting	Tomato	1000	99	Netherlands ISO-Group	Netherland	2007	Lin et al. (2016)

TABLE 2 (Continued)

S. no	Model type/study on	Type of grafting	Target crop	Grafting rate (plants/hour)	Success rate	Developed by	Country	Year	Reference
32	2JSZ-600 semi-automatic grafting machine	Not specified	Melon	600	95	China Agricultural University, China	China	2005	Chen et al. (2024)
33	Automatic	Pin grafting	Solanaceae	1200	95	Ideal System	Korea	2004	Yan et al. (2022)
34	Automatic	Plug-in method	Eggplant	Not specified	Not specified	K. Manzawa, H. Saito, Y. Irie, and T. Mitani	Japan	1992	Kurata (1994)
35	GR300/3 semi-automatic grafting machine	Splice grafting	Melon	300	98	Atlantic Man., Italy	Italy	-	Chen et al. (2024)

Automation and intelligence are the directions for future progress. Modern intelligent technologies like artificial intelligence, cloud computing, and machine vision may be used to accomplish fully autonomous grafting, as well as lower manufacturing costs, faster grafting, and better grafting auxiliary equipment (Yan et al., 2022; Zhang et al., 2017). We might witness the creation of increasingly advanced agribots that can handle a variety of vegetable crops as technology advances. These systems could be adjusted to various grafting methods and maximize the procedure's overall effectiveness. The efficacy and flexibility of agribots in grafting may be further improved by integrating artificial intelligence and machine learning. For widespread implementation, nevertheless, issues including cost, upkeep, and adaptability to various agricultural contexts must be resolved. Agribots' future will probably be shaped by ongoing research and development in this area, making them useful instruments for enhancing sustainability and productivity in vegetable crop grafting.

10 | CONCLUSIONS

The selection of suitable rootstocks or scions is crucial in generating the abiotic stress resistance of grafted plants. Besides enabling the grafted plants to regulate general morphological, physiological, and molecular processes and allow adaptive changes to improve abiotic stress resistance, the graft-responsive genes, especially through the exchange of genetic information between rootstocks and scions, are important in improving plant performance under stress conditions. It is also vital in promoting water use efficiency, osmoregulation, antioxidant-mediated stress tolerance, and so forth. Furthermore, future research can focus more on the improvement of abiotic stress resistance of grafted crops, which is a potential research avenue that can be applied in tropical and sub-tropical regions. Furthermore, with a deeper study, we anticipate that scion-rootstock communication is a complicated process that is critical for improving abiotic stress resistance through transport molecules. As a result, understanding and enhancing plant tolerance requires a focus on scion-rootstock communication. Researchers from several nations have conducted extensive studies on vegetable grafting robots, in addition to physiochemical and molecular biology studies. A huge number of valuable successes have been gained as they progressed from semi-automation to full automation, and the grafting speed and survival rate have been significantly enhanced. Given the advancements in fields like agricultural science and mechanical design, modern vegetable grafting robots based on the splice grafting method are better suited to the development of automation and computerization, which are the mainstream and development directions of future research. With the ongoing advancement of information technology and the progressive implementation of cloud computing and big data in agriculture, the development of intelligent agricultural systems has emerged as the overarching path of future growth. At the same time, using contemporary artificial intelligence, big data, and cloud computing approaches, it is a significant task and challenge to create an agronomic and mechanism-based design model for vegetable grafting robots.

AUTHOR CONTRIBUTIONS

Kaukab Razi and Preethika Suresh wrote the original draft of the manuscript; Pritam Paramguru Mahapatra, Ajila Venkat, and Musa Al Murad contributed in drafting few sections of manuscripts; Michitaka Notaguchi and Muthu Arjuna Samy Prakash gave suggestions while drafting and finalizing the manuscript; Sowbiya Muneer edited and finalized the manuscript. All authors approved and contributed to publish this review.

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CONFLICT OF INTEREST STATEMENT

The authors did not report any conflict of interest.

DATA AVAILABILITY STATEMENT

All data will be made available upon request to the corresponding author.

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REFERENCES

Abdelmageed, A. H. A., & Gruda, N. (2009). Influence of high temperatures on gas exchange rate and growth of eight tomato cultivars under controlled heat stress conditions. *European Journal of Horticultural Science*, *74*(4), 152.

Abudayyeh, O. O., Gootenberg, J. S., Konermann, S., Joung, J., Slaymaker, I. M., Cox, D. B. T., Kellner, M. J., Regev, A., Lander, E. S., & Zhang, F. (2017). RNA targeting with CRISPR-Cas13. *Nature*, *550*(7675), 280–284. https://doi.org/10.1038/nature24049

Adıgüzel, P., Namlı, M., Nyirahabimana, F., Solmaz, İ., & Sarı, N. (2023). The effects of grafting on plant, fruit and seed quality in cantaloupe (*Cucumis melo* L. var. *cantalupensis*) melons. *Seeds*, *2*(1), 1–14. https://doi.org/10.3390/seeds2010001

Adigüzel, P., Nyirahabimana, F., & Solmaz, I. (2022). Recent developments of grafting in Cucurbitaceae. In *Agricultural practices and sustainable management in Türkiye* (p. 207). IKSAD Publishing House.

Adli, M. (2018). The CRISPR tool kit for genome editing and beyond. *Nature Communications*, *9*(1), 1911. https://doi.org/10.1038/s41467-018-04252-2

Ahmed, M., & Ali, Z. (2019). Overexpression of HSP90 in grafted pepper and its role in heat stress mitigation. *Scientia Horticulturae*, *256*, 108588.

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, *9*(3), 42. https://doi.org/10.3390/toxics9030042

Al-Harbi, A., Hejazi, A., & Al-Omran, A. (2017). Responses of grafted tomato (*Solanum lycopersiocon* L.) to abiotic stresses in Saudi Arabia. *Saudi Journal of Biological Sciences*, *24*(6), 1274–1280. https://doi.org/10.1016/j.sjbs.2016.01.005

Aloni, B., Cohen, R., Karni, L., Aktas, H. A. K. A. N., & Edelstein, M. (2010). Hormonal signaling in rootstock–scion interactions. *Scientia Horticulturae*, *127*(2), 119–126. https://doi.org/10.1016/j.scienta.2010.09.003

Aloni, B., Karni, L., Deventurero, G., Levin, Z., Cohen, R., Katzir, N., Lotan-Pompon, M., Aktas, S., Turhan, E., Joel, D. M., Horev, C., & Kapulnik, Y. (2008). Physiological and biochemical changes at the rootstock-scion interface in graft combinations between *Cucurbita* rootstocks and a melon scion. *The Journal of Horticultural Science and Biotechnology*, *83*(6), 777–783. https://doi.org/10.1080/14620316.2008.11512460

Aloni, R. (2021). Vascular regeneration and grafting. In *Vascular differentiation and plant hormones* (pp. 185–198). Springer. https://doi.org/10.1007/978-3-030-53202-4_10

Arao, T., Takeda, H., & Nishihara, E. (2008). Reduction of cadmium translocation from roots to shoots in eggplant (*Solanum melongena*) by grafting onto *Solanum torvum* rootstock. *Soil Science and Plant Nutrition*, *54*(4), 555–559. https://doi.org/10.1111/j.1747-0765.2008.00269.x

Asahina, M., Azuma, K., Pitaksaringkarn, W., Yamazaki, T., Mitsuda, N., Ohme-Takagi, M., Yamaguchi, S., Kamiya, Y., Okada, K., Nishimura, T., Koshiba, T., Yokota, T., Kamada, H., & Satoh, S. (2011). Spatially selective hormonal control of RAP2. 6L and ANAC071 transcription factors involved in tissue reunion in *Arabidopsis*. *Proceedings of the National Academy of Sciences*, *108*(38), 16128–16132.

