Journal of Crop Health (2025)77:120
https://doi.org/10.1007/s10343-025-01181-1

REVIEW

Mitigating the Effect of Salt Stress Through Grafting Technology in Vegetables: a Review

Firdes Ulas[1] · Hawkar Hama Hadi Hama Ameen[2] · Abdullah Ulas[3] · Yusuf Cem Yücel[2]

Received: 21 February 2025 / Accepted: 2 June 2025
© The author(s), exclusively licensed to Springer-Verlag GmbH Germany, a part of Springer Nature 2025

Abstract

Water and soil salinity are among the most significant ecological factors limiting agricultural productivity, especially in saline-affected regions. In vegetable crops, salt stress adversely affects physiological practices like water uptake, photosynthesis, and nutrient absorption, leading to stunted growth, wilting, and reduced yields. Numerous approaches have been developed to improve the salinity tolerance of vegetable plants, especially in arid and semi-arid regions. Among these approaches, vegetable grafting, a horticultural practice, offers a suggesting alternative solution to overcome salt stress' harmful outcomes. Grafting technology, a horticultural practice where the tissues of two different plant parts (rootstock and scion) are joined to grow as one, has emerged as a promising solution to enhance salt tolerance in vegetable crops. By utilizing salt-tolerant rootstocks, grafting improves root system development, enhances nutrient uptake, and activates protective biochemical responses, including increased antioxidant activity. Vegetable grafting has been utilized commercially on numerous crops such as melons, watermelons, muskmelon, cucumbers, tomatoes, sweet peppers, eggplants, to improve tolerances to type of biotic and abiotic conditions, like salinity, alkalinity, waterlogging, high or low temperatures, drought, and heavy metal toxicity, as well as to enhance crop yield and quality. This review aims to present the adverse effects of salt stress at plants, the potential of grafting technology in mitigating salt stress in vegetable crops, and examining the physiological, biochemical, and morphological benefits of grafting by using salt resistant rootstocks under saline conditions. Furthermore, the paper highlights successful case studies and research findings that demonstrate the effectiveness of grafting in improving salt tolerance in various vegetable species using different rootstocks on improving plant growth, photosynthetic capacity, crop yield and quality. The integration of biotechnological and genetic engineering approaches with grafting also holds potential to further enhance its efficacy. The future of grafting technology in sustainable agriculture is promising, offering a viable solution to maintain crop productivity and resilience in the face of increasing salinity challenges worldwide. We conclude that vegetable grafting has great potential for maintaining and improving productivity in salt-stressed agricultural systems.

Keywords Stress tolerance · Salt-tolerant crops · Saline agriculture · Abiotic stress · Rootstock · Scion

Introduction

Vegetable crops contribute about 12% of the world annually horticultural produce (9 billion tons), containing Cucurbitaceae and Solanaceae family crops such as watermelon (117 million tons), cucumber (80 million tons), eggplant (54 million tons), and tomato (42 million tons) (FAOSTAT 2023). Reviewing their nutritional value, their consumption has considerably improved over the past few decades demanding progressed production practices (Dias 2012). Due to climate change, the global mean temperature has increased drastically. As climate change progresses, plants are increasingly exposed to various abiotic and biotic stress factors (Coskun 2025). Abiotic stresses, such as drought,

✉ Firdes Ulas
fulas@erciyes.edu.tr

[1] Department of Horticulture, Faculty of Agriculture, Erciyes University, Kayseri, Türkiye

[2] Department of Soil Science and Plant Nutrition, Graduate School of Natural and Applied Sciences, Erciyes University, Kayseri, Türkiye

[3] Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri, Türkiye

Published online: 07 July 2025

extreme temperatures, and salinity, directly impact plant growth and productivity by disrupting physiological and biochemical processes (Aydın and Coskun 2013). According to the FAO, the global area of salt-affected soils includes 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) (based on 73% of the land mapped so far) (FAO 2021). Other findings demonstrate that 1 billion hectares of land are adversely influenced by salinity, including more than 20% of all the irrigated arable land (Ghassemi et al. 1995; Qadir et al. 2014). It is predicted that by 2050 the high salinity of arable land will make half of it unusable for agriculture (Roychoudhury et al. 2013). Agriculture is highly contingent on land and water conditions progressively altered by climate change. Salinization is likely to have a negative influence on the economy, living conditions and ecosystem functions of affected regions (Ruto et al. 2018). Growing salinization increases specific matters for the global food supply system. However, appropriately managed salt-affected soils allow for considerably more agricultural production (de Vos et al. 2016). Salt stress is a considerable environmental challenge that adversely impacts agricultural productivity, especially in regions with high soil or water salinity. When plants are exposed to excess salt, their ability to absorb water is compromised, leading to dehydration, nutrient imbalances, and disrupted physiological processes such as photosynthesis and respiration (Ulas et al. 2024). Over time, prolonged exposure to salt stress can result in stunted plant growth, development, reduced yields, and in some cases, plant death (Zhu 2001). Crops demonstrated to salinity negative influences via two key factors: (1) osmotic stress because of raised solute levels in rhizosphere, mainly Na^+ and Cl^-, that delay uptake of water and stomatal conductance, leading to reduced transpiration rates and (2) enhancing toxicity of ion from surplus ionic strength, principally Na^+ and Cl^-, that disturbs physiological purposes and cellular homeostasis, certainly disturbing productivity of crops (Morton et al. 2019; Dasgan et al. 2002). This key factor is principally problematic in arid and semi-arid zones, where water scarcity is coupled with high levels of salinity in both soil and irrigation water (Flowers and Yeo 1995). As global populations increase and agricultural land becomes more scarce, addressing the impacts of salt stress on crops has become crucial for ensuring food security (FAOSTAT 2018).

To decline the negative influence of salt stress on horticultural production and to simplify the expansion and application of saline soil, numerous policies have been suggested such as reclamation of saline soil and alteration of soil salinity; yet these are temporary and expensive (Al Rubaye et al. 2021). Breeding-resistant crop cultivars have been studied

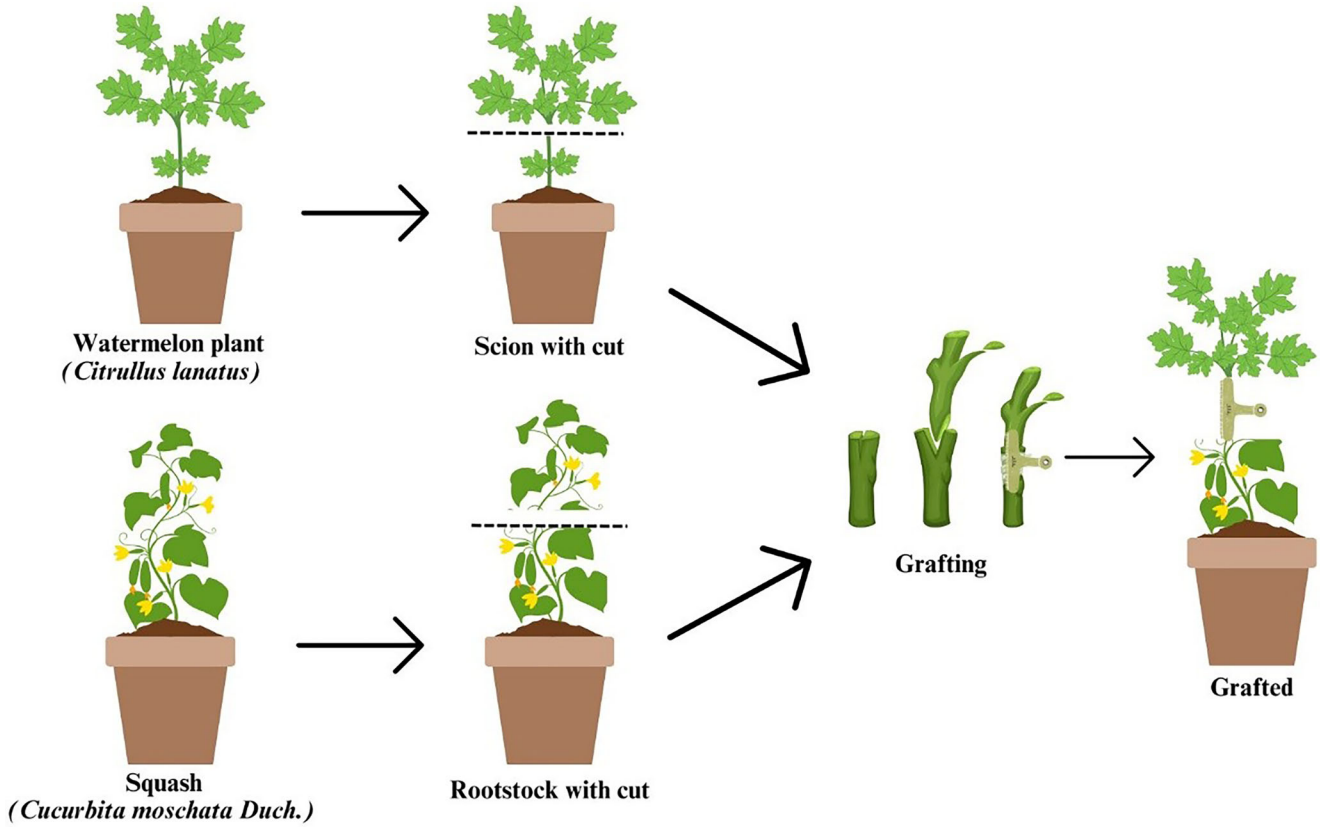


Fig. 1 Grafting of watermelon on squash plant (Ulas et al. 2025)

as a means for developing salt-tolerance crops. However, it is difficult, time-consuming and complex because of the polygenic characteristics of salt resistance (Yan and Tong 2018). Grafting technology has been developed as a proving solution to alleviate the influences of salinity in vegetable crop plants. Grafting involves joining the tissue of a salt-sensitive plant (scion) with a salt-tolerant rootstock to grow as a single plant for vegetative propagation. In this method, rootstocks or stock (lower plant part) used in the grafting process are commonly nearby relatives or wilds (typically in genera) of scion material, and have tolerance for biotic (pathogens), abiotic stresses (salt, drought, low and high temperatures, heavy metal, flooding, high and low nitrogen etc.) and plant vigor, while the scion (upper plant part) has certain curious qualitative and quantitative horticultural traits (Fig. 1). In the past, grafting at the vegetable plants has been practiced in Cucurbitaceae (watermelon, melon, and cucumber) and Solanaceae (tomato, eggplant, and pepper) families in the early 20th century (Ulas et al. 2025). In late 1920, the first grafting of vegetables was performed on watermelon with gourd rootstocks to control soilborne diseases such as Fusarium wilt (Fusarium spp.) (Sibomana et al. 2013). Nowadays vegetable grafting has also been widely considered to mitigate adverse influences of several abiotic stresses such as salinity, heavy metals; thermal stress, nutrient absorption and translocation; water deficit or drought, alkalinity, and as well as enhanced yield and fruit quality as examined for different vegetable crops such as watermelon, melon, cucumber, pepper, eggplant, pepino and tomato (Han et al. 2018; Kumar et al. 2019; Ulas et al. 2019a, b, c, 2020a, b, 2021a, b, c; Xie et al. 2020; Ulas 2021a, b, 2022; Al Rubaye et al. 2021; Naik et al. 2021; Adam and Ulas 2023).

The rootstock's resistance to salinity helps to enhance the overall salt tolerance of the plant, allowing the scion to maintain healthy growth and productivity even under stress-

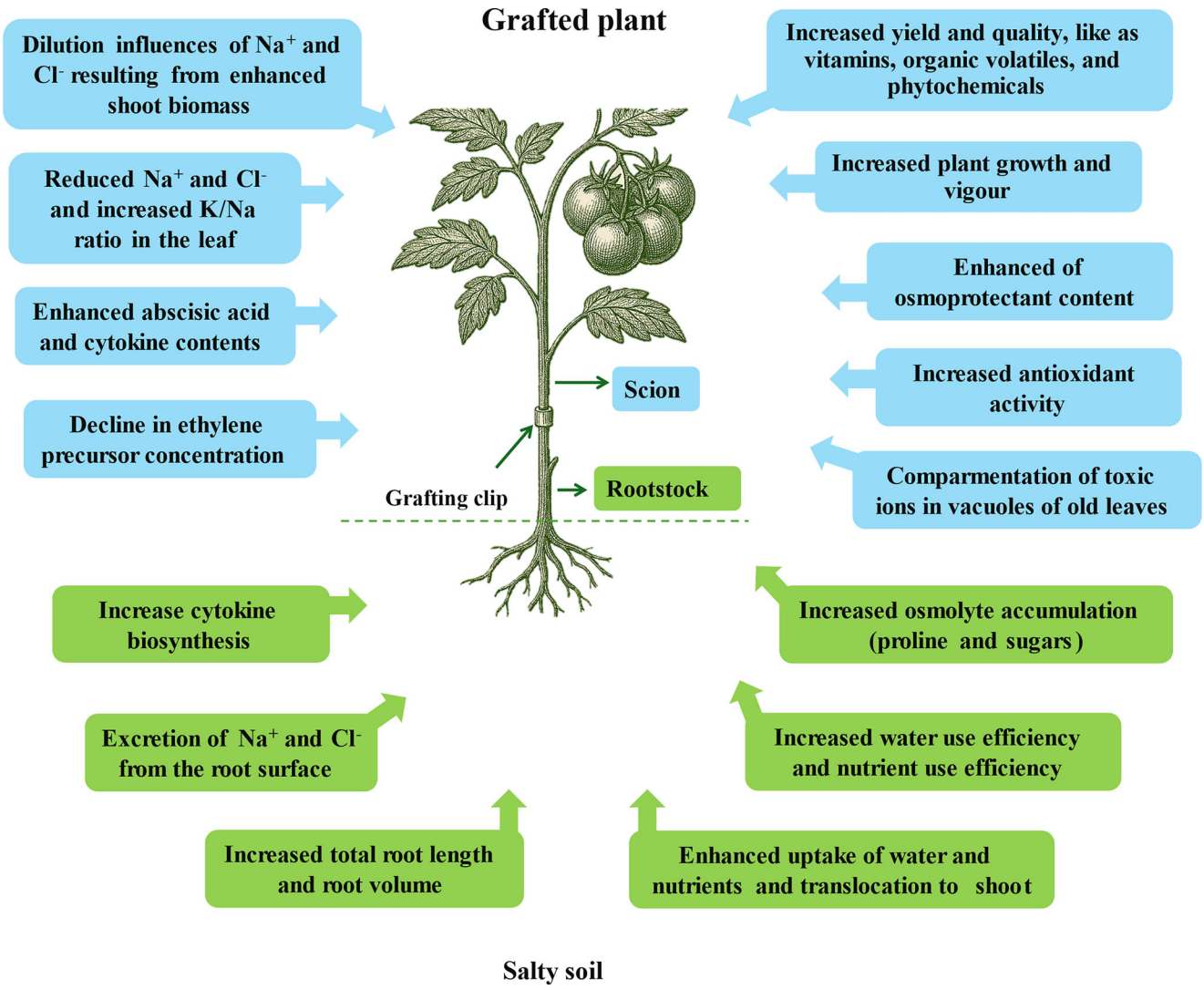


Fig. 2 Physiological adaptive attributes to alleviate the influence of salt stress in grafted plants (Yücel Y. C.)

ful conditions (Lee 1994). This technique has been used successfully to improve the resilience of various crops, including tomatoes, cucumbers, and melons, to environmental problems like drought and salinity (Coskun 2023a; Ulas et al. 2024). By vigorous root system of the rootstocks, grafting technology can play an important role in improving crop tolerance to salt stress and increasing agricultural sustainability. Physiological adaptive attributes to alleviate the influence of salt stress in grafted plants are shown in Fig. 2.