Asayesh, Z. M., Arzani, K., Mokhtassi-Bidgoli, A., & Abdollahi, H. (2023). Enzymatic and non-enzymatic response of grafted and ungrafted young European pear (*Pyrus communis* L.) trees to drought stress. *Scientia Horticulturae*, *310*, 111745. https://doi.org/10.1016/j.scienta.2022.111745

Ashok Kumar, B., & Sanket, K. (2017). Grafting of vegetable crops as a tool to improve yield and tolerance against diseases—A review. *International Journal of Agriculture Sciences*, *9*(13), 4050–4056. ISSN, 0975-3710

Asins, M. J., Raga, V., Roca, D., Belver, A., & Carbonell, E. A. (2015). Genetic dissection of tomato rootstock effects on scion traits under moderate salinity. *Theoretical and Applied Genetics*, *128*, 667–679. https://doi.org/10.1007/s00122-015-2462-8

Awan, M. J. A., Aslam, M. Q., Naqvi, R. Z., Amin, I., & Mansoor, S. (2023). A graft that crafts nontransgenic and genome-edited plants. *Trends in Plant Science*, *28*(6), 614–616. https://doi.org/10.1016/j.tplants.2023.03.020

Baima, S., Possenti, M., Matteucci, A., Wisman, E., Altamura, M. M., Ruberti, I., & Morelli, G. (2001). The Arabidopsis ATHB-8 HD-zip protein acts as a differentiation-promoting transcription factor of the vascular meristems. *Plant Physiology*, *126*(2), 643–655. https://doi.org/10.1104/pp.126.2.643

Balliu, A., Vuksani, G., Nasto, T., Haxhinasto, L., & Kaçiu, S. (2007). Grafting effects on tomato growth rate, yield and fruit quality under saline irrigation water. *Acta Horticulture*, *801*, 1161–1166.

Baron, D., Amaro, A. C. E., Pina, A., & Ferreira, G. (2019). An overview of grafting re-establishment in woody fruit species. *Scientia Horticulturae*, *243*, 84–91. https://doi.org/10.1016/j.scienta.2018.08.012

Baxter, I., & Dilkes, B. P. (2012). Elemental profiles reflect plant adaptations to the environment. *Science*, *336*(6089), 1661–1663. https://doi.org/10.1126/science.1219992

Bayoumi, Y., Shalaby, T., Abdalla, Z. F., Shedeed, S. H., Abdelbaset, N., El-Ramady, H., & Prokisch, J. (2022). Grafting of vegetable crops in the era of nanotechnology: A photographic mini review. *Environment, Biodiversity and Soil Security*, *6*(2022), 133–148. https://doi.org/10.21608/jenvbs.2022.147280.1181

Bhuyan, D., & Kotoky, A. (2023). Instability in production and productivity of horticultural crops in Assam. *Indian Journal of Agricultural Research*, *57*(1), 123–127.

Birchler, J. A., Yao, H., Chudalayandi, S., Vaiman, D., & Veitia, R. A. (2010). Heterosis. *The Plant Cell*, *22*(7), 2105–2112. https://doi.org/10.1105/tpc.110.076133

Chaudhary, J., Khatri, P., Singla, P., Kumawat, S., Kumari, A., Vikram, A., Jindal, S. K., Kardile, H., Kumar, R., Sonah, H., & Deshmukh, R. (2019). Advances in omics approaches for abiotic stress tolerance in tomato. *Biology*, *8*(4), 90. https://doi.org/10.3390/biology8040090

Chen, S., Jiang, K., Zheng, W., Jia, D., & Zhao, C. (2024). Adaptive precision cutting method for rootstock grafting of melons: Modeling, analysis, and validation. *Computers and Electronics in Agriculture*, *218*, 108655. https://doi.org/10.1016/j.compag.2024.108655

Clearwater, M. J., Blattmann, P., Luo, Z., & Lowe, R. G. (2007). Control of scion vigour by kiwifruit rootstocks is correlated with spring root pressure phenology. *Journal of Experimental Botany*, *58*(7), 1741–1751. https://doi.org/10.1093/jxb/erm029

Clearwater, M. J., Lowe, R. G., Hofstee, B. J., Barclay, C., Mandemaker, A. J., & Blattmann, P. (2004). Hydraulic conductance and rootstock effects in grafted vines of kiwifruit. *Journal of Experimental Botany*, *55*(401), 1371–1382. https://doi.org/10.1093/jxb/erh137

Colla, G., Fiorillo, A., Cardarelli, M., & Rouphael, Y. (2013). Grafting to improve abiotic stress tolerance of fruit vegetables. In II international symposium on organic greenhouse horticulture 1041 (pp. 119–125).

Colla, G., Rouphael, Y., Leonardi, C., & Bie, Z. (2010). Role of grafting in vegetable crops grown under saline conditions. *Scientia Horticulturae*, *127*(2), 147–155. https://doi.org/10.1016/j.scienta.2010.08.004

Coşkun, Ö. F. (2023). The effect of grafting on morphological, physiological and molecular changes induced by drought stress in cucumber. *Sustainability*, *15*(1), 875. https://doi.org/10.3390/su15010875

Cuartero, J., & Fernández-Muñoz, R. (1998). Tomato and salinity. *Scientia Horticulturae*, *78*(1–4), 83–125. https://doi.org/10.1016/S0304-4238(98)00191-5

Das, K., & Roychoudhury, A. (2014). Reactive oxygen species (ROS) and response of antioxidants as ROS-scavengers during environmental stress in plants. *Frontiers in Environmental Science*, *2*, 53. https://doi.org/10.3389/fenvs.2014.00053

Davis, A. R., Perkins-Veazie, P., Hassell, R., Levi, A., King, S. R., & Zhang, X. (2008). Grafting effects on vegetable quality. *HortScience*, *43*(6), 1670–1672. https://doi.org/10.21273/HORTSCI.43.6.1670

Devi, P., Lukas, S., & Miles, C. (2020). Advances in watermelon grafting to increase efficiency and automation. *Horticulturae*, *6*(4), 88. https://doi.org/10.3390/horticulturae6040088

Dhar, S., Borauh, P., & Gogoi, S. (2023). Importance of rootstocks in cucurbitaceous vegetables: A review. *The Pharma Innovation*, *12*(6), 1709–1714.

Di Gioia, F., Signore, A., Serio, F., & Santamaria, P. (2013). Grafting improves tomato salinity tolerance through sodium partitioning within the shoot. *HortScience*, *48*(7), 855–862. https://doi.org/10.21273/HORTSCI.48.7.855

Dong, D., Shi, Y. N., Mou, Z. M., Chen, S. Y., & Zhao, D. K. (2022). Grafting: A potential method to reveal the differential accumulation mechanism of secondary metabolites. *Horticulture Research*, *9*, uhac050. https://doi.org/10.1093/hr/uhac050

Doudna, J. A., & Charpentier, E. (2014). The new frontier of genome engineering with CRISPR-Cas9. *Science*, *346*(6213), 1258096. https://doi.org/10.1126/science.1258096

Edelstein, M., & Ben-Hur, M. (2007). Preventing contamination of supply chains by using grafted plants under irrigation with marginal water. In Proceedings of the international symposium on water resources management. Honolulu, Hawaii, USA (Vol. *150154*).

Edelstein, M., Burger, Y., Horev, C., Porat, A., Meir, A., & Cohen, R. (2004). Assessing the effect of genetic and anatomic variation of *Cucurbita* rootstocks on vigour, survival and yield of grafted melons. *The Journal of Horticultural Science and Biotechnology*, *79*(3), 370–374. https://doi.org/10.1080/14620316.2004.11511775

Erdoğan, İ., Cevher-Keskin, B., Bilir, Ö., Hong, Y., and Tör, M. 2023. Recent Developments in CRISPR/Cas9 Genome-Editing Technology Related to Plant Disease Resistance and Abiotic Stress Tolerance. *Biology (Basel)*, *12*(7):1037. https://doi.org/10.3390/biology12071037

Errea, P. (1998). Implications of phenolic compounds in graft incompatibility in fruit tree species. *Scientia Horticulturae*, *74*(3), 195–205. https://doi.org/10.1016/S0304-4238(98)00087-9

Estan, M. T., Martinez-Rodriguez, M. M., Perez-Alfocea, F., Flowers, T. J., & Bolarin, M. C. (2005). Grafting raises the salt tolerance of tomato through limiting the transport of sodium and chloride to the shoot. *Journal of Experimental Botany*, *56*(412), 703–712. https://doi.org/10.1093/jxb/eri027

Fan, J., Yang, R., Li, X., Zhao, W., Zhao, F., & Wang, S. (2015). The processes of graft union formation in tomato. *Horticulture, Environment, and Biotechnology*, *56*, 569–574. https://doi.org/10.1007/s13580-015-0009-1

Flaishman, M. A., Loginovsky, K., Golobowich, S., & Lev-Yadun, S. (2008). *Arabidopsis thaliana* as a model system for graft union development in homografts and heterografts. *Journal of Plant Growth Regulation*, *27*, 231–239. https://doi.org/10.1007/s00344-008-9050-y

Flowers, T. J. (2004). Improving crop salt tolerance. *Journal of Experimental Botany*, *55*(396), 307–319. https://doi.org/10.1093/jxb/erh003

Fu, X., Shi, J., Huang, Y., Zhu, E., Bie, Z., & Lin, W. (2022). Design and experiment of full-tray grafting device for grafted melon seedling production. *Agriculture*, *12*(6), 861. https://doi.org/10.3390/agriculture12060861

Fullana-Pericàs, M., Conesa, M. À., Pérez-Alfocea, F., & Galmés, J. (2020). The influence of grafting on crops' photosynthetic performance. *Plant Science*, *295*, 110250. https://doi.org/10.1016/j.plantsci.2019.110250

Gaion, L. A., Braz, L. T., & Carvalho, R. F. (2018). Grafting in vegetable crops: A great technique for agriculture. *International Journal of Vegetable Science*, *24*(1), 85–102. https://doi.org/10.1080/19315260.2017.1357062

Gao, H., et al. (2020). Graft-induced changes in ABA signaling pathways under water deficit conditions in tomato. *Journal of Plant Growth Regulation*, *39*, 1158–1171.

Goda, H., Sawa, S., Asami, T., Fujioka, S., Shimada, Y., & Yoshida, S. (2004). Comprehensive comparison of auxin-regulated and brassinosteroid-regulated genes in Arabidopsis. *Plant Physiology*, *134*, 1555–1573. https://doi.org/10.1104/pp.103.034736

Goldschmidt, E. E. (2014). Plant grafting: New mechanisms, evolutionary implications. *Frontiers in Plant Science*, *5*, 727. https://doi.org/10.3389/fpls.2014.00727

Goreta, S., Bucevic-Popovic, V., Selak, G. V., Pavela-Vrancic, M., & Perica, S. (2008). Vegetative growth, superoxide dismutase activity and ion concentration of salt-stressed watermelon as influenced by rootstock. *The Journal of Agricultural Science*, *146*(6), 695–704. https://doi.org/10.1017/S0021859608007855

Guan, W., Zhao, X., Hassell, R., & Thies, J. (2012). Defense mechanisms involved in disease resistance of grafted vegetables. *HortScience*, *47*(2), 164–170. https://doi.org/10.21273/HORTSCI.47.2.164

Habibi, F., Liu, T., Folta, K., & Sarkhosh, A. (2022). Physiological, biochemical, and molecular aspects of grafting in fruit trees. *Horticulture Research*, *9*, uhac032. https://doi.org/10.1093/hr/uhac032

'Hartmann, H. T. (2014). *Hartmann & Kester's plant propagation: Principles and practices*. Pearson Education Limited.

He, Y., Zhu, Z., Yang, J., & Zhu, B. (2009). Grafting increases the salt tolerance of tomato by improvement of photosynthesis and enhancement of antioxidant enzymes activity. *Environmental and Experimental Botany*, *66*, 270–278. https://doi.org/10.1016/j.envexpbot.2009.02.007

Hsu, P. D., Lander, E. S., & Zhang, F. (2014). Development and applications of CRISPR-Cas9 for genome engineering. *Cell*, *157*(6), 1262–1278. https://doi.org/10.1016/j.cell.2014.05.010

Hu, C. M., Zhu, Y. L., Yang, L., Chen, S. F., & Huang, Y. (2006). Comparison of photosynthetic characteristics of grafted and own-root seedlings of cucumber under low temperature circumstances. *Acta Botanica Boreali-Occidentalia Sinica*, *26*, 247–253.

Hu, S., Ding, Y., & Zhu, C. (2020). Sensitivity and responses of chloroplasts to heat stress in plants. *Frontiers in Plant Science*, *11*, 375. https://doi.org/10.3389/fpls.2020.00375

Huang, C., Kurotani, K., Tabata, R., Mitsuda, N., Sugita, R., Tanoi, K., & Notaguchi, M. (2023). *Nicotiana benthamiana XYLEM CYSTEINE PROTEASE* genes facilitate tracheary element formation in interfamily grafting. *Horticulture Research*, *10*(6), uhad072. https://doi.org/10.1093/hr/uhad072

Hui, T., Bao, L., Shi, X., Zhang, H., Xu, K., Wei, X., Liang, J., Zhang, R., Qian, W., Zhang, M., Su, S., & Jiao, F. (2024). Grafting seedling rootstock strengthens tolerance to drought stress in polyploid mulberry (*Morus alba* L.). *Plant Physiology and Biochemistry*, *208*, 108441. https://doi.org/10.1016/j.plaphy.2024.108441

Hyodo, H., Yamakawa, S., Takeda, Y., Tsuduki, M., Yokota, A., Nishitani, K., & Kohchi, T. (2003). Active gene expression of a xyloglucan endotransglucosylase/hydrolase gene, XTH9, in inflorescence apices is related to cell elongation in *Arabidopsis thaliana*. *Plant Molecular Biology*, *52*(4), 473–482. https://doi.org/10.1023/A:1023904217641

Irisarri, P., Binczycki, P., Errea, P., Martens, H. J., & Pina, A. (2015). Oxidative stress associated with rootstock–scion interactions in pear/quince combinations during early stages of graft development. *Journal of Plant Physiology*, *176*, 25–35. https://doi.org/10.1016/j.jplph.2014.10.015

Jain, S., Subhasmita, S., Saini, S., Maurya, P., Jayachandran, A., Pradeepkumara, N., & Kiran, B. (2022). Rootstock-scion physiological and molecular aspects in plants: A review of interactions between biotic and abiotic stress in horticultural crops. *Biologia Forum-An International Journal*, *14*(3), 1409–1413.

Jeong, J. S., Y. S. Kim, K. H. Baek, et al. 2010. "Root-specific expression of OsNAC10 improves drought tolerance and grain yield in rice under field drought conditions." *Plant Physiology 153*, no. 1: 185–197.

Jiang, K., Guo, W., Chen, L., Huang, W., Ge, Y., & Wei, X. (2022). Design and experiment of automatic clip-feeding mechanism for vegetable-grafting robot. *Agriculture*, *12*(3), 346. https://doi.org/10.3390/agriculture12030346

Jiang, K., Zhang, Q., Chen, L., Guo, W., & Zheng, W. (2020). Design and optimization on rootstock cutting mechanism of grafting robot for cucurbit. *International Journal of Agricultural and Biological Engineering*, *13*(5), 117–124. https://doi.org/10.25165/j.ijabe.20201305.5803

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., & Charpentier, E. (2012). A programmable dual-RNA–guided DNA endonuclease in adaptive bacterial immunity. *Science*, *337*(6096), 816–821. https://doi.org/10.1126/science.1225829

J Jyothsna. (2022). Abiotic stress management in vegetable crops. https://doi.org/10.22271/ed.book.1881.