Many studies have reported that the use of salt-resistant rootstocks in grafting improves plant to salinity tolerance (Ulas et al. 2020a, b, 2024; Al Rubaye et al. 2021; Aydın and Yetisir 2022; Aydın 2024; Tola et al. 2024; Alqardaeai et al. 2024; Cela et al. 2024). For example, Sanwal et al. (2022) demonstrated in tomato (cv. Kashi Aman) fruit yield was increased grafted with eggplant rootstocks IC-354557 and IC 111,056 than ungrafted control tomato plants at salinity (EC 6 and 9 dS m^{-1}). Salinity tolerance via grafting was because of preservation of competent water status as verified by increased relative water content (RWC) and leaf chlorophyll index (SPAD) by per greater proline and antioxidant enzyme activities (SOD, CAT and APX). Tolerant rootstocks facilitated the partitioning of toxic saline ions in scions by stimulating greater Na+ accumulation (24%) in the lower part of the plant's leaves than the upper part of the plant's leaves (14%) of grafted ones. Al-Harbi et al. (2017) stated that salinity decreased vegetative growth (i.e., diameter of the stem, stem length, and fresh biomass) and yield of grafted and non-grafted tomatoes. Though, there were no substantial decreased observed in yield in grafted ones across Unifort rootstock at moderate salinity level (3.76 dS m^{-1}). At cucumber, greater expression of CAT, SOD was stated via grafting at salinity (Aydın and Yetisir 2022). In plants salinity results in an enhance in proline at cucumber plants (Aydın and Yetisir 2022); aspartate at tomato plants (Akladious and Abbas 2013); glutamate at broad bean plants (Sadak et al. 2015); lysine at maize plants (Wang et al. 2013) and methionine at maize plants (Neto et al. 2009). Tola et al. (2024) studied the effect of grafting on hydroponically grown tomato plants at salinity (2.5, 6.0, and 9.5 dS m^{-1}). The outcomes showed that tomatoes can be effectively produce as hydroponically at salinity till 6.0 dS m^{-1} without surrendering yield and quality. Madugundu et al. (2023) stated that utilizing a sufficient nutrient recipe could alleviate the adverse influences of salt stress at grafted tomato plants under hydroponic conditions. In tomato, grafting salt-sensitive, high-yielding genotypes with salt-tolerant or resistant rootstocks is sustainable technique of opposing salinity (Singh et al., 2020). Cela et al. (2024) observed that salinity can improve nutritional quality and taste of Pisanello tomato. In this context, grafting at the vegetable crops study to increase plant resistance to salt stress significantly influences a better interpretation of the physiological and biochemical interactions between the shoot and root. The purpose of the review is to explain updated information of influences against salinity and to explore how grafting technology can alleviate salt stress in vegetable crops, focusing on the potential benefits and applications of this technique in enhancing salt tolerance in horticultural applications. This review will examine the physiological, biochemical, and morphological responses of grafted plants under saline conditions, along with the challenges and opportunities for incorporating grafting into modern agricultural practices. Through this investigation, the paper aims to highlight the potential of grafting as a viable solution to combat salt stress and promote sustainable vegetable production.

Salt Stress

Impact of Salt Stress On Plants

Worldwide, more than 50% of irrigated agricultural soils face salinization problems, which lead to a decline in plant growth, development, and survival (Guo et al. 2022). Therefore, salinization in agricultural soils threatens worldwide food safety, and this concern is combined with our changing climate (Mukhopadhyay et al. 2021). Salinity is one of the most critical challenges in horticulture. The impact of salinity varies depending on crop species, stress levels, and environmental conditions (Muhammad et al. 2024). Under salinity, plants can generate a variation of physiological and metabolic alterations in stressed crops at all growing periods, initiated from germination, photosynthesis, and other biosynthetic processes (Zhao et al. 2020; Hasanuzzaman et al. 2021; Pandey et al. 2023). Salinity negatively affects a type of physiological process in crops, primarily by disrupting water and nutrient uptake by roots, nonetheless disturbs the development of plants, comprising germination, vegetative growth, and reproductive structures/tissues (Muhammad et al. 2024). Also, it adversely influences morpho-physiological, anatomical, biochemical, and molecular functions in plants. Nasri et al. (2016) stated that in Arabidopsis, there is a decline in phosphatase activity, preventing seed germination. When soil or irrigation water salinity increases, plants cannot absorb adequate water due to reduced water potential, leading to dehydration and impaired physiological functions (Munns and Tester 2008). One of the initial responses to salinity is stomata closure to inhibit extreme water loss through transpiration. However, this limits the uptake of carbon dioxide (CO_2), reducing photosynthesis rates (Zhu 2001). Extreme salt level leads to a decline in photosystem II (PSII) action by splitting PSII response area and

restricting quinone acceptors activity. Salt stress hinders transpiration and decreases stomatal conductance; therefore, affecting less gaseous exchange and negatively affecting photosynthetic electron transport chain (Çiçek et al. 2018). The action of ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) and photosynthetic attributes (PSII maximum photochemical efficiency; Fv/Fm) are decreased under salinity (Yan and Tong 2018). Consequently, a reduction in photosynthesis leads to lower sugar production, impairing growth and energy reserves for the plant. Zhang et al. (2016) stated that under salt stress conditions, photosynthesis is necessary physiological procedure, that describes tomato growth. Satti and Lopez (1994) emphasized importance of leaf photosynthesis diomensions for observing crops at salinity, and there is indication that salinity effects basic photosynthetic enzyme activities as well as chlorophyll and carotenoid contents (Yang et al. 2021).

Salt stress also causes osmotic stress and ionic imbalance in plant cells, as high salinity increases the external osmotic potential, making it harder for the plant to maintain internal turgor pressure (Marschner 2012). This results in wilting, reduced leaf expansion, and overall stunted growth (Shannon and Grieve 1999). Sodium ions (Na^+) are commonly known to be the main toxic ions at high levels. Three stress signaling pathways are involved under salt stress: osmotic stress, ionic stress, and secondary stress (Sewelam et al. 2014; Yang and Guo 2018a). High salt concentrations enhance the osmotic pressure and decrease the water potential of soil solutions, leading to water deficiency in plants (Hasegawa et al. 2000). Na^+ in plant cells influences the absorption of additional ions required for normal physiological activities (Yang and Guo 2018b). Osmotic stress and ionic stress initiate long-term secondary stresses, including oxidative stress. Salt-induced oxidative stress leads to the accumulation of reactive oxygen species (ROS) in plant cells, including singlet oxygen ($^1O_2$), superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (HO). Additional ROS initiate oxidative damage to DNA, proteins, and lipids, affecting the integrity of plant cell organelles. In maize, extended salinity decreases leaf relative water content, leaf water potential and rises MDA and H_2O_2 content (Kaya et al. 2018). Growth injury and nutrient mobilization by salinity buildup cause plants more susceptible to soil-borne diseases (Egamberdieva 2011). Prolonged salt exposure may lead to irreversible cellular damage, ultimately causing plant death in severe cases (Flowers and Yeo 1995). Furthermore, salt-induced oxidative stress, depicted by reactive oxygen species (ROS) accumulation, causes cellular destruction to membranes, proteins, and DNA, compounding overall stress impact (Gill and Tuteja 2010). It can improve soluble sugar, starch, and abscisic acid (ABA) contents and reduce gibberellin (GA) level, initiating decrease in germination rate. Furthermore, salt stress might initiate harmful effects on yield. Numerous findings stated that salt stress could decline stem biomass and length, root length, total leaf area, yield, and quality (El-Tarabily et al. 2019; Zorb et al. 2019). Up to now it was observed by many researchers that one of the standard fruit quality parameters of tomato juice sugars increases as an increasing salinity level (Moles et al. 2019; Egea et al. 2023; Botella et al. 2021; Krauss et al. 2006; Rosca et al. 2023). Costan et al. (2020) and De Pascale et al. (2012) determined that the total soluble sugars (TSSs) and citric acid (CA) concentrations enhanced in tomato fruits under salt stress. Azarmi et al. (2010) stated that salinity higher than 3.0 dS m^{-1} increased titratable acidity (TA) and TSSs in hydroponically grown tomatoes at salt stress (2.5, 3.0, 4.0, 5.0, and 6.0 dS m^{-1}). According to Rouphael et al. (2018) salt stress increased CA and TSS levels, indicating that salinity increases fruit taste and flavour in tomato. Previous studies have been informed of a positive correlation between high salt level and little fruit production in tomato (Moles et al. 2019).

Under high salinity, ion concentrations in cell wall are altered, that are identified by restricted sensors or receptors like kinases (RLKs) and glycosyl inositol phosphoryl ceramide (GIPC). These sensors may stimulate signaling pathways like salt overly sensitive (SOS) pathway to re-distribute ions and achieve homeostasis. The Salt Overly Sensitive (SOS) pathway is an important regulatory mechanism for Na^+ exclusion from the cytosol and for alleviating long-distance transport of toxic Na^+ from the root to the shoot tissues (Shi et al. 2002; Olias et al. 2009; EI Mahi et al. 2019). The SOS pathway is composed of three parts: SOS3 (a calcineurin B-like (CBL) family Ca^{2+}-binding protein), SOS2 (a CBL-interacting protein kinase (CIPK) family kinase), and SOS1 (a plasma membrane-localized NHX family Na^+/H^+ antipoter). The activation of the SOS pathway under salt conditions contains various phases. In essence, the salt stress triggers an enhance in the cytoplasmic Ca^{2+} concentration (Kudla et al. 2018; Jiang et al. 2019; Steinhorst and Kudla 2019; Chen et al. 2021); the change of the Ca^{2+} concentration is sensed by SOS3, and then SOS3 binds and activates SOS2 (Halfter et al. 2000; Guo et al. 2004; Sánchez-Barrena et al. 2007); the activated SOS2 phosphorylates and activates the Na^+/H^+ antipoter SOS1 (Quintero et al. 2011); the activated SOS1 pumps the excess Na^+ out of the cell, therefore reducing cytosolic Na^+ concentration (Qiu et al. 2002; Yang and Guo 2018a). The SOS pathway promotes salt tolerance by mediating Na^+ regulation at various levels. For instance, it acts at the soil-cell interface to pump Na^+ back into the soil (Shi et al. 2002; Yang and Guo 2018a); it promotes salt tolerance in shoot tissues probably by reducing cytosolic Na^+ concentrations (Lin et al. 2009; Yang and Guo 2018a); it also associates with the regulation of root-to-shoot delivery of Na^+ (Shi et al. 2002). To minimize accumulation of Na^+ in shoots during salt stress, the

control of net Na^+ loading into the xylem is as important as Na^+/H^+ exchanger-mediated Na^+ exclusion from roots and sequestration in root vacuoles (Ismail and Horie 2017). Osmotic potential systems from fluctuations in balance among ion concentrations inside and outside of cell, procedure that is observed by precise sensors like nicotinamide adenine dinucleotide phosphate (NSCCs), via high-osmolarity glycerol (HOG) pathway to adjust organic osmolytes (e.g., betaine and proline) synthesis. Osmotic homeostasis is accomplished through ion uptake. Crops create and gather ROS via plasma membrane-bound nicotinamide adenine dinucleotide phosphate (NADPH) oxidase at salinity, that accomplishes ROS homeostasis through secondary metabolites (Wang et al. 2022). Extreme salt stress can increase osmotic stress initiated by salt, potentially concerning ion uptake in tomato (Meza et al. 2020; Zushi and Higashijima 2022; Rodríguez-Ortega et al. 2019).

Depending on salt tolerance, plants are categorized into glycophytes (salt-sensitive plants) and halophytes (salt-tolerant plants). Halophytes have progressed to thrive in saline conditions, and identifying salt tolerance systems may recommend important perceptions for horticulture (Flowers Colmer 2015). Various physiological, biochemical, and anatomical adjustments enable halophytes to deal with salinity. These variations might contain adjustments in root construction, leaf anatomy, and vascular systems, that simplify uptake of salt, transport, and storage while lessening injury to vital tissues (Grigore and Toma 2017), additionally to precise ion uptake and exclusion mechanisms, osmotic adjustment, water uptake and retention, and tissue tolerance to salt accumulation (Flowers and Colmer 2015). The process of salt resistance in halophytes is commonly categorized into two major classifications, i.e., salt avoidance and salt tolerance (Sabovljevic and Sabovljevic 2007). The policy behind salt tolerance may involve specific physiological and/or biochemical adaptations in the plants that enable the plant to maintain the viability of protoplasm during the accumulation of salt ions inside the cells. Salt tolerance in halophytes can be accomplished either by salt exclusion or salt inclusion, and salt-tolerant plants utilize the energy for the exclusion of additional salt to defend themselves from the toxic effects of excess salt (Ashraf et al. 2006). Salt avoidance may involve some structural and physiological adaptations so as to exclude salt through the root membrane or minimize the salt concentrations in the cell. This may involve passive exclusion of ions through the permeable membrane or the active expulsion of ions through ion channels. Furthermore, physiological adaptation, halophytes also adjust some anatomical modifications to cope with high external soil salinity (Ola et al. 2012). These modifications include an improvement in the epidermal thickness and spongy tissue of the leaves and a decline in the conducting tissue component of the stem and root, like xylem vessel (Hussein et al. 2012). Halophytes possess more salt-tolerant genes than glycophytes (Askari et al. 2006; Yu et al. 2011), which are mostly involved in membrane transport, redox reactions, signal transduction, and other processes (Zhang et al. 2008). Additionally, *Mesembryanthemum crystallinum* and *Chenopodium quinoa*, which are salt-tolerant genotypes, have the presence of salt-excreting glands in mangroves or specified compositions such as bladder cells. These forms facilitate salt-tolerant genotypes to vigorously eliminate additional salt from their tissues, continuing beneficial ion balance and cellular function in salinity (Yuan et al. 2016). By exposing these adaptation mechanisms, investigators might reveal approaches for increasing salt tolerance, thus developing horticultural resilience in saline soils.