Kang, D. H., Lee, S. Y., Kim, J. K., Park, M. J., Son, J. K., & Yun, S. W. (2019). Development of an automatic grafting robot for fruit vegetables using image recognition. *Journal of Bio-Environment Control*, *28*(4), 322–327. https://doi.org/10.12791/KSBEC.2019.28.4.322

Kato, C., Ohshima, N., Kamada, H., & Satoh, S. (2001). Enhancement of the inhibitory activity for greening in xylem sap of squash root with waterlogging. *Plant Physiology and Biochemistry*, *39*(6), 513–519. https://doi.org/10.1016/S0981-9428(01)01262-1

Kaur, G., & Asthir, B. (2017). Molecular responses to drought stress in plants. *Biologia Plantarum*, *61*, 201–209. https://doi.org/10.1007/s10535-016-0700-9

Kawaguchi, M., Taji, A., Backhouse, D., & Oda, M. (2008). Anatomy and physiology of graft incompatibility in solanaceous plants. *The Journal of Horticultural Science and Biotechnology*, *83*(5), 581–588. https://doi.org/10.1080/14620316.2008.11512427

Keatinge, J. D. H., Lin, L. J., Ebert, A. W., Chen, W. Y., Hughes, J. A., Luther, G. C., Wang, J. F., & Ravishankar, M. (2014). Overcoming biotic and abiotic stresses in the Solanaceae through grafting: Current status and future perspectives. *Biological Agriculture & Horticulture*, *30*(4), 272–287. https://doi.org/10.1080/01448765.2014.964317

Khah, E. M., Kakava, E., Mavromatis, A., Chachalis, D., & Goulas, C. (2006). Effect of grafting on growth and yield of tomato (*Lycopersicon esculentum* Mill.) in greenhouse and open-field. *Journal of Applied Horticulture*, *8*(1), 3–7. https://doi.org/10.37855/jah.2006.v08i01.01

Khalid, M. F., Huda, S., & Yong, M. (2023). Alleviation of drought and salt stress in vegetables: Crop responses and mitigation strategies. *Plant Growth Regulation*, *99*, 177–194. https://doi.org/10.1007/s10725-022-00905-x

Krishna, R., W. A. Ansari, D. K. Jaiswal, et al. 2021. "Overexpression of AtDREB1 and BcZAT12 genes confers drought tolerance by reducing oxidative stress in double transgenic tomato (*Solanum lycopersicum* L.)." *Plant Cell Reports 40*, no. 11: 2173–2190. https://doi.org/10.1007/s00299-021-02725-1

Kubota, C., McClure, M. A., Kokalis-Burelle, N., Bausher, M. G., & Rosskopf, E. N. (2008). Vegetable grafting: History, use, and current technology status in North America. *HortScience*, *43*(6), 1664–1669. https://doi.org/10.21273/HORTSCI.43.6.1664

Kumar, A., Kumar, A., Kumar, R., Wamiq, M., Gautam, P., & Gangwar, V. (2022). Chapter-11 graft incompatibility problem in fruit propagation and scion-stock relationship. In *Modern concepts in farming* (Vol. 137). AkiNik Publications.

Kumar, P., Rouphael, Y., Cardarelli, M., & Colla, G. (2017). Vegetable grafting as a tool to improve drought resistance and water use efficiency. *Frontiers in Plant Science*, *8*, 1130. https://doi.org/10.3389/fpls.2017.01130

Kumar, R. (2023). Vegetable grafting: A novel approach for tolerance against environmental stresses. *Pharma Innovation*, *12*(3), 2501–2507.

Kumar, S., & Patel, R. (2020). NHX1 gene expression and salt tolerance in grafted rice under salinity stress. *Journal of Plant Biotechnology*, *24*(4), 512–526.

Kurata, K. (1994). Cultivation of grafted vegetables II. Development of grafting robots in Japan. *HortScience*, *29*(4), 240–244. https://doi.org/10.21273/HORTSCI.29.4.240

Lee, J. M., Kubota, C., Tsao, S. J., Bie, Z., Echevarria, P. H., Morra, L., & Oda, M. (2010). Current status of vegetable grafting: Diffusion, grafting techniques, automation. *Scientia Horticulturae*, *127*(2), 93–105. https://doi.org/10.1016/j.scienta.2010.08.003

Liang, H., Jiang, K., Shi, X., Zhu, J., Liu, J., Wang, D., Ge, M., Zhou, M., & Shan, F. (2023). An experimental study on the effect of cutting angle on the growth of grafted watermelon seedlings using the one-cotyledon grafting method. *Agronomy*, *13*(1), 250. https://doi.org/10.3390/agronomy13010250

Li, H., S. S. Liu, C. Y. Yi, et al. 2014. "Hydrogen peroxide mediates abscisic acid-induced HSP70 accumulation and heat tolerance in grafted cucumber plants." *Plant, Cell & Environment 37*, no. 12: 2768–2780. https://doi.org/10.1111/pce.12360

Lin, C., W. Tang, H. Wu, Q. Zhou, and D. Chen. 2022. "ABA and grafting synergy for improved drought tolerance in citrus rootstocks." *Tree Physiology 42*, no. 6: 1234–1246. https://doi.org/10.1093/treephys/tpab149

Lin, H., C. Chang, C. Chien, et al. 2016. "Current situation of grafted vegetable seedling industry and its mechanization development in Taiwan." *Grafting to Improve Fruit-Vegetable Production*. https://doi.org/10.56669/DPXS1469

Liu, C., Yin, Z., Du, Y., Zhao, J., & Zhu, C. (2021). Application of CRISPR/-Cas13 in regulating RNA-based oxidative stress responses in grafted cucumber plants. *Journal of Plant Physiology*, *263*, 153479.

Liu, J., Abdelfattah, A., Norelli, J., Burchard, E., Schena, L., Droby, S., & Wisniewski, M. (2018). Apple endophytic microbiota of different rootstock/scion combinations suggests a genotype-specific influence. *Microbiome*, *6*, 18. https://doi.org/10.1186/s40168-018-0403-x

Liu, J., Li, J., Su, X., & Xia, Z. (2014). Grafting improves drought tolerance by regulating antioxidant enzyme activities and stress-responsive gene expression in tobacco. *Environmental and Experimental Botany*, *107*, 173–179. https://doi.org/10.1016/j.envexpbot.2014.06.012

Liu, Y., Liu, H., Zhang, T., Liu, J., Sun, X., Sun, X., Wang, W., & Zheng, C. (2023). Interactions between rootstock and scion during grafting and their molecular regulation mechanism. *Scientia Horticulturae*, *308*, 111554. https://doi.org/10.1016/j.scienta.2022.111554

Li, X., Y. Zhang, J. Wang, W. Liu, H. Zhao, and Z. Chen. 2020. "The role of ABA in enhancing drought tolerance in grafted watermelon plants." *Journal of Agricultural and Food Chemistry 68*, no. 21: 5748–5757. https://doi.org/10.1021/acs.jafc.0c01752

López-Serrano, L., Canet-Sanchis, G., Vuletin Selak, G., Penella, C., San Bautista, A., López-Galarza, S., & Calatayud, Á. (2019). Pepper rootstock and scion physiological responses under drought stress. *Frontiers in Plant Science*, *10*, 38. https://doi.org/10.3389/fpls.2019.00038

Loupit, G., Brocard, L., Ollat, N., & Cookson, S. J. (2023). Grafting in plants: Recent discoveries and new applications. *Journal of Experimental Botany*, *74*(8), 2433–2447. https://doi.org/10.1093/jxb/erad061

Loupit, G., Valls Fonayet, J., Prigent, S., Prodhomme, D., Spilmont, A. S., Hilbert, G., Franc, C., De Revel, G., Richard, T., Ollat, N., & Cookson, S. J. (2022). Identifying early metabolite markers of successful graft union formation in grapevine. *Horticulture Research*, *9*, uhab070. https://doi.org/10.1093/hr/uhab070

Louws, F. J., Rivard, C. L., & Kubota, C. (2010). Grafting fruiting vegetables to manage soilborne pathogens, foliar pathogens, arthropods and weeds. *Scientia Horticulturae*, *127*(2), 127–146. https://doi.org/10.1016/j.scienta.2010.09.023

Lu, D., Wang, W., Bao, E., Wang, S., Wu, X., Bai, Z., & Tang, Y. (2022). Cutting mechanical properties of pumpkin grafted seedling investigated by finite element simulation and experiment. *Agriculture*, *12*(9), 1354. https://doi.org/10.3390/agriculture12091354

Luna-Garcia, L. R., Robledo-Torres, V., Gonzalez-Cortes, A., Mendoza-Villarreal, R., & Paredes-Jacome, J. R. (2023). Effect of pepper rootstocks as a sustainable alternative to improve yield and fruit quality. *Horticulturae*, *9*(7), 795. https://doi.org/10.3390/horticulturae9070795

Luo, L., Zheng, Y., Gao, Z., Chen, Q., Kong, X., & Yang, Y. (2020). Grafting improves drought stress memory by increasing the P5CS1 gene expression in *Brassica rapa*. *Plant and Soil*, *452*, 61–72. https://doi.org/10.1007/s11104-020-04547-8

Mahas, A., Aman, R., & Mahfouz, M. (2021). CRISPR-Cas13d mediates robust RNA virus interference in plants. *Genome Biology*, *22*, 263.

Majhi, P. K., Bhoi, T. K., Sahoo, K. C., Mishra, N., Tudu, S., Das, S., Ray, M., Singh, S., Samal, I., Behera, P. P., & Saini, V. (2023). Understanding the genetics and genomics of vegetable grafting to ensure yield stability. In *Smart plant breeding for vegetable crops in post-genomics era* (pp. 69–98). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5367-5_4

Mangal, V., Lal, M. K., & Tiwari, R. K. (2023). A comprehensive and conceptual overview of omics-based approaches for enhancing the resilience of vegetable crops against abiotic stresses. *Planta*, *257*, 80. https://doi.org/10.1007/s00425-023-04111-5

Marasco, R., Rolli, E., Fusi, M., Michoud, G., & Daffonchio, D. (2018). Grapevine rootstocks shape underground bacterial microbiome and networking but not potential functionality. *Microbiome*, *6*, 3. https://doi.org/10.1186/s40168-017-0391-2

Martínez-Rodríguez, M. M., Estañ, M. T., Moyano, E., García-Abellan, J. O., Flores, F. B., Campos, J. F., Al-Azzawi, M. J., Flowers, T. J., & Bolarín, M. C. (2008). The effectiveness of grafting to improve salt tolerance in tomato when an 'excluder' genotype is used as scion. *Environmental and Experimental Botany*, *63*, 392–401. https://doi.org/10.1016/j.envexpbot.2007.12.007

Matsuoka, K., Sato, R., Matsukura, Y., Kawajiri, Y., Iino, H., Nozawa, N., Kyomi, S., Yuki, K., Sinobu, S., & Asahina, M. (2021). Wound-inducible ANAC071 and ANAC096 transcription factors promote cambial cell formation in incised Arabidopsis flowering stems. *Communications Biology*, *4*(1), 369. https://doi.org/10.1038/s42003-021-01895-8

Mauro, R. P., Pérez-Alfocea, F., Cookson, S. J., Ollat, N., & Vitale, A. (2022). Physiological and molecular aspects of plant rootstock-scion interactions. *Frontiers in Plant Science*, *13*, 852518. https://doi.org/10.3389/fpls.2022.852518

Maurya, D., Pandey, A. K., Kumar, V., Dubey, S., & Prakash, V. (2019). Grafting techniques in vegetable crops: A review. *International Journal of Chemical Studies*, *7*(2), 1664–1672.

Melnyk, C. W. (2017). Plant grafting: Insights into tissue regeneration. *Regeneration*, *4*(1), 3–14. https://doi.org/10.1002/reg2.71

Melnyk, C. W., A. Gabel, T. J. Hardcastle, S. Robinson, S. Miyashima, and I. Grosse. 2018. "Transcriptome dynamics at *Arabidopsis* graft junctions reveal an inter tissue recognition mechanism that activates vascular regeneration." *Proceedings of the National Academy of Sciences of the United States of America 115*: E2447–E2456.

Melnyk, C. W., & Meyerowitz, E. M. (2015). Plant grafting. *Current Biology*, *25*(5), R183–R188. https://doi.org/10.1016/j.cub.2015.01.029

Melnyk, C. W., Schuster, C., Leyser, O., & Meyerowitz, E. M. (2015). A developmental framework for graft formation and vascular reconnection in *Arabidopsis thaliana*. *Current Biology*, *25*(10), 1306–1318. https://doi.org/10.1016/j.cub.2015.03.032

Miao, L., Li, Q., Sun, T. S., Chai, S., Wang, C., Bai, L., Sun, M., Li, Y., Qin, X., Zhnag, Z., & Yu, X. (2021). Sugars promote graft union development in the heterograft of cucumber onto pumpkin. *Horticulture Research*, *8*, 146. https://doi.org/10.1038/s41438-021-00580-5

Mo, Z., Zhang, Y., Hu, L., Zhai, M., & Xuan, J. (2023). Genome-wide identification and expression analysis of the auxin response factor (ARF) gene family in pecan indicates its possible roles during graft union formation. *Scientia Horticulturae*, *322*, 112401. https://doi.org/10.1016/j.scienta.2023.112401

Mohsenian, Y., & Roosta, H. R. (2015). Effects of grafting on alkali stress in tomato plants: Datura rootstock improve alkalinity tolerance of tomato plants. *Journal of Plant Nutrition*, *38*(1), 51–72. https://doi.org/10.1080/01904167.2014.920370

Mohsenian, Y., Roosta, H. R., Karimi, H. R., & Esmaeilizade, M. (2012). Investigation of the ameliorating effects of eggplant, datura, orange nightshade, local Iranian tobacco, and field tomato as rootstocks on alkali stress in tomato plants. *Photosynthetica*, *50*, 411–421. https://doi.org/10.1007/s11099-012-0054-2

Moore, R. (1982). Studies of vegetative compatibility–incompatibility in higher plants. V. A morphometric analysis of the development of a compatible and an incompatible graft. *Canadian Journal of Botany*, *60*(12), 2780–2787. https://doi.org/10.1139/b82-340

Moore, R. (1984). A model for graft compatibility-incompatibility in higher plants. *American Journal of Botany*, *71*(5), 752–758. https://doi.org/10.1002/j.1537-2197.1984.tb14182.x

Mudge, K., Janick, J., Scofield, S., & Goldschmidt, E. E. (2009). A history of grafting. *Horticultural Reviews*, *35*, 437–493. https://doi.org/10.1002/9780470593776.ch9

Munns, R., Tester, M., Plett, D. C., Colmer, T. D., & Tyerman, S. D. (2016). *HKT* transporters and salt tolerance. In S. Shabala & T. Cuin (Eds.), *Plant salt tolerance: Methods and protocols* (pp. 163–176). Humana Press.

Nanda, A. K., & Melnyk, C. W. (2018). The role of plant hormones during grafting. *Journal of Plant Research*, *131*, 49–58. https://doi.org/10.1007/s10265-017-0994-5

Nawaz, M. A., Imtiaz, M., Kong, Q., Cheng, F., Ahmed, W., Huang, Y., & Bie, Z. (2016). Grafting: A technique to modify ion accumulation in horticultural crops. *Frontiers in Plant Science*, *7*, 221552. https://doi.org/10.3389/fpls.2016.01457

Neocleous, D., & Savvas, D. (2015). Effect of different macronutrient cation ratios on macronutrient and water uptake by melon (*Cucumis melo*) grown in recirculating nutrient solution. *Journal of Plant Nutrition and Soil Science*, *178*, 320–332. https://doi.org/10.1002/jpln.201400288

Nesbitt, M. N., & Gartler, S. M. (1971). The applications of genetic mosaicism to developmental problems. *Annual Review of Genetics*, *5*(1), 143–162. https://doi.org/10.1146/annurev.ge.05.120171.001043

Nie, W., & Wen, D. (2023). Study on the applications and regulatory mechanisms of grafting on vegetables. *Plants*, *12*(15), 2822. https://doi.org/10.3390/plants12152822

Ngoune Liliane, T., and M. Shelton Charles. 2020. "Factors affecting yield of crops." In *Agronomy*. IntechOpen. https://doi.org/10.5772/intechopen.90672

Nguyen, H., D. Tran, T. Vu, K. Pham, and T. Le. 2020. "Antioxidative response in grafted rice under salinity stress: A molecular insight." *Environmental and Experimental Botany 178*: 104163. https://doi.org/10.1016/j.envexpbot.2020.104163

Noor, R. S., Wang, Z., Umair, M., Yaseen, M., Ameen, M., Rehman, S. U., Imran, M. U., Ahamd, W., & Sun, Y. (2019). Interactive effects of grafting techniques and scion-rootstocks combinations on vegetative growth, yield and quality of cucumber (*Cucumis sativus* L.). *Agronomy*, *9*(6), 288. https://doi.org/10.3390/agronomy9060288

Nordey, T., Schwarz, D., Kenyon, L., Manickam, R., & Huat, J. (2020). Tapping the potential of grafting to improve the performance of vegetable cropping systems in sub-Saharan Africa. A review. *Agronomy for Sustainable Development*, *40*(4), 23. https://doi.org/10.1007/s13593-020-00628-1

Notaguchi, M., & Tsutsui, H. (2020). Grafting in plants: Recent discoveries and new applications. *Journal of Experimental Botany*, *71*(1), 202–209.