Susceptibility of Vegetable Crops to Salt Stress

Salinity is one of the highest critical issues in horticulture. This issue mostly varies crop species and level of stress, as well as environmental situations (Muhammad et al. 2024). Different vegetable species exhibit varying degrees of susceptibility to salt stress. Factors such as plant species, cultivar, and the rootstock used significantly influence a plant's tolerance to high salinity (Ulas et al. 2019b, 2020a, 2024). For instance, vegetable species like tomatoes, cucumbers, and lettuce are particularly sensitive to salt stress, showing a sharp decline in growth and yield when exposed to high salinity levels (Parida and Das 2005). On the other hand, crops like spinach, mustard, and radishes are relatively more tolerant to salinity, exhibiting better physiological adaptation mechanisms like osmotic regulation and ion exclusion (Flowers and Yeo 1995). Most vegetable cultivars with minimal salt tolerance are negatively influenced by soil salinity. Even though there are minimal rates of salinity, most vegetable genotypes suffer considerable yield failures at salinity (Munns 2011). The difference in salinity tolerance between species can be attributed to several factors, including the plant's ability to maintain osmotic balance, activate stress-responsive genes, and enhance antioxidant defense mechanisms (Zhu 2001). Moreover, the type of root system and the ability to exclude or compartmentalize sodium ions also play crucial roles in determining a plant's resistance to salt stress (Munns and Tester 2008). Understanding these mechanisms is vital for selecting or breeding salt-tolerant vegetable crops that can thrive in saline conditions, ensuring better productivity and food security in areas with saline soil or brackish water. Destructive effects of salinity on cucumber lead to reduced plant growth and productivity (Haghighi and Pessarakli 2013; Sarwar et al. 2017; Gurmani et al. 2018). Yildirim et al. (2008) observed that enhancing salt stress level reduced the SPAD reading values in cucumber leaves. The decline of chlorophyll contents under

NaCl stress may be because of the closure of stomata, inhibition of chlorophyll synthesis, improved degradation of chlorophyll by the elevated chlorophyllase enzyme activity, or damage to the photosynthetic apparatus (Sevengor et al. 2011; Rahdari et al. 2012). Assimakopoulou et al. (2015) studied the responses of tomato cultivars and hybrids (Santorini Authentic, Santorini Kaisia, Chios, Cherelino F1, Scintilla F1, Delicassi F1, and Zucchero F1) at three NaCl levels (0, 75 and 150 mM). They exposed that Chios cultivar was the most influenced at 150 mM and a high decline in its total plant dry biomass occurred by 65.37% in compared to other varieties/hybrids, growth inhibition was due to the toxicity of Cl and Na^+ ions and to the nutritional imbalance induced by salinity. Batista et al. (2021) studied the production of cherry tomato plants in hydroponic conditions and observed reductions with increments in nutrient solution salinity above 2.5 dS m^{-1}. Samarah et al. (2021) assessed the effect of different salinity levels (0, 5, 10, and 15 dS m^{-1}) on tomato seedling growth. They showed that the seedlings grown at 15 dS m^{-1} had the lower length and dry weights compared to other saline levels (0, 5, 10 dS m^{-1}). Herison et al. (2024) studied the effects of different salt levels (0, 3750, and 7500 ppm NaCl) on hot pepper genotypes (PBC396, Bogota, Ferosa, Kopay and Keriting Hitam) and they observed that the 'Keriting Hitam' genotype showed a tolerant response to salinity stress at 3750 ppm, while the 'PBC 396' genotype was relatively tolerant to salinity at 7500 ppm. NaCl level of 7500 ppm can prevent the plant growth and yield of hot pepper up to 80%.

Grafting Technology

Grafting is a prehistoric practice where two plant fragments, scion (the upper part that produces fruit bearing vegetable) and rootstock (the lower part that provides support and nutrients), are linked together to grow as definite plant material. The purpose of grafting vegetables is to combine the desirable traits of both plant parts into one plant. Grafting is an especially valuable technique in vegetable production as it allows for the enhancement of rootstock properties like disease resistance, drought tolerance, and salt tolerance, while maintaining the fruit quality of the scion (Coskun 2023b). Common vegetable crops that are grafted include tomatoes, cucumbers, peppers, eggplant, and watermelons, particularly in regions where soil-borne diseases or environmental stresses such as salinity, drought, or extreme temperatures threaten horticultural crop productivity (Ulas et al. 2025).

Grafting Methods

Several grafting methods have been used depending on the type of plant and the desired outcome, including hole insertion grafting, tongue approach grafting, splice grafting, tube grafting, one cotyledon splice grafting, cleft grafting, and pin grafting. Hole insertion hypocotyl grafting is ideal for cucurbits. During the grafting process, gourd (scion) seeds are seeded 5–7 days before watermelon (scion) seeds. The scion and rootstock seedlings should be uniform and have nearly similar stem diameters. The true leaf containing the growing part must be gently and completely eliminated, and a hole must be achieved with a bore at a slant angle to a longitudinal way. The scion hypocotyl part is trained by slant cutting to have a pointed end for simple attachment (Lee et al. 2010) (Fig. 3a, b). The tongue approach grafting method can be used for cucurbits and solanaceous plants. Scion seeds (commonly watermelons, cucumbers, and melons) are seeded 5–7 days before than rootstock seeds. The grafting process is done at the hypocotyl portion of rootstock and scion of cucurbitaceous crops and at the lower epicotyl portion in solanaceous plants. Rootstock is cut in a down way, and scion is cut an up way at an angle of 30–40 to the perpendicular axis, and deep sufficient to permit fusion of as many vascular bundles. Afterward, grafting clips are placed to fix the scion and rootstock. The scion lower hypocotyl of numerous trial seedlings is cut to assess the degree of graft-take 10–12 days after the grafting process. Root and lower hypocotyl of scion are eliminated from the grafted plant by simply cutting off at the desired position, preferably at the closer position to grafted position held grafting clip (Lee et al. 2010) (Fig. 3c). Splice grafting is particularly popular for cucurbits and solanaceous crops and is also called as one cotyledon splice grafting. It is commonly chosen by commercial grafted seedling producers (Fig. 3d, e, j). Main benefit is robust and vigorous grafted seedlings cultivation while all scion vascular bundles are fused with those of rootstock and graft formation is effective sufficient to take all rough post-graft handling. For Cucurbita rootstocks, one cotyledon and growing point are cut. Once putting scion on to rootstock (Fig. 3d, e), clips are done to install grafted position strictly together. For solanaceous crops, grafting is generally used at lower epicotyl and fixed by using clips (Fig. 3j). Tube grafting is accomplished by maintaining grafted situation together in a split flexible tube (Lee et al. 2010). Cleft grafting is applied to solanaceous crops. This method involves pruning scion plants to retain 1–3 true leaves. Firstly, stem is cut longwise, rootstock is executed, and longitudinal cut is done in down way, 1–1.5 cm long and 3/4 depth of stem diameter. The lower stem is cut to slant angle to create a tapered wedge. After putting scion into split made on rootstock, a clip is put to hold in place till grafting formation (Fig. 3f, g). At the Pin

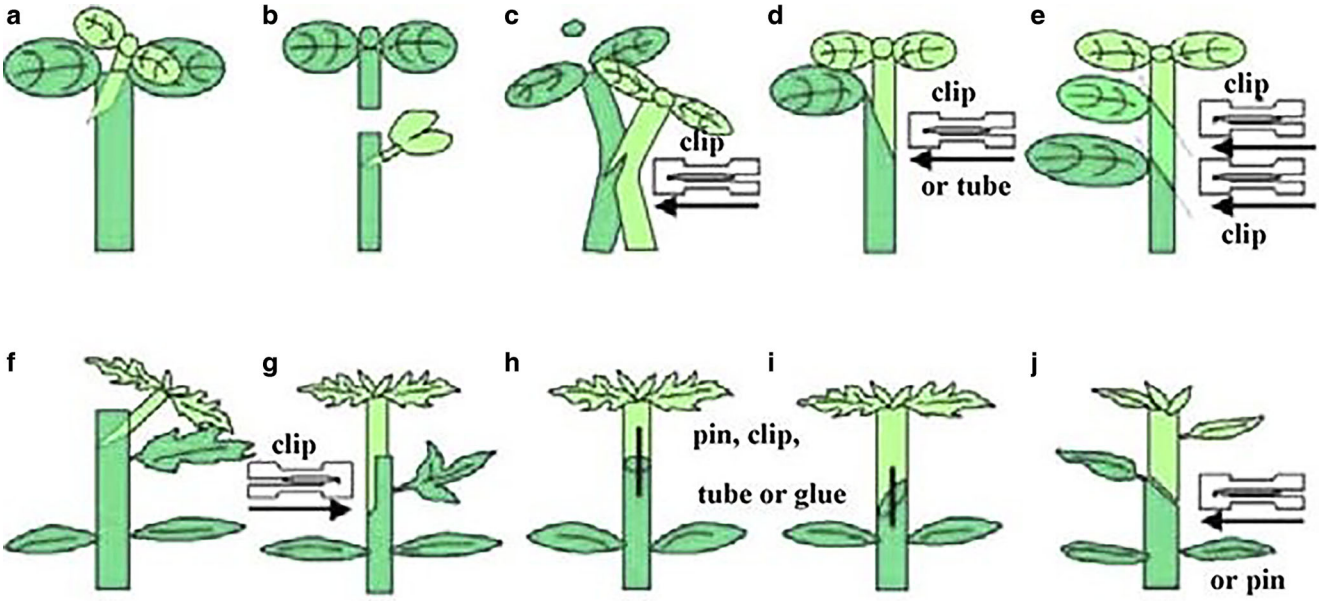


Fig. 3 Grafting techniques in cucurbits and solanaceous vegetables: Hole insertion grafting (**a**, **b**); tongue approach grafting (**c**); splice grafting (**d**, **e**, **j**); cleft grafting (**f**, **g**); pin grafting (**h**, **i**) (Lee et al. 2010)

grafting method, individually designed pins are employed to hold the grafted point (Fig. 3h, i). Ceramic pin developed by Takii Seed Co., in Japan is almost 15 mm long and 0.5 mm in diagonal width of hexagonal cross-section. Scientific outcomes observed that bamboo pins, rectangular in cross-sectional shape, might effectively substitute expensive ceramic pins with minimal cost (Lee et al. 2010).

Role of Grafting in Enhancing Salt Stress Tolerance

Grafting has proven to be an effective technique for improving salt tolerance in vegetable crops, as it combines the beneficial traits of both the scion and rootstock. The rootstock, which is selected for its ability to tolerate high salinity, helps protect the scion from the negative effects of salt stress. This is particularly important in vegetable crops, where high salinity can lead to stunted growth, declined yields, and plant death (Rouphael et al. 2018).

Rootstocks used in grafting can improve salt tolerance in several ways. They may limit the uptake of sodium ions, enhance the plant's ability to compartmentalize salt in vacuoles, or improve water and nutrient uptake efficiency under saline conditions. For example, the use of salt-tolerant rootstocks for tomatoes and cucumbers has been shown to increase fruit yield and improve growth when subjected to saline conditions (Zhao et al. 2016a). Additionally, grafting can activate stress-responsive pathways in the plant, enhancing antioxidant enzyme activity and reducing oxidative damage caused by salt stress. Grafting can develop several procedures to survive at salinity. These are; (1) eliminating salt in rhizosphere (selective ion uptake), (2) maintenance of salt in roots and incapability to transfer it to upper part of plant, (3) keeping the potassium and calcium stability, (4) keeping osmotic pressure, (5) antioxidant defense systems activation (6) counteracting stress situations thru hormonal regulation (Colla et al. 2010; Ulas et al. 2020a; Aydın and Yetisir 2022). Grafting has shown promising results in vegetable crops such as tomatoes, cucumbers, and melons, making it a viable technique for sustainable agriculture in regions where salinity poses a significant challenge. By selecting the right combination of scion and rootstock, it is possible to produce crops that are not only more resistant to salt but also capable of thriving in saline environments. Some vegetable species that have shown improved salt tolerance through grafting include tomatoes, cucumbers, melons, and eggplants. For example, in tomatoes, the rootstock 'Maxifort' has been shown to enhance salt tolerance significantly, leading to better growth and yield under saline conditions (Miao et al. 2024). Similarly, cucumbers grafted onto the salt-tolerant rootstock 'Becada' exhibited improved resistance to salt stress, showing enhanced root development and better nutrient uptake (Chen et al. 2020). Öztekin et al. (2006) stated that grafting might enhance water use efficiency and tolerance to salt stress in tomato plants. Grafted plants afford tolerance to salt stress by enhancing stomatal conductance, chlorophyll index and membrane selectivity (Colla et al. 2012). In cucumber, rootstock genotype of PS 1313 has exhibited inherent capacity at salinity by supporting greater stomatal conductance, chlorophyll index and membrane selectivity. Elsheery et al. (2020) studied four rootstocks (bottle gourd, pumpkin, winter squash, and Nubian watermelon) to examine biochem-

ical, and physiological mechanisms of salinity stress tolerance using grafting and compared them with self-grafted cucumber under three different salt levels (0, 50, 100 mM). Grafted plants had better growth and yield parameters than non-grafted plants, in addition to improve photosynthetic activity and membrane stability. Grafting increased plant hormones such as auxin, gibberellin, cytokinin, and salicylic acid compared with non-grafted plants, while abscisic acid was decreased under salinity stress. Bayoumi et al. (2021) grafted cucumber hybrid Gianco F1 on to five various rootstocks (Ferro, Cobalt, VSS-61 F1, Bottle gourd, and Super Shintoza) and tested under combined heat and salinity to assess the growth, productivity, physiological, and mineral composition. Grafting rootstock genotypes of VSS-61 F1 and Ferro had maximum marketable yield, also they had maximum scion vigor, lower flower abortion rates and higher chlorophyll contents. A study examined by Zhu et al. (2008) stated that in grafted cucumber, high salinity tolerance is related to improved potassium level in leaves. *Cucumis sativus* L. grafted on to fig leaf gourd (*Cucurbita ficifolia* Bouche L.) enhanced yield and salinity tolerance (Huang et al. 2009). These examples highlight how grafting can improve the physiological resilience of vegetable crops to saline environments, making it a practical solution in regions affected by soil salinization.