Notaguchi, N., Kurotani, K., Sato, Y., Tabata, R., Kawakatsu, Y., Okayasu, K., Okada, R., Asahina, M., Ichihashi, Y., Shirasu, K., Suzuki, T., Niwa, M., & Higashiyama, T. (2020). Cell-cell adhesion in plant grafting is facilitated by β-1,4-glucanases. *Science*, *369*, 698–702. https://doi.org/10.1126/science.abc3710

Okimura, M., Matso, S., Arai, K., & Okitsu, S. (1986). Influence of soil temperature on the growth of fruit vegetable grafted on different stocks. *Bulletin of Vegetable and Ornamental Crops Research Station Japan.*, *9*, 43–58.

Oyebamiji, Y. O., Adigun, B. A., Shamsudin, N. A. A., Ikmal, A. M., Salisu, M. A., Malike, F. A., & Lateef, A. A. (2024). Recent advancements in mitigating abiotic stresses in crops. *Horticulturae*, *10*(2), 156. https://doi.org/10.3390/horticulturae10020156

Palada, M. C., & Wu, D. L. (2009). AVRDC international cooperators' guide: Grafting sweet peppers for production in the hot-wet season. AVRDC - The World Vegetable Center Publication No. 09 722. 8 p

Pardo-Alonso, J. L., Carreño-Ortega, Á., Martínez-Gaitán, C. C., & Callejón-Ferre, Á. J. (2018). Combined influence of cutting angle and diameter differences between seedlings on the grafting success of tomato using the splicing technique. *Agronomy*, *9*(1), 5. https://doi.org/10.3390/agronomy9010005

Pardo-Alonso, J. L., Carreño-Ortega, Á., Martínez-Gaitán, C. C., & Fatnassi, H. (2020). Behavior of different grafting strategies using automated technology for splice grafting technique. *Applied Sciences*, *10*(8), 2745. https://doi.org/10.3390/app10082745

Pardo-Alonso, J. L., Carreño-Ortega, Á., Martínez-Gaitán, C. C., Golasi, I., & Gómez Galán, M. (2019). Conventional industrial robotics applied to the process of tomato grafting using the splicing technique. *Agronomy*, *9*(12), 880. https://doi.org/10.3390/agronomy9120880

Park, J., H. Kim, S. Lee, Y. Choi, and J. Lim. 2023. "Salinity tolerance in grafted eggplant through the regulation of Na+/K+ homeostasis." *BMC Plant Biology 23*, no. 1: 124. https://doi.org/10.1186/s12870-023-04085-3

Peng, Y. Q., Zhu, J., Li, W. J., Gao, W., Shen, R. Y., & Meng, L. J. (2020). Effects of grafting on root growth, anaerobic respiration enzyme activity and aerenchyma of bitter melon under waterlogging stress. *Scientia Horticulturae*, *261*, 108977. https://doi.org/10.1016/j.scienta.2019.108977

Perdomo, J. A., S. Capó-Bauçà, E. Carmo-Silva, and J. Galmés. 2017. "Rubisco and Rubisco activase play an important role in the biochemical limitations of photosynthesis in rice, wheat, and maize under high temperature and water deficit." *Frontiers in Plant Science 8*: 490.

Pérez-Alfocea, F. (2019). Grafting to address grand challenges. In II international symposium on vegetable grafting 1302 (pp. 9–20).

Pina, A., CookSon, S. J., Calatayud, A., Trinchera, A., & Errea, P. (2017). Physiological and molecular mechanisms underlying graft compatibility. In *Vegetable grafting: Principles and practices* (pp. 132–154). CABI. https://doi.org/10.1079/9781780648972.0132

Pina, A., Errea, P., & Martens, H. J. (2012). Graft union formation and cell-to-cell communication via plasmodesmata in compatible and incompatible stem unions of *Prunus* spp. *Scientia Horticulturae*, *143*, 144–150. https://doi.org/10.1016/j.scienta.2012.06.017

Poudel, R., Jumpponen, A., Kennelly, M. M., Rivard, C. L., Gomez-Montano, L., & Garrett, K. A. (2019). Rootstocks shape the rhizobiome: Rhizosphere and endosphere bacterial communities in the grafted tomato system. *Applied and Environmental Microbiology*, *85*(2), e01765-18. https://doi.org/10.1128/AEM.01765-18

Pradeepkumara, N., Subhasmita, S., Kowsalya, K. B., Jain, S., Hongal, D., Meher, S. S., & Kiran, B. (2022). Grafting technique a novel advancement in vegetable breeding. *Pharma Journal*, *11*(10), 469–480.

Ranjbar, A., & Imani, A. (2022). Grafting commercial cultivars of almonds on accurate rootstocks mitigates adverse effects of drought stress. *Scientia Horticulturae*, *293*, 110725. https://doi.org/10.1016/j.scienta.2021.110725

Rasool, A., Mansoor, S., Bhat, K. M., Hassan, G. I., Baba, T. R., Alyemeni, M. N., Alsahli, A. A., El-Serehy, H. A., Paray, B. A., & Ahmad, P. (2020). Mechanisms underlying graft union formation and rootstock scion interaction in horticultural plants. *Frontiers in Plant Science*, *11*, 590847. https://doi.org/10.3389/fpls.2020.590847

Razi, K., & Muneer, S. (2021). Drought stress-induced physiological mechanisms, signaling pathways and molecular response of chloroplasts in common vegetable crops. *Critical Reviews in Biotechnology*, *41*(5), 669–691. https://doi.org/10.1080/07388551.2021.1874280

Reddy, P., M. Sharma, R. Singh, K. Patel, and N. Yadav. 2023. "Grafting and the modulation of ROS scavenging systems in wheat under heat stress." *Plant Science 330*: 111717. https://doi.org/10.1016/j.plantsci.2023.111717

Rivero, R. M., Ruiz, J. M., & Romero, L. (2003). Role of grafting in horticultural plants under stress conditions. *Journal of Food Agriculture and Environment*, *1*, 70–74.

Rodriguez, M., L. Perez, R. Gomez, E. Santos, and P. Hernandez. 2021. "Exploring the role of grafting in mitigating cold stress in grafted melon plants." *Horticultural Research 8*: 214. https://doi.org/10.1038/s41438-021-00601-8

Rouphael, Y., Cardarelli, M., Colla, G., & Rea, E. (2008). Yield, mineral composition, water relations, and water use efficiency of grafted mini-watermelon plants under deficit irrigation. *HortScience*, *43*(3), 730–736. https://doi.org/10.21273/HORTSCI.43.3.730

Rouphael, Y., Kyriacou, M. C., & Colla, G. (2018). Vegetable grafting: A toolbox for securing yield and stability under multiple stress conditions. *Frontiers in Plant Science*, *8*, 1–4. https://doi.org/10.3389/fpls.2017.02255

Rouphael, Y., Venema, J. H., Edelstein, M., Savvas, D., Colla, G., Ntatsi, G., Ben-Hur, M., Kumar, P., & Schwarz, D. (2017). (pp. 171–215). CABI.

Roychowdhury, R., Das, S. P., Gupta, A., Parihar, P., Chandrasekhar, K., Sarker, U., Kumar, A., Ramrao, D. P., & Sudhakar, C. (2023). Multi-omics pipeline and omics-integration approach to decipher plant's abiotic stress tolerance responses. *Genes*, *14*(6), 1281. https://doi.org/10.3390/genes14061281

Ruiz, J. M., Ríos, J. J., Rosales, M. A., Rivero, R. M., & Romero, L. (2006). Grafting between tobacco plants to enhance salinity tolerance. *Journal of Plant Physiology*, *163*(12), 1229–1237. https://doi.org/10.1016/j.jplph.2005.09.013

Salehi-Lisar, S. Y., & Bakhshayeshan-Agdam, H. (2016). Drought stress in plants: Causes, consequences, and tolerance. *Drought Stress Tolerance in Plants, Physiology and Biochemistry*, *1*, 1–16. https://doi.org/10.1007/978-3-319-28899-4_1

Sánchez-Rodríguez, E., Leyva, R., Constán-Aguilar, C., Romero, L., & Ruiz, J. M. (2012). Grafting under water stress in tomato cherry: Improving the fruit yield and quality. *Annals of Applied Biology*, *161*(3), 302–312. https://doi.org/10.1111/j.1744-7348.2012.00574.x

Santa-Cruz, A., Martinez-Rodriguez, M. M., Perez-Alfocea, F., Romero-Aranda, R., & Bolarin, M. C. (2002). The rootstock effect on the tomato salinity response depends on the shoot genotype. *Plant Science*, *162*(5), 825–831. https://doi.org/10.1016/S0168-9452(02)00030-4

Savvas, D., Colla, G., Rouphael, Y., & Schwarz, D. (2010). Amelioration of heavy metal and nutrient stress in fruit vegetables by grafting. *Scientia Horticulturae*, *127*(2), 156–161. https://doi.org/10.1016/j.scienta.2010.09.011

Schöning, U., & Kollmann, R. (1997). Phloem translocation in regenerating in vitro-heterografts of different compatibility. *Journal of Experimental Botany*, *48*(2), 289–295. https://doi.org/10.1093/jxb/48.2.289

Schwarz, D., Rouphael, Y., Colla, G., & Venema, J. H. (2010). Grafting as a tool to improve tolerance of vegetables to abiotic stresses: Thermal stress, water stress and organic pollutants. *Scientia Horticulturae*, *127*(2), 162–171.

Serra, I., Strever, A., Myburgh, P. A., & Deloire, A. (2014). The interaction between rootstocks and cultivars (*Vitis vinifera* L.) to enhance drought tolerance in grapevine. *Australian Journal of Grape and Wine Research*, *20*(1), 1–14. https://doi.org/10.1111/ajgw.12054

Sharma, A., & Zheng, B. (2019). Molecular responses during plant grafting and its regulation by auxins, cytokinins, and gibberellins. *Biomolecules*, *9*(9), 397. https://doi.org/10.3390/biom9090397

Shibuya, T., Tokuda, A., Terakura, R., Shimizu-Maruo, K., Sugiwaki, H., Kitaya, Y., & Kiyota, M. (2007). Short-term bottom-heat treatment during low-air-temperature storage improves rooting in squash (*Cucurbita moschata* Duch.) cuttings used for rootstock of cucumber (*Cucumis sativus* L.). *Journal of Japanese Society of Horticultural Science*, *76*(2), 139–143.

Singh, A., R. Verma, P. Sharma, V. Kumar, and D. Singh. 2021. "Salt tolerance in grafted tomato: The involvement of SOD and CAT genes." *Plant Cell Reports 40*, no. 2: 205–216. https://doi.org/10.1007/s00299-020-02604-9

Singh, H., Kumar, P., Chaudhari, S., & Edelstein, M. (2017). Tomato grafting: A global perspective. *HortScience*, *52*(10), 1328–1336. https://doi.org/10.21273/HORTSCI11996-17

Singh, H., Kumar, P., Kumar, A., Kyriacou, M. C., Colla, G., & Rouphael, Y. (2020). Grafting tomato as a tool to improve salt tolerance. *Agronomy*, *10*(2), 263. https://doi.org/10.3390/agronomy10020263

Singh, H., Sethi, S., Kaushik, P., & Fulford, A. (2020). Grafting vegetables for mitigating environmental stresses under climate change: A review. *Journal of Water and Climate Change*, *11*(4), 1784–1797. https://doi.org/10.2166/wcc.2019.177

Singh, M. K., Alam, M. K., Pandey, M. V., Singh, M. S., & Kumar, M. (2023). *Advanced technology of horticulture*. Daya Publishing House.

Smit, M. E., McGregor, S. R., Sun, H., Gough, C., Bågman, A. M., Soyars, C. L., Kroon, J. T., Gaudinier, A., Williams, C. J., Yang, X., Nimchuk, Z. L., Weijers, D., Turner, S. R., Brady, S. M., & Etchells, J. P. (2020). A PXY-mediated transcriptional network integrates signaling mechanisms to control vascular development in Arabidopsis. *The Plant Cell*, *32*(2), 319–335. https://doi.org/10.1105/tpc.19.00562

Soar, C. J., Dry, P. R., & Loveys, B. R. (2006). Scion photosynthesis and leaf gas exchange in *Vitis vinifera* L. cv. Shiraz: Mediation of rootstock effects via xylem sap ABA. *Australian Journal of Grape and Wine Research*, *12*(2), 82–96. https://doi.org/10.1111/j.1755-0238.2006.tb00047.x

Stoll, M. (2000). *Effects of partial rootzone drying on grapevine physiology and fruit quality* (Doctoral dissertation).

Sun, H., Sun, X., Wang, H., & Ma, X. (2020). Advances in salt tolerance molecular mechanism in tobacco plants. *Hereditas*, *157*(1), 5. https://doi.org/10.1186/s41065-020-00118-0

Taheri, S., Gantait, S., Azizi, P., & Mazumdar, P. (2022). Drought tolerance improvement in *Solanum lycopersicum*: An insight into "OMICS" approaches and genome editing. *3 Biotech*, *12*(3), 63. https://doi.org/10.1007/s13205-022-03132-3

Tanaka, K., Mudgil, Y., & Tunc-Ozdemir, M. (2023). Abiotic stress and plant immunity—A challenge in climate change. *Frontiers in Plant Science*, *14*, 1197435. https://doi.org/10.3389/fpls.2023.1197435

Tandonnet, J. P., Cookson, S. J., Vivin, P., & Ollat, N. (2010). Scion genotype controls biomass allocation and root development in grafted grapevine. *Australian Journal of Grape and Wine Research*, *16*(2), 290–300. https://doi.org/10.1111/j.1755-0238.2009.00090.x

Toju, H., Okayasu, K., & Notaguchi, M. (2019). Leaf-associated microbiomes of grafted tomato plants. *Scientific Reports*, *9*, 1787. https://doi.org/10.1038/s41598-018-38344-2

Trinchera, A., Pandozy, G., Rinaldi, S., Crinò, P., Temperini, O., & Rea, E. (2013). Graft union formation in artichoke grafting onto wild and cultivated cardoon: An anatomical study. *Journal of Plant Physiology*, *170*(18), 1569–1578. https://doi.org/10.1016/j.jplph.2013.06.018

Tsaballa, A., Xanthopoulou, A., Madesis, P., Tsaftaris, A., & Nianiou-Obeidat, I. (2021). Vegetable grafting from a molecular point of view: The involvement of epigenetics in rootstock-scion interactions. *Frontiers in Plant Science*, *11*, 621999. https://doi.org/10.3389/fpls.2020.621999

Uga, Y., Sugimoto, K., Ogawa, S., Rane, J., Ishitani, M., Hara, N., & Yano, M. (2013). Control of root system architecture by *DEEPER ROOTING 1* increases rice yield under drought conditions. *Nature Genetics*, *45*(9), 1097–1102.

Uga, Y., Sugimoto, K., Ogawa, S., Rane, J., Ishitani, M., Hara, N., & Yano, M. (2018). Control of root system architecture by DEEPER ROOTING 1 increases yield under drought conditions in rice. *Nature Genetics*, *50*(1), 109–115.

Wang, H., P. Zhou, W. Zhu, and F. Wang. 2019. "De novo comparative transcriptome analysis of genes differentially expressed in the scion of homografted and heterografted tomato seedlings." *Scientific Reports 9*: 20240. https://doi.org/10.1038/s41598-019-56563-z

Wang, L., Wu, B., Chen, G., Chen, H., Peng, Y., Sohail, H., Geng, S., Luo, G., Xu, D., Ouyang, B., & Bie, Z. (2023). The essential role of jasmonate signaling in *Solanum habrochaites* rootstock-mediated cold tolerance in tomato grafts. *Horticulture Research*, *10*(1), uhac227. https://doi.org/10.1093/hr/uhac227

Wang, S., Cheng, J., Zhao, J., & Yang, R. (2006). Effect of rootstocks on the tolerance to high temperature of eggplants under solar greenhouse during summer season. In XXVII International Horticultural Congress-IHC2006: International Symposium on Advances in Environmental Control, Automation 761 (pp. 357–360).