Root Development and Nutrient Uptake

One of the most significant benefits of grafting for salt stress tolerance is the improvement in root development. Rootstocks used in grafting are often selected for their ability to develop deep, extensive, and efficient root systems, which are essential for accessing water and nutrients from deeper soil layers under saline conditions. By grafting a salt-sensitive scion onto a salt-tolerant rootstock, plants can benefit from improved water uptake and nutrient absorption, which are critical for maintaining growth in environments with high salinity.

Rootstocks with better salt tolerance can also help reduce accumulation of toxic ions like sodium (Na^+) in the plant tissues. In some cases, salt-tolerant rootstocks possess mechanisms that compartmentalize sodium ions in vacuoles, preventing them from interfering with metabolic processes in the scion (Rouphael et al. 2018). This leads to improved nutrient balance, as the plant is able to maintain higher levels of essential nutrients like potassium (K^+) and calcium (Ca_2^+) even under saline stress. Moreover, the enhanced root system in grafted plants allows for better nutrient uptake, which supports the overall growth and development of the scion. As a result, grafting not only improves the plant's ability to withstand saline conditions but also ensures that it can continue to thrive and produce high-quality yields despite the challenging environmental stress (Zhao et al. 2016b). In a study by Tola et al. (2024), tomato plants were grafted onto salt-tolerant rootstocks, such as *Solanum lycopersicum* cv. 'Maxifort', which significantly enhanced their tolerance to salinity. The grafted plants exhibited improved root development and increased osmotic regulation, resulting in enhanced photosynthesis and growth under salt stress conditions. This study demonstrated that grafting can be a viable solution for maintaining tomato production in areas with high soil salinity.

The impact of root architecture in alteration of salinity tolerance was studied in potato genotypes with salt sensitivity or tolerance (Shaterian et al. 2005). Another successful case is in watermelon (*Citrullus lanatus*), where grafting onto salt-tolerant rootstocks, such as *Cucurbita* spp., has shown promise in improving salt stress resistance. In a study conducted by Ulas et al. (2019b), grafted melon plants exhibited enhanced salt tolerance, with a notable increase in fruit yield and quality compared to non-grafted controls. The rootstocks not only improved water and nutrient uptake but also helped in minimizing the accumulation of toxic salts in the plant tissues. This success story highlights the potential of grafting to improve salt tolerance in cucurbit crops, which are often highly sensitive to salinity.

Similarly, research by El-Shraiy et al. (2011) focused on cucumber (*Cucumis sativus*) grafted onto salt tolerance rootstock (Shintosa Supreme pumpkin) to enhance salt tolerance. The findings demonstrated that grafted cucumbers had improved root development, which allowed the plants to access deeper water reserves and nutrients in saline soils. Furthermore, grafted plants exhibited higher concentrations of antioxidant enzymes, which helped protect the plants from oxidative stress induced by salt. This research supports the idea that grafting can provide a comprehensive solution for improving the tolerance of vegetable crops to environmental stressors, particularly salinity. Ulas (2021b) observed grafted pepino plants produced higher root biomass, total root length, root volume and root diameter under salinity.

Physiological and Biochemical Responses

Grafting can improve salt tolerance in plants by inducing various physiological and biochemical changes that enhance the plant's ability to cope with saline conditions. One key physiological adaptation is the increased osmotic regulation in grafted plants. The rootstock plays a crucial role in adjusting the osmotic potential of the plant, helping to prevent water loss and improve water retention in the scion (Rouphael et al. 2018). In response to salt stress, grafted plants often show an increased accumulation of osmotic regulators, such as proline, sugars, and soluble proteins, which stabilize cellular structures and function under water deficit conditions (Zhang et al. 2016). Additionally, graft-

ing can promote the production of antioxidants, like SOD, CAT, and peroxidases, which mitigate damaging effects of ROS produced during salt stress. These antioxidants play a critical role in protecting plant cells from oxidative damage and maintaining overall plant health during prolonged exposure to saline conditions (Zhao et al. 2016b).

Furthermore, grafting has been found to influence synthesis of compatible solutes, like glycerol and betaine, that help the plant adjust to the osmotic stress initiated by salt accumulation in soil. By enhancing the accumulation of these solutes, grafted plants are able to maintain their cellular integrity and prevent dehydration, which is crucial for survival in saline environments. In essence, grafting enhances the plant's biochemical pathways responsible for osmotic adjustment, antioxidant defense, and cellular protection, enabling it to better tolerate salt stress (Aydın 2024).

Recent research has highlighted the effectiveness of grafting technology in improving salt tolerance in various vegetable crops. One notable study by Al Rubaye et al. (2021) explored the impact of grafting on pepper inbred lines in saline conditions. The study showed that pepper grafted onto different rootstock genotypes exhibited superior growth and development, with improved chlorophyll content and increased shoot biomass. This research emphasized how grafting can mitigate adverse consequences of salinity by increasing plant's ability to absorb water and maintain physiological functions at stress conditions. Ulas et al. (2020a) stated that Cucurbita cultivars have superior rootstock capability for melon, and their considerable influences on salt tolerance were strongly correlated with stimulating physiological and biochemical reactions of scions.

The procedure of salt resistance at vegetable crops via grafting are diverse pepper with tolerant rootstock (e.g., *Capsicum chinense* Jacq., *Capsicum baccatum* L.) may accomplish more plant productivity due to restricting of Cl^- transfer to upper part of the plant by rootstock and decrease of Na^+ fill in roots and leaves. This allocates uptake of additional cations (i.e., K^+, Ca_2^+, Mg_2^+), for lesser osmotic potential at lower energy cost (Penella et al. 2016). Nevertheless, these influences cannot be widespread because of extreme specificity of scion/rootstock interactions (Giuffrida et al. 2013; Serrano et al. 2017). The fruit quality attributes in grafted pepper have been studied in a few research (Kyriacou et al. 2017; Chávez-Mendoza et al. 2013). These have stated a robust effect of rootstock on variations in morphometric attributes, and biochemical composition of fruit in pepper crops (Rouphael et al. 2010; Kyriacou et al. 2017), with many contradictory results (Colla et al. 2010; Leal-Fernández et al. 2013; Ropokis et al. 2019; Gisbert Domenech et al. 2010). In pepper, concentrations of soluble sugars and total acid in fruits mostly do not be influenced via grafting, though specific conflicting findings might be noticed in writings (López-Marín et al. 2013, 2017). In pepper, the polyphenols content of fruit was confirmed not to be altered via grafting as functional combinations (Chávez-Mendoza et al. 2013; Leal-Fernández et al. 2013; Sánchez-Torres et al. 2016). The ascorbic acid in pepper fruit is of substantial consequence, though there are conflicting information in researches presently accessible, in terms of alterations of ascorbic acid content in response to grafting (Chávez-Mendoza et al. 2013; Gisbert Domenech et al. 2010; López-Marín et al. 2017; Sánchez-Torres et al. 2016). It has been affirmed that greater genotype confidence of ascorbic acid content in scions damages additional restricted influences of rootstock in pepper (Kyriacou et al. 2017). Fullana-Pericas et al. (2018) have been assessed that rootstock may encourage a modification in hormone balance in scions, as it causes modifications in scion features, like plant hydraulics, and uptake of water and nutrients, that are affected by vascular linking disruptions. In addition, a study by Gupta and Huang (2014) studied the molecular mechanisms behind salt tolerance in grafted plants. The study found that grafting increased the expression of genes involved in ion homeostasis, osmotic regulation, and antioxidant defense, contributing to improved plant resilience under salt stress. This molecular insight provides a deeper understanding of how grafting can enhance salt tolerance at the genetic and biochemical levels, offering new avenues for future research and application in crop improvement.

Biotechnological Approaches in Grafting

Trans-grafting process matches standard grafting technique with genetic engineering at plants. Trans-grafting process includes grafting of a non-genetically revised scion with a genetically changed rootstock. Scion acquires advantages and attributes conferred by transgenes in rootstock, nonetheless finale results, like fruits, do not include transgene and therefore are not genetically revised (Limera et al. 2017; Sidorova et al. 2021). This approach also enhances genetic stability in salt-stressed plants by maintaining the unaltered genetic structure of the scion while benefiting from stress tolerance conferred by the rootstock (Coskun 2023a). An additional revolution is micrografting, that includes in vitro grafting of tiny shoot apices or lateral buds with decapitated rootstock (Chilukamarri et al. 2021; Vidoy-Mercado et al. 2021). It is influential to understand the molecular biology of grafting for knowledge the graft compatibility. Although the vegetable grafting method has been practiced since the 1920s, its molecular research has been performed recently. Grafting induces the expression of genes involved in defence, oxidative stress, vascular growth, JA signalling, receptor kinase and pathogenesis-related genes. They have suggested that the stress tolerance in grafted plants is often due to graft induced molecular

changes in rootstock. Transcriptome findings in different grafted plants have been studied to identify the genes that are essential for grafting compatibility and associated stress tolerance imparted by rootstock to scions. Many studies recommend that diverse plant hormones, proteins, epigenetic events, and various styles of miRNA might be accountable for alterations in scion (Tsaballa et al. 2021; Sidorova et al. 2021; Vidoy-Mercado et al. 2021; Wang et al. 2017; Thomas and Frank 2019; Rasool et al. 2020).

The combination of grafting with biotechnological and genetic engineering techniques holds great promise in developing salt-tolerant vegetable crops. By using genetic modification, scientists can develop rootstocks that possess enhanced salt tolerance traits, such as improved ion compartmentalization or higher efficiency in water uptake (Rouphael et al. 2018). In addition, biotechnological methods like gene editing, and transgenic approaches can be used to modify the genetic makeup of the scion or rootstock to express salt-tolerant genes, further enhancing grafting outcomes. For example, researchers have successfully introduced genes that regulate the synthesis of compatible solutes like proline and glycerol in rootstocks, improving their ability to withstand saline stress (Rodríguez-Ortega et al. 2019). By integrating biotechnological advancements with grafting, it is possible to produce crops that not only exhibit salt tolerance but also maintain high yield and quality in saline environments, offering a sustainable solution to salinity challenges in agriculture. Numerous experiments have demonstrated that growth of grafted plants might be modified in rootstocks and scion by modifying its gene expression patterns (Prassinos et al. 2009). Experiment of gene regulatory networks might recognize significant genes in rootstocks, that might stimulate growth variations in scion (Liu et al. 2017).

CRISPR-Cas12a's attributes make it specifically efficient for fine-tuning complex characteristics like nutrient intake and stress resistance, both of that are valuable in grafting at vegetable crops. Cas12a may enhance rootstock attributes, indicating in greater nutrient absorption and resistance to several abiotic stresses such as salinity, water stress, and nutrient deficiencies. CRISPR-Cas12a might be applied to alter rootstock genes implicated in ion transfer and compartmentalization, like HKT1 (controls sodium transport) and NHX1 (regulates vacuolar sodium sequestration). Scientists fine-tuned these genes to generate rootstocks that are better able to handle extreme salinity, decreasing detrimental outcomes of additional sodium. For instance, in *Cucumis sativus*, varied rootstocks with better sodium exclusion capability were exhibited to flourish in salty soils. Grafting with non-edited scions, these rootstocks increase crops' whole salt tolerance (Erdogan et al. 2023).

CRISPR-Cas9 knowledge has assisted in enhancing tolerances to drought and salinity by utilizing rootstocks that are additional resistant to water and salt stress. CRISPR-Cas9 might target genes like HKT1 and NHX1, that control salt transport and sequestration in plants. CRISPR-Cas9 alters these genes, permitting plants to better control ion balance and decrease detrimental outcomes of salinity. During grafting process, rootstocks altered for better ion control enhance plant's overall salinity tolerance (Munns et al. 2016; Zhao et al. 2016a).

Numerous miRNAs, like miR169, miR395, miR398, and miR399, have been found that respond to high salinity in *Arabidopsis thaliana* (Liu et al. 2008), *Glycine max* (Ding et al. 2009), and *Populus euphratica* (Li et al. 2013a). A previous study observed that grafting can modify the expression of miRNAs and their target genes; over 40 miRNAs were found to change in the leaves of watermelon (*Citrullus lanatus*) when grafted onto bottle gourd (*Lagenaria siceraria*) or pumpkin (*Cucurbita maxima* × *Cucurbita moschata*) (Li et al. 2013b; Liu et al. 2013). Under salt stress, the post-transcriptional effects of the miRNA target network may be significant in graft-dependent. An experiment showed that the expression levels of most miRNAs in the leaves of pumpkin (*Cucurbita moschata*)-grafted cucumber seedlings enhance after 6 and 24 h of salt stress than self-grafted cucumbers (Li et al. 2016). Additionally, the expression levels of most miRNAs in the roots of pumpkin (*Cucurbita moschata*)-grafted cucumber enhance at salinity (Xie et al. 2015).