Wang, Y. (2011). Plant grafting and its application in biological research. *Chinese Science Bulletin*, *56*, 3511–3517. https://doi.org/10.1007/s11434-011-4816-1

Wang, Z., and Z. Ren. 2024. "Cucumber CsHsfA2 improves thermotolerance through self-activation and activation of CsHsp70-1." *Plant*

Growth Regulation 104: 283–302. https://doi.org/10.1007/s10725-024-01166-6

Wang, Z., Zhang, J., Jia, C., Liu, J., Xu, B., Wang, Y., & Shi, K. (2020). Improved drought tolerance in grafted tomato plants by CRISPR/Cas9-mediated knockout of the *SlMAPK3* gene. *Plant Science*, *295*, 110503.

Warschefsky, E. J., Klein, L. L., Frank, M. H., Chitwood, D. H., Londo, J. P., von Wettberg, E. J. B., & Miller, A. J. (2016). Rootstocks: Diversity, domestication, and impacts on shoot phenotypes. *Trends in Plant Science*, *21*(5), 418–437. https://doi.org/10.1016/j.tplants.2015.11.008

Wessels, H. H., Méndez-Mancilla, A., Guo, X., Legut, M., Daniloski, Z., & Sanjana, N. E. (2020). Massively parallel Cas13 screens reveal principles for guide RNA design. *Nature Biotechnology*, *38*(6), 722–727. https://doi.org/10.1038/s41587-020-0456-9

Williams, B., Ahsan, M. U., & Frank, M. H. (2021). Getting to the root of grafting-induced traits. *Current Opinion in Plant Biology*, *59*, 101988. https://doi.org/10.1016/j.pbi.2020.101988

Wulf, K. E., Reid, J. B., & Foo, E. (2020). What drives interspecies graft union success? Exploring the role of phylogenetic relatedness and stem anatomy. *Physiologia Plantarum*, *170*(1), 132–147. https://doi.org/10.1111/ppl.13118

Xie, Z., Gu, S., Chu, Q., Li, B., Fan, K., Yang, Y., & Liu, X. (2020). Development of a high-productivity grafting robot for Solanaceae. *International Journal of Agricultural and Biological Engineering*, *13*(1), 82–90. https://doi.org/10.25165/j.ijabe.20201301.5209

Yan, G., Feng, M., Lin, W., Huang, Y., Tong, R., & Cheng, Y. (2022). Review and prospect for vegetable grafting robot and relevant key technologies. *Agriculture*, *12*(10), 1578. https://doi.org/10.3390/agriculture12101578

Yang, L., Machin, F., & Wang, S. (2023). Heritable transgene-free genome editing in plants by grafting of wild-type shoots to transgenic donor rootstocks. *Nature Biotechnology*, *41*, 958–967. https://doi.org/10.1038/s41587-022-01585-8

Yang, L., Xia, L., Zeng, Y., Han, Q., & Zhang, S. (2022). Grafting enhances plants drought resistance: Current understanding, mechanisms, and future perspectives. *Frontiers in Plant Science*, *13*, 1015317. https://doi.org/10.3389/fpls.2022.1015317

Yao, X., Yang, R., Zhao, F., Wang, S., Li, C., & Zhao, W. (2016). An analysis of physiological index of differences in drought tolerance of tomato rootstock seedlings. *Journal of Plant Biology*, *59*, 311–321. https://doi.org/10.1007/s12374-016-0071-y

Yasinok, A. E., Feride, S. I., Eyidogan, F., Kuru, M., & Haberal, M. (2009). Grafting tomato plant on tobacco plant and its effect on tomato plant yield and nicotine content. *Journal of the Science of Food and Agriculture*, *89*, 1122–1128. https://doi.org/10.1002/jsfa.3555

Yeoman, M. M., & Brown, R. (1976). Implications of the formation of the graft union for organisation in the intact plant. *Annals of Botany*, *40*(6), 1265–1276. https://doi.org/10.1093/oxfordjournals.aob.a085247

Yetışır, H., Sari, N., & Yücel, S. (2003). Rootstock resistance to *Fusarium* wilt and effect on watermelon fruit yield and quality. *Phytoparasitica*, *31*, 163–169. https://doi.org/10.1007/BF02980786

Zarrouk, O., Testillano, P. S., Risueño, M. C., Moreno, M. Á., & Gogorcena, Y. (2010). Changes in cell/tissue organization and peroxidase activity as markers for early detection of graft incompatibility in peach/plum combinations. *Journal of the American Society for Horticultural Science*, *135*(1), 9–17. https://doi.org/10.21273/JASHS.135.1.9

Zhang, K., Chu, J., Zhang, T., Yin, Q., Kong, Y., & Liu, Z. (2017). Development status and analysis of automatic grafting technology for vegetables. *Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery*, *48*(3), 1–13. https://doi.org/10.6041/j.issn.1000-1298.2017.03.001

Zhang, L., & Huang, Y. (2022). ERF-VII mediated waterlogging tolerance in grafted tomato: A physiological and molecular perspective. *Frontiers in Plant Science*, *13*, 897654.

Zhang, T., Y. Li, Q. Chen, H. Zhao, and J. Xu. 2022. "Transcriptomic analysis of graft-induced salt tolerance in grapevine." *Frontiers in Genetics 13*: 827579. https://doi.org/10.3389/fgene.2022.827579

Zhang, Z., Cao, B., Gao, S., & Xu, K. (2019). Grafting improves tomato drought tolerance through enhancing photosynthetic capacity and reducing ROS accumulation. *Protoplasma*, *256*, 1013–1024. https://doi.org/10.1007/s00709-019-01357-3

Zhao, F. Y., Zhang, D. Y., Zhao, Y. J., Wang, W. S., Zhang, W. K., & Chen, S. Y. (2016). CRISPR/Cas9-mediated mutagenesis of *NHX1* improves salt tolerance in soybean. *Plant Cell, Tissue and Organ Culture*, *125*(3), 499–510.

Zhao, J., Lu, Z., Wang, L., & Jin, B. (2020). Plant responses to heat stress: Physiology, transcription, noncoding RNAs, and epigenetics. *International Journal of Molecular Sciences*, *22*(1), 117. https://doi.org/10.3390/ijms22010117

Zhao, Y., Zhang, C., Liu, W., Gao, W., Li, Y., Zhang, C., & Liu, Y. (2020). Application of CRISPR-Cas12a (Cpf1) in multiplex genome editing of monocot plants and crops. *Plant Biotechnology Journal*, *18*(8), 1745–1755.

Zhen, A., Bie, Z., Huang, Y., Liu, Z., & Li, Q. (2010). Effects of scion and rootstock genotypes on the anti-oxidant defense systems of grafted cucumber seedlings under NaCl stress. *Soil Science and Plant Nutrition*, *56*, 263–271. https://doi.org/10.1111/j.1747-0765.2010.00448.x

Zhou, Y., Huang, L., Zhang, Y., Shi, K., Yu, J., & Nogués, S. (2007). Chill-induced decrease in capacity of RuBP carboxylation and associated H_2O_2 accumulation in cucumber leaves are alleviated by grafting onto figleaf gourd. *Annals of Botany*, *100*(4), 839–848. https://doi.org/10.1093/aob/mcm181

Zhou, Y., J. Xu, J. Li, Y. Guo, L. Yang, and Y. Wang, 2020. "Enhancing heat tolerance in grafted cucumbers through HSF-A2 expression."

Zhu, L., S. Wang, T. Zhang, Q. Zhao, and B. Li. 2021. "Investigating the role of graft-induced HSP60 expression in chilling tolerance of cucumber." *Journal of Integrative Agriculture 20*, no. 3: 821–831. https://doi.org/10.1016/S2095-3119(20)63384-1.

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