Under salt stress conditions, in grafted plants, salt-induced production of ROS normally persists quite low than in non-grafted plants, as evidenced by a considerable enhancement in the antioxidant activity in salt-treated (grafted) tomatoes. While activities of SOD and CAT tended to rise with an increase in salinity in grafted plants, the converse was confirmed for non-grafted and self-grafted plants (He et al. 2009). Furthermore, enzymatic antioxidants, a non-enzymatic antioxidant system (ascorbate peroxidase, monodehydro ascorbate reductase, reduced glutathione, etc.) is also recognized to eliminate the additional ROS (Bartoli et al. 2017). Higher expression of CAT mRNA, Cu/Zn-SOD, Mn-SOD and higher activities of CAT, Cu/Zn-SOD, Mn-SOD and SOD have been found in grafted plants under salt stress conditions (Gao et al. 2008). In eggplant, grafted plants formed lower O_2^-, H_2O_2, and MDA than non-grafted plants at $Ca(NO_3)_2$ stress. Higher activities of SOD, APX, and GR were also observed in grafted than non-grafted plants (Wei et al. 2009). In tomatoes, a widespread stress protein gene (SpUSP) cloned from *Solanum pennellii* (a wild relative tomato) and functionally differentiated in commercial tomato genotype revealed increased expression under salt stress conditions. About 15 primers were identified via fifteen salinity-responsive candidate genes. The genotype UC82B showed the highest vegetative growth and yield. Exploiting this identified geno-

Table 1 Growth and yield performance of grafted plants under salt stress

Plant Species	Scion	Rootstock	Salt stress level	Findings	Reference
Melon (*Cucumis melo* L.)	Rockmelon (*Cucumis melo* L.) var. Glamour	Bottle gourd (*Lagenaria siceraria*) var Mutiara and bitter gourd (*Momordica charantia*) var Wira	0, 25, 50 and 75 mM NaCl	Rockmelon/bottle gourd was categorized as slightest salt-sensitive and appropriate for fruit quality development	Hassan et al. (2024)
Pepper (*Capsicum annuum* L.)	Gacela (*Capsicum annuum*)	Creonte, Atlante, and Terran' (commercial rootstocks)	35 mM NaCl	Pepper plants grafted onto Creonte and Atlante produced drastically greater yield (by 60 and 75%, respectively) than non-grafted plants under salinity	Gálvez et al. (2021)
Pepper (*Capsicum annuum* L.)	Adige (*Capsicum annuum*)	NIBER® (*Capsicum annuum* × *Capsicum annuum*)	70 mM NaCl	The hybrid NIBER®, a new salinity-tolerant pepper rootstock, produced 32–80% higher yields than non-grafted plants	López-Serrano et al. (2020)
Cucumber (*Cucumis sativus* L.)	Hesham commercial cucumber cultivar	*C. maxima* × *C. moschata*, L. s. PI 534556 × L. s. PI 491365, Kalabsha × L. s. PI 491365, L. s. PI 534556 × L. s. PI 554556, Kalabsha × L. s. PI 534556, L. s. PI 554556 × L. s. PI 491365, L. s. PI 554556 × L. s. PI 534556, L. s. PI 534556, L. s. PI 491365, Kalabsha, L. s. PI 554556, *C. maxima, C. moschata*	70.9 and 2.77 dS m^{-1} EC levels	The maximum yield per m^2 were recorded with Kalabsha rootstock in the first season (15.83 kg) and with *Cucurbita maxima* rootstock in the second season (16.21 kg)	Abdel-Wahab et al. (2024)
Tomato (*Solanum lycopersicum* L.)	Ghandowra-F1, Forester-F1, and Feisty-Red	Maxifort, Unifort, Dynafort, Vivifort, and Beaufort	2.5, 6.0, and 9.5 dS m^{-1} EC levels	Salinity reduced yield, also rootstock did not increase yield. Vivifort and Beaufort are appropriate for grafting under low and moderate stress	Tola et al. (2024)
Bell Pepper (*Capsicum annuum* L. var. grossum (L.) Sendtn.)	Vedrana	Rocal F1 salt tolerant rootstock	20 and 40 mM NaCl	The fruit phenolic compounds were influenced by rootstock, and total phenolic content was enhanced with 40 mM NaCl. Fruit ascorbic acid content enhanced under salinity without mediation of rootstock	Kacjan Maršic et al. (2021)
Tomato (*Solanum lycopersicum* L.)	Galaxy and H2274 (*S. lycopersicum* L.)	Six wild tomatoes SP3 [LA1269], SP4 [LA2914], SP5 [LA1279] (*S. pimpinellifolium*), SH1 [LA1764], SH3 [LA1378], SH5 [LA2650] (*S. habrochaites*) and two hybrid L × SP5 [L × LA1279] (*S. lycopersicum* L. × *S. pimpinellifolium*) and L × SH3 [L × LA1378] (*S. lycopersicum* L. × *S. habrochaites*)	1.5 dS m^{-1} and 8 dS m^{-1} EC levels	Salinity decreased the shoots (68.71%) and roots (23.59%) fresh matters, though increased H_2O_2 content (93.90%) and MDA content (63.71%). Salt stress in leaf tissues POD (204.49%), CAT (83.87%), SOD (204.49%), GR (88.23%), GST (100.16%), G6PD (32.85%), 6GPD (46.19%), APX (157.29%) caused an increase in enzymes and total amino acid content (160.57%)	Aydın (2024)
Watermelon (*Citrullus lanatus* L.)	Watermelon	Hybrid Bottle Gourd (*Lagenaria siceraria*) Rootstock	1.8 and 10 dS m^{-1} EC levels	Salinity reduced shoot dry weight (63%), root dry weight (43%), main stem diameter (18%), number of leaves per plant (41%), main stem length (68%), root length (45%), leaf K/Na (100%), leaf Ca/Na (97%), leaf tissue IAA (3%), ABA (63%), and root tissue IAA (28%), GA_3 (32%), and SA (63%) content, but increased leaf tissue GA_3 (196%), SA (27%) and root tissue ABA (47%) content	Başak et al. (2025)

Table 1 (Continued)

Plant Species	Scion	Rootstock	Salt stress level	Findings	Reference
Melon (*Cucumis melo* L.)	Salt-susceptible melon genotypes, SCP-1 and SCP-2	TLR-1 and TLR-2, which are salt-tolerant melon genotypes, and Albatros commercial melon rootstock	0, and 200 mM NaCl	Under salt stress, declined in the shoot fresh (70 and 33%) and dry (55 and 24%), root fresh (48 and 26%) and dry weight (43 and 29%), and leaf area (82 and 26%) of ungrafted and grafted plants were observed. However, increased in the SOD activity in the grafted plants, by about 35 and 115%, when compared with the ungrafted salt-stressed plants	Kuşvuran et al. (2021)
Cucumber (*Cucumis sativus* L.)	Nagene variety	Pumpkin rootstock (*Cucurbita maxima)*	0, 50, 100 mM NaCl	Se biofortification and grafting substantially increased salinity tolerance in cucumbers, leading to increased yield and growth. Grafting onto pumpkin improved the salinity tolerance of cucumber through a decline of Na uptake and translocation to the scion	Amerian et al. (2024)
Tomato (*Solanum lycopersicum* L.)	Tone Guitar F1 (commercial scion)	Maxifort F1, X-218, X-238, and Alawamiya365	2.0, and 4.0 dS m^{-1} EC levels	Yield increased by 53% at low salt stress (2 dS m^{-1}) at volcanic rock at the grafted plants	Alqardaeai et al. (2024)
Pepper (*Capsicum annuum* L.)	Pepper inbred lines (ERÜ-462 and ERÜ-1227)	Scarface F1, 11B14, and Yaocali F1	1.5, and 8.0 dS m^{-1} EC levels	Vigorous rootstock alleviated adverse influences of salinity. Salt stress substantially reduced shoot dry matter (3.48 and 58.11%), root dry matter (6.36 and 38.07%) and photosynthesis (16.3 and 41.2%) in ERÜ-462/11B14 and ERÜ 1227/ Scarface F1 plants compared to unstressed plants	Al Rubaye et al. (2021)
Cucumber (*Cucumis sativus)*	*Cucumis sativus* L. cv 1010	Bottle gourd, pumpkin, winter squash, and nubian watermelon	0, 50, 100 mM NaCl	The maximum enhancement in net assimilation rate (33.1%), stomatal conductance (25.4%), Chl a (46.8%), Chl b (45.2%), carotenoid (17.8%), chlorophyll fluorescence parameters (Fv/Fm (12.1%) and NPQ (39.4%)) were observed in pumpkin compared with self-grafted plants under salt stress. The maximum increase for total phenols (2.9%), total sugars (48.2%), proline (14.4%) and gibberellin (12.3%), cytokinin (12.6%), and salicylic acid (55.1%) were observed in pumpkin, while maximum total protein (7.2%) and auxin (31.2%) were produced in bottle gourd over self-grafted plants	Elsheery et al. (2020)
Melon (*Cucumis melo* L.)	Citirex and Altinbas	Kardosa and Nun9075	1.5, and 8.0 dS m^{-1} EC levels	Salinity declined shoot (49.9%) and root growth (17.6%), shoot-to-root ratio (45.8%), leaf area (49.1%), photosynthesis (9.1%), leaf chlorophyll (14.8%), and carotenoid contents (20.4%), leaf K^+ concentration (20.1%). However, salt stress enhanced substantially proline (59.1%), MDA (31.3%) contents and leaf (56.8%) and root (36.7%) ion leakages, leaf Na^+ (1137.5%), Cl^- (1392.3%) and Ca^{++} (353.3%) concentrations	Ulas et al. (2020a)
Cucumber (*Cucumis sativus)*	*Cucumis sativus* cv. Deer No. 99	*Cucurbita ficifolia* Bouché	0, 5, 10, 20, and 30 mM L^{-1} NaCl	Under salinity, grafting increased the absorption of K^+ and Ca^{2+} in cucumber stems and leaves. However, it significantly reduced the accumulation of Na^+ in those parts by 61.58–89.40%. The 10 mM L^{-1} Ca^{2+} had the highest biomass, compared with control and non-grafted, with an increase of 49.95 and 20.47%, respectively, the lowest sodium ion (Na^+). At 11 days, compared with 0 mM L^{-1} Ca^{2+} treatment, pro content was increased by 4.70–25.31, and MDA content was decreased by 1.08–4.90 times, respectively	Wang et al. (2021)

Table 1 (Continued)

Plant Species	Scion	Rootstock	Salt stress level	Findings	Reference
Tomato (*Solanum lycopersicum* L.)	Jiaxina	Maxifort	0, and 150 mM NaCl	Salicylic acid, grafting, their combination (GSA) improved the plant height by 22.5%, 26.5%, and 40.2%; the stem diameter by 11.0%, 26.0%, and 23.7%; the shoot fresh weight by 76.3%, 113.2%, and 247.4%; the root fresh weight by 150.9%, 238.6%, and 286.0%; the shoot dry weight by 53.5%, 65.1%, and 162.8%; the root dry weight by 150.0%, 150.0%, and 166.7%, and photosynthesis by 4.0%, 16.3%, and 32.7%, with GSA presenting the most pronounced positive effect	Miao et al. (2024)
Tomato (*Solanum lycopersicum* L.)	Valouro-RZ Ghandora-F1, and Feisty-Red commercial tomato cultivars	Maxifort	2.5, 6.0, and 9.0 dS m^{-1} EC levels	The variations in transpiration rate, net photosynthetic rate, stomatal conductance, chlorophyll content of leaf, and yield between medium and high salinity trials were reported at 3%, 5%, 9%, 5%, and 7.1%, respectively. In contrast, no significant differences were observed between low and medium salinities	Al-Gaadi et al. (2024)
Tomato (*Solanum lycopersicum* L.)	Izmir F1	Arnold, Dohkko, Emperador, He-man, Kaiser, and Suzuka	0, and 50 mM NaCl	Grafting enhances root architecture (root length, specific root length, and root length ratio), which increases the capacities of grafted plants to exploit a larger volume of soil or enhance root density under root restriction conditions. Since the root traits and nutrient concentrations in grafted plants were less impacted by a change in the salinity level, the study of rootstocks (Arnold, Dohkko, Kaiser) could contribute to the constant growth and yield of tomatoes under salt stress	Balliu et al. (2024)
Cucumber (*Cucumis sativus)*	Aramon (*Cucumis sativus*)	Becada (*Cucurbita moschata*)	50 mM NaCl	In grafted cucumber, Cl– would accumulate to a toxic level in leaves. Instead, mechanisms exist to avoid overaccumulation. Mechanisms of Na^+ exclusion and tissue tolerance vary independently in selected cucumber cultivars	Chen et al. (2020)
Tomato (*Solanum lycopersicum* L.)	Ikram (*Solanum lycopersicum*)	Charlotte (*Solanum lycopersicum*)	5.0 dS m^{-1} NaCl level	Grafted plants produced 78.9% fruit yield of tomatoes under the non-saline conditions. Under salinity, the fruit TSS content of grafted (19.6%) and tomato (19.2%) plants was substantially higher. The total tuber yields of the potato and grafted plants were significantly reduced due to a decrease in the number of tubers per plant (18.2%) and average tuber dry mass (45.8%) under salinity	Parthasarathi et al. (2021)
Tomato (*Solanum lycopersicum* L.)	Tom 121 and Tom 174 (*Solanum lycopersicum*)	Tom 121 and Tom 174 (*Solanum lycopersicum*)	50 mM NaCl	Under salinity, self-grafted plants of Tom 174 had an increase in fruit yield (16.6%), self-grafted plants of Tom 121 had a decrease in fruit yield (44.4%). In contrast, Tom 121/Tom 174 graft combination decreased the fruit yield by only 2.5%	Coban et al. (2020)
Tomato (*Solanum lycopersicum* L.)	Bark (*Solanum lycopersicum* L.)	LA1995, LA2711, LA2485, and LA3845 (*Solanum lycopersicum* L.)	100, and 200 mM NaCl	Bark rootstock enhanced shoot (fresh weight, stem length, branch number), and root growth (total root length, fresh and dry weight), yield (total yield, fruit number and fruit weight) and quality (Vitamin C, firmness and total soluble solids). Three considers (molecular, physiological and agronomical) showed that four genotypes (LA1995, LA2711, LA2485 and LA3845) showed excellent functioning at salt stress	Abdeldym et al. (2020)

Table 1 (Continued)

Plant Species	Scion	Rootstock	Salt stress level	Findings	Reference
Cucumber (*Cucumis sativus)*	Jinchun No. 2 (*Cucumis sativus*)	Chaojiquanwang (*Cucurbita moschata*)	75 mM NaCl	Pumpkin roots enhance scion sensitivity to ABA transferred from roots to shoots and increase osmotic tolerance at salt stress	Niu et al. (2019)
Eggplant (*Solanum melongena*)	Naomi and Artvin	AGr703 *(Solanum aethiopicum),* Yula*, and* Vista *(Solanum incanum* × *Solanum melongena)*	6.0 and 7.0 dS m^{-1} NaCl levels	Grafting made plants more effective in avoiding Na^+ ions sent to plants' upper parts and had maximum SOD, CAT, and APX activity than self-grafted and non-grafted plants that developed improved tolerance and plant growth	Talhouni et al. (2019)
Eggplant (*Solanum melongena*)	Angela (*Solanum melongena*)	Maxifort (*Solanum lycopersicum*)	55.5 mM Na^+ and 148 mM Cl^-	Maxifort rootstock had yield decreases of 6.8, 53, 66 and 80%, relative to the control, for salinity levels of –0.15, –0.30, –0.45 and –0.60 MPa, respectively. The yield alterations among Maxifort grafted and nongrafted plants were much more obvious under moderate and high salinity, with the yield differences at 3.98 and 8.26 dSm^{-1} being 80.5 and 68.1%, respectively	Semiz and Suarez (2019)

type could be known for salt tolerance (Ja'afar et al. 2018). Asins et al. (2015) reported that the genetic dissection of rootstock influences scion characteristics under moderate salinity in tomato plants. The rootstock HKT1 genotype influences the Na^+ level in fruits, which was observed to be bigger when the rootstock genotype was homozygote for SpHKT1. The 37 QTLs, which control the valuable rootstock-mediated scion attributes like the leaf concentration of nutrients, harvesting time, fruit yield, and soluble-solids content under moderate salinity, were detected. The high amount of Na^+ can encourage a calcium signaling cascade, activating the salt-overly-sensitive (SOS) pathway and encouraging Na^+/H^+ exchange (Zhao et al. 2016b). An ER chaperone protein, Calreticulin, is considered a controlling protein for the Ca^{2+} homeostasis by binding to Ca^{2+}. Salinity initiates the calreticulin to bind with the Ca^{2+} ions, which are later collected in the cell. The collected calcium ions act as a secondary messenger for ABA, resulting in the amelioration of salt stress (Mahajan et al. 2008). Wu et al. (2023) demonstrated the essential function of WRKY transcription factors, PosF21 and xyloglucan endotransglucosylase-hydrolases (XTHs) in imparting salt stress tolerance in grafted tomato seedlings through RNA-seq analysis.

Peng et al. (2023) identified the key genes responsible for salt stress tolerance in cucumber grafted on pumpkin rootstock. They performed transcriptome analysis and functional characterization of a candidate gene high-affinity K^+ 5;3(*CsHAK5;3*). They stated that *CsHAK5;3* gene is the major regulator of K^+ homoeostasis under salinity. Salt stress responsive transcriptome and proteome profiling in bottle gourd rootstock-grafted watermelon seedlings showed 3207 and 5255 genes as up- and down-regulated, respectively, and 28 proteins with at least 1.5-folds change (Wang et al. 2023). The differentially stated genes involved transcription factors such as MYB, WRKY, bHLH, and NAC family and genes included in signal transduction pathway, although the differentially stated protein included the proteins involved in amino acid and protein synthesis, photosynthesis, mitochondrial metabolism and carbon metabolism, and stress defense. Furthermore, additional research on vegetable grafting technology and its molecular mechanism of compatibility and stress responses by utilizing modern omics and biotechnological approaches will help to exploit this technology in crop breeding programs (Table 1).

Conclusions

Soil or water salinity is a significant problem for plant growth and development and prevents plants from reaching their genetic potential, which declines crop yield and quality. To approach the negative impact of salinity on vegetable plants, the plants involve specific processes that enhance salinity resistance. Insight the enhancing salinity conditions caused by climate change and their influence on agricultural production underscores the growing importance of vegetable grafting technology. Vegetable crops can be efficiently grafted onto suitable rootstocks to enhance production, yield, and quality in Cucurbitaceous and Solanaceous vegetables while reducing the sensitivity of the scion to salt stress. By applying salt-tolerant vegetable rootstocks, grafting increases the plant's ability to withstand the negative outcomes of salinity, like declined water uptake, ion toxicity, and osmotic imbalance. This method not only increases plant growth and development as well as root system de-

velopment, allowing for better nutrient and water absorption, nevertheless also encourages biochemical responses, including the activation of antioxidant systems and the regulation of osmotic pressure, which further contributes to stress tolerance. Therefore, the study of this technique under salinity has the ability to strengthen ecosystem sustainability. Considering its various benefits, this innovative technology has potential to become one of the major tools in the coming years for enhancing vegetable productivity, particularly under salt stress for sustainable agriculture.

Author Contribution FU, HHHHA, AU, YCY: investigation and document search; FU and HHHHA: writing; FU, AU, YCY: design, writing and editing. All authors have read and agreed to the published version of the manuscript. We insist that no author be omitted.

Conflict of interest F. Ulas, H. H.H.H. Ameen, A. Ulas and Y.C. Yücel declare that they have no competing interests.

References

Abdel-Wahab A, Mohamed M, Hanafy S, El-Mohammady M (2024) Improving salinity tolerance of cucumber plants grown under shadehouse conditions by grafting onto some genotypes and F1 hybrids of Cucurbit rootstocks. Sci J Agric Sci 6(1):84–97. https://doi.org/10.21608/sjas.2024.275848.1401

Abdeldym EA, El-Mogy MM, Abdellateaf HRL, Atia MAM (2020) Genetic characterization, agro-morphological and physiological evaluation of grafted tomato under salinity stress conditions. Agronomy 10:1948. https://doi.org/10.3390/agronomy10121948

Adam MB, Ulas A (2023) Vigorous rootstocks improve Nitrogen efficiency of tomato by inducing morphological, physiological and biochemical responses. Gesunde Pflanz 75:565–575

Akladious SA, Abbas SM (2013) Alleviation of seawater stress on tomato by foliar application of aspartic acid and glutathione. J Stress Physiol Biochem 9:3

Al Rubaye OAM, Yetişir H, Ulaş F, Ulaş A (2021) Enhancing salt stress tolerance of different pepper (Capsicum annuum l.) inbred line genotypes by rootstock with vigorous root system. Gesunde Pflanz 73(3):375–389

Al-Gaadi KA, Tola E, Madugundu R, Zeyada AM, Alameen AA, Edris MK et al (2024) Response of leaf photosynthesis, chlorophyll content and yield of hydroponic tomatoes to different water salinity levels. PLoS ONE 19(2):e293098. https://doi.org/10.1371/journal.pone.0293098

Al-Harbi A, Hejazi A, Al-Omran A (2017) Responses of grafted tomato (Solanum lycopersicon L.) to abiotic stresses in Saudi Arabia. Saudi J Biol Sci 24(6):1274–1280. https://doi.org/10.1016/j.sjbs.2016.01.005

Alqardaeai T, Alharbi A, Alenazi M, Alomran A, Elfeky A, Osman M, Obadi A, Aldubai A, Ortiz NR, Melino V et al (2024) Effect of tomato grafting onto novel and commercial rootstocks on improved salinity tolerance and enhanced growth, physiology, and yield in soilless culture. Agronomy 14:1526. https://doi.org/10.3390/agronomy14071526

Amerian M, Palangi A, Gohari G, Ntatsi G (2024) Enhancing salinity tolerance in cucumber through Selenium biofortification and grafting. BMC Plant Biol 24:24. https://doi.org/10.1186/s12870-023-04711-z

Ashraf M, Hameed M, Arshad M, Ashraf Y, Akhtar K (2006) Salt tolerance of some potential forage grasses from cholistan desert of Pakistan. In: Khan MA, Weber DJ (eds) Ecophysiology of high salinity tolerant plants. Springer, Amsterdam, pp 31–54 https://doi.org/10.1007/1-4020-4018-0_3

Asins MJ, Raga V, Roca D, Belver A, Carbonell EA (2015) Genetic dissection of tomato rootstock effects on scion traits under moderate salinity. Theor Appl Genet 128:667–679

Askari H, Edqvist J, Hajheidari M, Kafi M, Salekdeh GH (2006) Effects of salinity levels on proteome of Suaeda aegyptiaca leaves. Proteomics 6:2542–2554. https://doi.org/10.1002/pmic.200500328

Assimakopoulou A, Nifakos K, Salmas I, Kalogeropoulos P (2015) Growth, ion uptake, and yield responses of three indigenous small-sized greek tomato (Lycopersicon esculentum L.) cultivars and four hybrids of cherry tomato under NaCl salinity stress. Commun Soil Sci Plant Anal 46(18):2357–2377. https://doi.org/10.1080/00103624.2015.1081924

Aydın A (2024) The growth, leaf antioxidant enzymes and amino acid content of tomato as affected by grafting on wild tomato rootstocks 1 (S. pimpinellifolium and S. habrochaites) under salt stress. Sci Hortic 325:112679

Aydın A, Yetisir H (2022) Rootstock effect of auto- and allotetraploid citron (Citrullus lanatus var. citroides) on hydroponically grown cucumber under salt stress. Gesunde Pflanz. https://doi.org/10.1007/S10343-022-00782-4/TABLES/9

Aydın D, Coskun ÖF (2013) Comparison of edta-enhanced phytoextraction strategies with nasturtium officinale (Watercress) on an artificially arsenic contaminated water. Pak J Bot 45(4):1423–1429

Azarmi R, Taleshmikail RD, Gikloo A (2010) Effects of salinity on morphological and physiological changes and yield of tomato in hydroponics system. J Food Agric Environ 8:573–576

Balliu A, Babaj I, Sallaku G (2024) Root morphology parameters and nutrient acquisition capabilities of grafted tomato plants in root-restricted conditions are subject to salinity and rootstock characteristics. Int J Veg Sci 30(5):503–526. https://doi.org/10.1080/19315260.2024.2383847

Bartoli CG, Buet A, Grozeff GG (2017) Ascorbate-glutathione cycle and abiotic stress tolerance in plants. In: Ascorbic acid in plant. Growth, development and stress tolerance. Springer, Cham, pp 177–200

Bartusch K, Melnyk CW (2020) Insights into plant surgery: an overview of the multiple grafting techniques for Arabidopsis thaliana. Front Plant Sci 11:613442. https://doi.org/10.3389/fpls.2020.613442

Başak H, Aydin A, Yetişir H et al (2025) Salt stress effects on hybrid bottle gourd (Lagenaria siceraria) rootstock candidates plant growth, hormones and nutrient content. J Crop Health 77:28. https://doi.org/10.1007/s10343-024-01087-4

Batista MC, do Nascimento R, Maia Júnior OECRF, Nascimento ECS, Bezerra CVC, Lima RF (2021) Physiology and production of cherry tomato cultivars in a hydroponic system using brackish water. Rev Bras Eng Agríc Ambient 25:219–227

Bayoumi Y, Abd-Alkarim E, El-Ramady H, El-Aidy F, Hamed ES, Taha N, Rakha M (2021) Grafting improves fruit yield of cucumber plants grown under combined heat and soil salinity stresses. Horticulturae 7(3):61

Botella MÁ, Hernández V, Mestre T, Hellín P, García-Legaz MF, Rivero RM, Martínez V, Fenoll J, Flores P (2021) Bioactive compounds of tomato fruit in response to salinity, heat and their combination. Agriculture 11:534

Cela F, Carmassi G, Najar B, Taglieri I, Sanmartin C, Cialli S, Ceccanti C, Guidi L, Venturi F, Incrocci L (2024) Salinity impact on yield, quality and sensory profile of 'pisanello' tuscan local tomato (Solanum lycopersicum L.) in closed soilless cultivation. Horticulturae 10(6):570

Chávez-Mendoza C, Sánchez E, Carvajal-Millán E, Muñoz-Márquez E, Guevara-Aguilar A (2013) Characterization of the nutraceutical

quality and antioxidant activity in bell pepper in response to grafting. Molecules 18:15689–15703
Chen TW, Gomez Pineda IM, Brand AM, Stützel H (2020) Determining ion toxicity in cucumber under salinity stress. Agronomy 10:677. https://doi.org/10.3390/agronomy10050677
Chen X, Ding Y, Yang Y, Song C, Wang B, Yang S, Guo Y, Gong Z (2021) Protein kinases in plant responses to drought, salt, and cold stress. J Integr Plant Biol 63:53–78
Chilukamarri L, Ashrafzadeh S, Leung DWM (2021) In-vitro grafting—Current applications and future prospects. Sci Hortic 280:109899. https://doi.org/10.1016/j.scienta.2021.109899
Çiçek N, Oukarroum A, Strasser RJ, Schansker G (2018) Salt stress effects on the photosynthetic electron transport chain in two chickpea lines differing in their salt stress tolerance. Photosynth Res 136:291–301. https://doi.org/10.1007/s11120-017-0463-y
Coban A, Akhoundnejad Y, Dere S, Yildiz Dasgan H (2020) Impact of salt-tolerant rootstock on the enhancement of sensitive tomato plant responses to salinity. HortScience 55(1):35–39
Colla G, Rouphael Y, Leonardi C, Bie Z (2010) Role of grafting in vegetable crops grown under saline conditions. Sci Hortic 127:147–155
Colla G, Rouphael Y, Rea E, Cardarelli M (2012) Grafting cucumber plants enhance tolerance to sodium chloride and sulfate salinization. Sci Hortic 135:177–185
Coskun OF (2023a) Effects of grafting on genomic stability in salinity stress conditions in cucumber (Cucumis sativus L.). Erciyes Tarım Ve Hayvan Bilimleri Dergisi 6(1):23–30. https://doi.org/10.55257/ethabd.1231233
Coskun OF (2023b) The effect of grafting on morphological, physiological and molecular changes induced by drought stress in cucumber. Sustainability 15:875. https://doi.org/10.3390/su15010875
Coskun OF (2025) Association mapping for drought tolerance in watermelons (Citrullus lanatus L.). Horticulturae 11(2):193–199
Costan A, Stamatakis A, Chrysargyris A, Petropoulos SA, Tzortzakis N (2020) Interactive effects of salinity and silicon application on Solanum lycopersicum growth, physiology and shelf-life of fruit produced hydroponically. J Sci Food Agric 100:732–743
Dasgan HY, Aktas H, Abak K, Cakmak I (2002) Determination of screening techniques to salinity tolerance in tomatoes and investigation of genotype responses. Plant Sci 163:695–703
De Pascale S, Orsini F, Caputo R, Palermo MA, Barbieri G, Maggio A, De Pascale S, Orsini F, Caputo R, Palermo MA et al (2012) Seasonal and multiannual effects of salinisation on tomato yield and fruit quality. Funct Plant Biol 39:689–698
Dias JS (2012) Nutritional quality and health benefits of vegetables: a review. Food Nutr Sci 3:1354–1374. https://doi.org/10.4236/fns.2012.310179
Ding D, Zhang L, Wang H, Liu Z, Zhang Z et al (2009) Differential expression of miRNAs in response to salt stress in maize roots. Ann Bot 103:29–38
Egamberdieva D (2011) Survival of Pseudomonas extremorientalis TSAU20 and P. chlororaphis TSAU13 in the rhizosphere of common bean (Phaseolus vulgaris) under saline conditions. Plant Soil Environ 57:122–127. https://doi.org/10.17221/316/2010-PSE
Egea I, Estrada Y, Faura C, Egea-Fernández JM, Bolarin MC, Flores FB (2023) Salt-tolerant alternative crops as sources of quality food to mitigate the negative impact of salinity on agricultural production. Front Plant Sci 14:304
El Mahi H, Pérez-Hormaeche J, De Luca A, Villalta I, Espartero J, Gámez-Arjona F, Quintero FJ (2019) A critical role of sodium flux via the plasma membrane Na+/H+ exchanger SOS1 in the salt tolerance of rice. Plant Physiol 180(2):1046–1065
El-Shraiy AM, Mostafa MA, Zaghlool SA, Shehata SAM (2011) Alleviation of salt injury of cucumber plant by grafting onto salt tolerance rootstock. Aust J Basic Appl Sci 5(10):1414–1423
El-Tarabily KA, AlKhajeh AS, Ayyash MM, Alnuaimi LH, Sham A, ElBaghdady KZ, Tariq S, AbuQamar SF (2019) Growth promotion of Salicornia bigelovii by Micromonospora chalcea UAE1, an endophytic 1-aminocyclopropane-1-carboxylic acid deaminase-producing actinobacterial isolate. Front Microbiol 10:1694. https://doi.org/10.3389/fmicb.2019.01694
Elsheery NI, Helaly MN, Omar SA, John SV, Zabochnicka-Swiątek M, Kalaji Rastogi HMA (2020) Physiological and molecular mechanisms of salinity tolerance in grafted cucumber. S Afr J Bot 130:90–102
Erdogan I, Cevher-Keskin B, Bilir Ö, Hong Y, Tör M (2023) Recent developments in CRISPR/Cas9 genome-editing technology related to plant disease resistance and abiotic stress tolerance. Biology 12(7):1037. https://doi.org/10.3390/biology12071037
FAO (2021) Food and Agriculture Organization of the United Nations. Global map of salt affected soils version 1.0. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils/en/. Accessed 04.2025
FAOSTAT (2018) Food and Agriculture Organization of the United Nations. Statistics division. www.fao.org/faost at/. Accessed 17 Nov 2024
FAOSTAT (2023) Food and Agriculture Organization of the United Nations. Statistics division. www.fao.org/faost at/. Accessed 10 Sept 2024
Flowers TJ, Colmer TD (2015) Plant salt tolerance: adaptations in halophytes. Ann Bot 115:327–331. https://doi.org/10.1093/aob/mcu267
Flowers TJ, Yeo AR (1995) Breeding for salinity resistance in crop plants: where next? Aust J Plant Physiol 22:875–884. https://doi.org/10.1071/PP9950875
Fullana-Pericas M, Ponce J, Conesa MÀ, Juan A, Ribas-Carbó M, Galmés J (2018) Changes in yield, growth and photosynthesis in a drought-adapted Mediterranean tomato landrace (Solanum lycopersicum 'Ramellet') when grafted onto commercial rootstocks and Solanum pimpinellifolium. Sci Hortic 233:70–77. https://doi.org/10.1016/j.scienta.2018.01.045
Gálvez A, Albacete A, Martínez-Andújar C, del Amor FM, López-Marín J (2021) Contrasting rootstock-mediated growth and yield responses in salinized pepper plants (Capsicum annuum L.) are associated with changes in the hormonal balance. Int J Mol Sci 22:3297. https://doi.org/10.3390/ijms22073297
Gao JJ, Zhang L, Qin AG, Yu XC (2008) Relative expression of SOD and CAT mRNA and activities of SOD and CAT in grafted cucumber leaves under NaCl stress. Ying yong sheng tai xue bao. J Appl Ecol 19:1754–1758
Ghassemi F, Jakeman AJ, Nix HA (1995) Salinisation of land and water resources: human causes, extent, management and case studies, pp xviii–526
Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem 48(12):909–930. https://doi.org/10.1016/j.plaphy.2010.08.016
Gisbert Domenech MC, Sánchez-Torres P, Raigón Jiménez M, Nuez Viñals F (2010) Phytophthora capsici resistance evaluation in pepper hybrids. Agronomic performance and fruit quality of pepper grafted plants. J Food Agric Environ 8:116–121
Giuffrida F, Cassaniti C, Leonardi C (2013) The influence of rootstock on growth and ion concentrations in pepper (Capsicum annuum L.) under saline conditions. Hortic Sci Biotech 88:110–116
Grigore MN, Toma C (2017) Anatomical adaptations of halophytes: a review of classic literature and recent findings. Springer, Cham, p 338 https://doi.org/10.1007/978-3-319-66480-4
Guo J, Shan C, Zhang Y, Wang X, Tian H, Han G, Zhang Y, Wang B (2022) Mechanisms of salt tolerance and molecular breeding of salt-tolerant ornamental plants. Front Plant Sci 13:854116

Guo Y, Qiu QS, Quintero FJ, Pardo JM, Ohta M, Zhang C, Schumaker KS, Zhu JK (2004) Transgenic evaluation of activated mutant alleles of SOS2reveals a critical requirement for its kinase activity and C-terminal regulatory domain for salt tolerance in Arabidopsis thaliana. Plant Cell 16:435–449

Gupta B, Huang B (2014) Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. Int J Genomics. https://doi.org/10.1155/2014/701596

Gurmani AR, Khan SU, Ali A et al (2018) Salicylic acid and kinetin mediated stimulation of salt tolerance in cucumber (Cucumis sativus L.) genotypes varying in salinity tolerance. Hortic Environ Biotechnol 59:461–471. https://doi.org/10.1007/s13580-018-0056-5

Haghighi M, Pessarakli M (2013) Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (Solanum lycopersicum L.) at early growth stage. Sci Hortic 161:111–117

Halfter U, Ishitani M, Zhu JK (2000) The Arabidopsis SOS2 protein kinase physically interacts with and is activated by the calcium-binding protein SOS3. Proc Natl Acad Sci U S A 97:3735–3740

Han M, Cao B, Liu S, Xu K (2018) Effects of rootstock and scion interaction on chilling tolerance of grafted tomato seedlings. Acta Hortic Sin 45(2):279–288

Hasanuzzaman M, Raihan RH, Masud AAC, Rahman K, Nowroz F, Rahman M, Nahar K, Fujita M (2021) Regulation of reactive oxygen species and antioxidant defense in plants under salinity. Int J Mol Sci 22:9326

Hasegawa PM, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. Annu Rev Plant Physiol Plant Mol Biol 51:463–499. https://doi.org/10.1146/annurev.arplant.51.1.463

Hassan MHM, Ghani MNO, Awang Y, Jaafar JN, Nazli MH (2024) Charaterization of salinity tolerance level m grafted rockmelon as affected by cucurbit rootstocks and NaCl levels. Aust J Crop Sci 18(12):811–818

He Y, Zhu Z, Yang J (2009) Grafting increases the salt tolerance of tomato by improvement of photosynthesis and enhancement of antioxidant enzymes activity. Environ Exp Bot 66:270–278

Herison C, Putri YE, Hasanudin H, Rustikawati R (2024) Growth and Yield Responses of Hot Pepper (*Capsicum annuum* L) to Salinity Stress. In International Agriculture Meeting (IAM 2023). Atlantis Press, pp 112–121

Huang Y, Tang R, Cao Q, Bie Z (2009) Improving the fruit yield and quality of cucumber by grafting onto the salt tolerant rootstock under NaCl stress. Sci Hortic 122:26–31. https://doi.org/10.1016/j.scienta.2009.04.004

Hussein MM, Abo-Leila BH, Metwally SA, Leithy SZ (2012) Anatomical structure of jatropha leaves affected by proline and salinity conditions. J Appl Res 8:491–496

Ismail AM, Horie T (2017) Genomics, physiology, and molecular breeding approaches for improving salt tolerance. Annu Rev Plant Biol 68(1):405–434

Ja'afar U, Aliero AA, Shehu K, Abubakar L (2018) Genetic diversity in tomato genotypes (Solanum lycopersicum) based on salinity responsive candidate gene using simple sequence repeats. Int Lett Nat Sci 72:37–46

Jiang Z, Zhou X, Tao M, Yuan F, Liu L, Wu F, Wu X, Xiang Y, Niu Y, Liu F et al (2019) Plant cell-surface GIPC sphingolipids sense salt to trigger Ca^{2+}influx. Nature 572:341–346

Kacjan Maršić N, Štolfa P, Vodnik D, Košmelj K, Mikulič-Petkovšek M, Kump B, Vidrih R, Kokalj D, Piskernik S, Ferjančič B et al (2021) Physiological and biochemical responses of ungrafted and grafted bell pepper plants (Capsicum annuum L. var. grossum (L.) Sendtn.) grown under moderate salt stress. Plants 10:314. https://doi.org/10.3390/plants10020314

Kapazoglou A, Tani E, Avramidou EV, Abraham EM, Gerakari M, Megariti S, Doupis G, Doulis AG (2021) Epigenetic changes and transcriptional reprogramming upon woody plant grafting for crop sustainability in a changing environment. Front Plant Sci 11:613004. https://doi.org/10.3389/fpls.2020.613004

Kaya C, Akram NA, Ashraf M, Sonmez O (2018) Exogenous application of humic acid mitigates salinity stress in maize (Zea mays L.) plants by improving some key physico-biochemical attributes. Cereal Res Commun 46:67–78. https://doi.org/10.1556/0806.45.2017.064

Krauss S, Schnitzler WH, Grassmann J, Woitke M (2006) The influence of different electrical conductivity values in a simplified recirculating soilless system on inner and outer fruit quality characteristics of tomato. J Agric Food Chem 54:441–448

Kudla J, Becker D, Grill E, Hedrich R, Hippler M, Kummer U, Parniske M, Romeis T, Schumacher K (2018) Advances and current challenges in calciumsignaling. New Phytol 218:414–431

Kumar P, Khapte PS, Saxena A, Singh A, Panwar NR, Kumar P (2019) Intergeneric grafting for enhanced growth, yield and nutrient acquisition in greenhouse cucumber during winter. J Environ Biol 40:295–301

Kuşvuran Ş, Kaya E, Ellialtıoğlu ŞŞ (2021) Role of grafting in tolerance to salt stress in melon (Cucumis melo L.) plants: Ion regulation and antioxidant defense systems. Biotech Stud 30(1):22–32. https://doi.org/10.38042/biotechstudies.932376

Kyriacou MC, Rouphael Y, Colla G, Zrenner R, Schwarz D (2017) Vegetable grafting: the implications of a growing agronomic imperative for vegetable fruit quality and nutritive value. Front Plant Sci 8:741

Leal-Fernández C, Godoy-Hernández H, Núñez-Colín C, Anaya-López J, Villalobos-Reyes S, Castellanos J (2013) Morphological response and fruit yield of sweet pepper (Capsicum annuum L.) grafted onto different commercial rootstocks. Biol Agric Hortic 29:1–11

Lee JM (1994) Cultivation of grafted vegetables. I. Current status, grafting methods and benefits. HortScience 29:235–239

Lee JM, Kubota C, Tsao SJ, Bie Z, Hoyos Echevarria P, Morra L, Oda M (2010) Current status of vegetable grafting: diffusion, grafting techniques, automation. Sci Hortic 127:93–105

Li B, Duan H, Li J, Deng X, Yin W et al (2013a) Global identification of miRNAs and targets in Populus euphratica under salt stress. Plant Mol Biol 81:525–539

Li C, Li Y, Bai L, Zhang T, He C et al (2013b) Grafting-responsive miRNAs in cucumber and pumpkin seedlings identified by highthroughput sequencing at whole genome level. Physiol Plant 151:406–422

Li Y, Li C, Bai L, He C, Yu X (2016) MicroRNA and target gene responses to salt stress in grafted cucumber seedlings. Acta Physiol Plant 38:12

Limera C, Sabbadini S, Sweet JB, Mezzetti B (2017) New biotechnological tools for the genetic improvement of major woody fruit species. Front Plant Sci 8:1418. https://doi.org/10.3389/fpls.2017.01418

Lin H, Yang Y, Quan R, Mendoza I, Wu Y, Du W, Zhao S, Schumaker KS, Pardo JM, Guo Y (2009) Phosphorylation of SOS3-LIKE CALCIUMBINDING PROTEIN8 by SOS2 protein kinase stabilizes their proteincomplex and regulates salt tolerance in Arabidopsis. Plant Cell 21:1607–1619

Liu H, Tian X, Li Y, Wu C, Zheng C (2008) Microarray-based analysis of stress-regulated microRNAs in Arabidopsis thaliana. RNA 14:836–843

Liu N, Yang J, Guo S, Xu Y, Zhang M (2013) Genome-wide identification and comparative analysis of conserved and novel microRNAs in grafted watermelon by high-throughput sequencing. PLoS ONE 8:e57359

Liu XY, Li J, Liu MM, Yao Q, Chen JZ (2017) Transcriptome profiling to understand the effect of citrus rootstocks on the growth of 'Shatangju' Mandarin. PLoS ONE 12(1):1–22

López-Marín J, González A, Pérez-Alfocea F, Egea-Gilabert C, Fernández JA (2013) Grafting is an efficient alternative to shading screens to alleviate thermal stress in greenhouse-grown sweet pepper. Sci Hortic 149:39–46

López-Marín J, Gálvez A, del Amor FM, Albacete A, Fernández JA, Egea-Gilabert C, Pérez-Alfocea F (2017) Selecting vegetative/generative/dwarfing rootstocks for improving fruit yield and quality in water stressed sweet peppers. Sci Hortic 214:9–17

López-Serrano L, Canet-Sanchis G, Selak GV, Penella C, San Bautista A et al (2020) Physiological characterization of a pepper hybrid rootstock designed to cope with salinity stress. Plant Physiol Biochem 148:207–219. https://doi.org/10.1016/j.plaphy.2020.01.016

Madugundu R, Al-Gaadi KA, Tola E, Patil VC, Sigrimis N (2023) The impact of salinity and nutrient regimes on the agro-morphological traits and water use efficiency of tomato under hydroponic conditions. Appl Sci 13:9564

Magán JJ, Gallardo M, Thompson RB, Lorenzo P (2008) Effects of salinity on fruit yield and quality of tomato grown in soil-less culture in greenhouses in mediterranean climatic conditions. Agric Water Manag 95:1041–1055

Mahajan S, Pandey GK, Tuteja N (2008) Calcium-and salt-stress signaling in plants: Shedding light on SOS pathway. Arch Biochem Bioph 471:146–158

Marschner H (2012) Mineral nutrition of higher plants, 3rd edn. Academic Press

Meza SLR, Egea I, Massaretto IL, Morales B, Purgatto E, Egea-Fernández JM, Bolarin MC, Flores FB (2020) Traditional tomato varieties improve fruit quality without affecting fruit yield under moderate salt stress. Front Plant Sci 11:1717

Miao C, Zhang Y, Cui J, Zhang H, Wang H, Jin H, Lu P, He L, Zhou Q, Yu J et al (2024) An enhanced interaction of graft and exogenous Sa on photosynthesis, phytohormone, and transcriptome analysis in tomato under salinity stress. Int J Mol Sci 25:10799. https://doi.org/10.3390/ijms251910799

Moles TM, de Brito Francisco R, Mariotti L, Pompeiano A, Lupini A, Incrocci L, Carmassi G, Scartazza A, Pistelli L, Guglielminetti L et al (2019) Salinity in autumn-winter season and fruit quality of tomato landraces. Front Plant Sci 10:1078

Morton MJ, Awlia M, Al-Tamimi N, Saade S, Pailles Y, Negrão S, Tester M (2019) Salt stress under the scalpel-dissecting the genetics of salt tolerance. Plant J 97:148–163

Muhammad M, Waheed A, Wahab A, Majeed M, Nazim M, Liu YH, Li L, Li WJ (2024) Soil salinity and drought tolerance: an evaluation of plant growth, productivity, microbial diversity, and amelioration strategies. Plant Stress 11:100319. https://doi.org/10.1016/j.stress.2023.100319

Mukhopadhyay R, Sarkar B, Jat HS, Sharma PC, Bolan NS (2021) Soil salinity under climate change: challenges for sustainable agriculture and food security. J Environ Manag 280:111736

Munns R (2011) Plant adaptations to salt and water stress: differences and commonalities. Adv Bot Res 57:1–32. https://doi.org/10.1016/B978-0-12-387692-8.00001-1

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Munns R, Tester M, Plett DC, Colmer TD, Tyerman SD (2016) HKT transporters and salt tolerance. In: Shabala S, Cuin T (eds) Plant salt tolerance: methods and protocols. Humana Press, pp 163–176

Naik SATS, Hongal S, Harshavardhan M, Chandan K, Kumar AJS, Ashok Kyriacou MC, Rouphael Y, Kumar P (2021) Productive characteristics and fruit quality traits of cherry tomato hybrids as modulated by grafting on different Solanum spp. rootstocks under Ralstonia solanacearum infested greenhouse soil. Agronomy 11:1311

Nasri N, Maatallah S, Kaddour R, Lachaal M (2016) Effect of salinity on Arabidopsis thaliana seed germination and acid phosphatase activity. Arch Biol Sci 68:17–23. https://doi.org/10.2298/ABS150620003N

Neto ADA, Prisco JT, Gomes-Filho E (2009) Changes in soluble amino-N, soluble proteins and free amino acids in leaves and roots of salt-stressed maize genotypes. J Plant Interact 4:137–144

Niu M, Sun S, Nawaz MA, Sun J, Cao H et al (2019) Grafting cucumber onto pumpkin induced early stomatal closure by increasing ABA sensitivity under salinity conditions. Front Plant Sci 10:1290. https://doi.org/10.3389/fpls.2019.01290

Ola HAE, Reham EF, Eisa SS, Habib SA (2012) Morpho-anatomical changes in salt stressed kallar grass (Leptochloa fusca L. Kunth). Res J Agric Biol Sci 8:158–166

Olias R, Eljakaoui Z, Li JUN, De Morales PA, Marin-Manzano MC, Pardo JM, Belver A (2009) The plasma membrane Na^+/H^+ antiporter SOS1 is essential for salt tolerance in tomato and affects the partitioning of Na^+ between plant organs. Plant Cell Environ 32(7):904–916

Öztekin G, Tüzel Y, Gül A, Tüzel I (2006) Effects of grafting in saline conditions. Proceedings of the XXVII International Horticultural Congress-IHC2006: International Symposium on Advances in Environmental Control, Automation 761, Seoul, Republic of Korea, 13–19 August 2006, pp 349–355

Pandey P, Tripathi A, Dwivedi S, Lal K, Jhang T (2023) Deciphering the mechanisms, hormonal signaling, and potential applications of endophytic microbes to mediate stress tolerance in medicinal plants. Front Plant Sci 14:1250020

Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants: a review. Ecotoxicol Environ Saf 60(3):324–349

Parthasarathi T, Ephrath JE, Lazarovitch N (2021) Grafting of tomato (Solanum lycopersicum L.) onto potato (Solanum tuberosum L.) to improve salinity tolerance. Sci Hortic 282:110050. https://doi.org/10.1016/j.scienta.2021.110050

Penella C, Landi M, Guidi L, Nebauer SG, Pellegrini E, San Bautista A, Remorini D, Nali C, López-Galarza S, Calatayud A (2016) Salt-tolerant rootstock increases yield of pepper under salinity through maintenance of photosynthetic performance and sinks strength. J Plant Physiol 193:1–11

Peng Y, Cao H, Peng Z, Zhou L, Sohail H, Cui L, Yang L, Huang Y, Bie Z (2023) Transcriptomic and functional characterization reveals CsHAK5; 3 as a key player in K^+ homeostasis in grafted cucumbers under saline conditions. Plant Sci 326:111509. https://doi.org/10.1016/j.plantsci.2022.111509

Prassinos C, Ko JH, Lang G, Iezzoni AF, Han KH (2009) Rootstock-induced dwarfing in cherries is caused by differential cessation of terminal meristem growth and is triggered by rootstock-specific gene regulation. Tree Physiol 29(7):927–936

Putri YE, Hasanudin H, Rustikawati R (2024) Growth and yield responses of hot pepper (Capsicum annuum L) to salinity stress. Proceedings of the International Agriculture Meeting (IAM 2023), Advances in Biological Sciences Research, vol 42

Qadir M, Quillérou E, Nangia V, Murtaza G, Singh M, Thomas RJ, Noble AD (2014) Economics of salt-induced land degradation and restoration. Nat Resour Forum 38(4):282–295

Qiu QS, Guo Y, Dietrich MA, Schumaker KS, Zhu JK (2002) Regulation of SOS1, a plasma membrane Na^+/H^+ exchanger in Arabidopsis thaliana, by SOS2 and SOS3. Proc Natl Acad Sci U S A 99:8436–8441

Quintero FJ, Martinez-Atienza J, Villalta I, Jiang X, Kim WY, Ali Z, Pardo JM (2011) Activation of the plasma membrane Na/H antiporter Salt-Overly-Sensitive 1 (SOS1) by phosphorylation of an auto-inhibitory C-terminal domain. Proc Natl Acad Sci U S A 108(6):2611–2616

Rahdari P, Tavakoli S, Hosseini SM (2012) Studying of salinity stress effect on germination, proline, sugar, protein, lipid and chlorophyll content in purslane (Portulaca oleracea L.) leaves. J Stress Physiol Biochem 8(1):182–193

Rasool A, Mansoor S, Bhat KM, Hassan GI, Baba TR, Alyemeni MN, Alsahli AA, El-Serehy HA, Paray BA, Ahmad P (2020) Mechanisms underlying graft union formation and rootstock scion interaction in horticultural plants. Front Plant Sci 11:590847. https://doi.org/10.3389/fpls.2020.590847

Rodríguez-Ortega WM, Martínez V, Nieves M, Simón I, Lidón V, Fernandez-Zapata JC, Martinez-Nicolas JJ, Cámara-Zapata JM, García-Sánchez F (2019) Agricultural and physiological responses of tomato plants grown in different soilless culture systems with saline water under greenhouse conditions. Sci Rep 9:1–13

Ropokis A, Ntatsi G, Kittas C, Katsoulas N, Savvas D (2019) Effects of temperature and grafting on yield, nutrient uptake, and water use efficiency of a hydroponic sweet pepper crop. Agronomy 9:110

Rosca M, Mihalache G, Stoleru V (2023) Tomato responses to salinity stress: from morphological traits to genetic changes. Front Plant Sci 14:341

Rouphael Y, Schwarz D, Krumbein A, Colla G (2010) Impact of grafting on product quality of fruit vegetables. Sci Hortic 127:172–179

Rouphael Y, Petropoulos SA, Cardarelli M, Colla G (2018) Salinity as eustressor for enhancing quality of vegetables. Sci Hortic 234:361–369

Roychoudhury A, Paul S, Basu S (2013) Cross-talk between abscisic acid-dependent and abscisic acid-independent pathways during abiotic stress. Plant Cell Rep 32:985–1006

Ruto E, Gould I, Bosworth G, Wright I (2018) The state, causes and impact of soil salinization: a global overview. SALFAR work package, vol 3

Sabovljevic M, Sabovljevic A (2007) Contribution to the coastal bryophytes of the Northern Mediterranean: are there halophytes among bryophytes? Phytol Balc 13:131–135

Sadak MS, Abdelhamid MT, Schmidhalter U (2015) Efecto de la aplicaci'on foliar de amino'acidos sobre el rendimiento y par'ametros fisiol'ogicos en plantas de haba irrigadas con agua de mar. Acta Biol Colomb 20:141–152. https://doi.org/10.15446/ABC.V20N1.42865

Samarah NH, Bany Hani MMI, Makhadmeh IM (2021) Effect of magnetic treatment of water or seeds on germination and productivity of tomato plants under salinity stress. Horticulturae 7:220. https://doi.org/10.3390/horticulturae7080220

Sanchez-Barrena MJ, Fujii H, Angulo I, Martınez-Ripoll M, Zhu JK, Albert A (2007) The structure of the C-terminal domain of the protein kinase AtSOS2bound to the calcium sensor AtSOS3. Mol Cell 26:427–435

Sánchez-Torres P, Raigón MD, Gammoudi N, Gisbert C (2016) Effects of grafting combinations on the nutritional composition of pepper fruit. Fruits 71:249–256

Sanwal SK, Mann A, Kumar A, Kesh H, Kaur G, Rai AK, Kumar R, Sharma PC, Kumar A, Bahadur A, Singh B, Kumar P (2022) Salt tolerant eggplant rootstocks modulate sodium partitioning in tomato scion and improve performance under saline conditions. Agriculture 12(2):183. https://doi.org/10.3390/agriculture12020183

Sarwar M, Amjad M, Ayyub CM (2017) Alleviation of salt stress in cucumber (Cucumis sativus L.) through seed priming with triacontanol. Int J Agric Biol 19:771–778

Satti SM, Lopez M (1994) Salinity induced changes in vegetative and reproductive growth in tomato. Commun Soil Sci Plant Anal 25:2807–2823. https://doi.org/10.1080/00103629409369057

Semiz GD, Suarez DL (2019) Impact of grafting, salinity and irrigation water composition on eggplant fruit yield and ion relations. Sci Rep 9:19373. https://doi.org/10.1038/s41598-019-55841-0

Serrano LL, Penella C, San Bautista A, Galarza SL, Chover AC (2017) Physiological changes of pepper accessions in response to salinity and water stress. Span J Agric Res 15:15

Sevengor S, Yasar F, Kusvuran S, Ellialtioglu S (2011) The effect of salt stress on growth, chlorophyll content, lipid peroxidation and antioxidative enzymes of pumpkin seedling. Afr J Agric Res 6(21):4920–4924

Sewelam N, Oshima Y, Mitsuda N, Ohme-Takagi M (2014) A step towards understanding plant responses to multiple environmental stresses: a genome-wide study. Plant Cell Environ 37(9):2024–2035. https://doi.org/10.1111/pce.12274

Shannon MC, Grieve CM (1999) Tolerance of vegetable crops to soil salinity. Sci Hortic 78:5–38

Shaterian J, Georges F, Hussain A, Wateret D, Jung H, Tanin K (2005) Root to shoot communication and abscisic acid in calreticulin (CR) gene expression and salt stress tolerance in grafted diploid potato (Solanum sp.) clones. Environ Exp Bot 53:323–332

Shi H, Quintero FJ, Pardo JM, Zhu JK (2002) The putative plasma membrane Na^+/H^+ antiporter SOS1 controls long-distance Na^+ transport in plants. Plant Cell 14(2):465–477

Sibomana IC, Aguyoh JN, Opiyo AM (2013) Water stress affects growth and yield of container grown tomato (Lycopersicon esculentum Mill) plants. Glob J Bio Sci Biotechnol 2(4):461–466

Sidorova T, Miroshnichenko D, Kirov I, Pushin A, Dolgov S (2021) Effect of grafting on viral resistance of non-transgenic plum scion combined with transgenic PPV-Resistant rootstock. Front Plant Sci 12:621954. https://doi.org/10.3389/fpls.2021.621954

Singh H, Kumar P, Kumar A, Kyriacou MC, Colla G, Rouphael Y (2020) Grafting tomato as a tool to improve salt tolerance. Agronomy 10:263

Steinhorst L, Kudla J (2019) How plants perceive salt. Nature 572:318–320

Talhouni M, Sönmez K, Kiran S, Beyaz R, Yildiz M et al (2019) Comparison of salinity effects on grafted and non-grafted eggplants in terms of ion accumulation, MDA content and antioxidative enzyme activities. Adv Hortic Sci 33:87–95. https://doi.org/10.13128/ahs-23794

Thomas HR, Frank MH (2019) Connecting the pieces: uncovering the molecular basis for long-distance communication through plant grafting. New Phytol 223:582–589. https://doi.org/10.1111/nph.15772

Tola E, Al-Gaadi KA, Madugundu R, Zeyada AM, Edrris MK, Edrees HF, Mahjoop O (2024) Yield response of grafted and self-rooted tomato plants grown hydroponically under varying levels of water salinity. Agronomy 14:1240. https://doi.org/10.3390/agronomy14061240

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. Front Plant Sci 11:621999. https://doi.org/10.3389/fpls.2020.621999

Tsutsui H, Notaguchi M (2017) The use of grafting to study systemic signaling in plants. Plant Cell Physiol 58:1291–1301. https://doi.org/10.1093/pcp/pcx098

Ulas A (2022) Crossbreeding rootstocks improve nitrogen efficiency of grafted watermelon by inducing leaf physiological and root morphological responses. Horticulturae 8:879

Ulas F (2021a) Response of different rootstocks on vegetative growth, fruit and seed yield of eggplant (Solanum melongena L.). Genetika 53(2):593–608

Ulas F (2021b) Effects of grafting on growth, root morphology and leaf physiology of pepino (Solanum muricatum Ait.) as affected by salt stress under hydroponic conditions. Int J Agric Environ Food Sci 5(2):203–212

Ulas A, Doganci E, Ulas F, Yetisir H (2019a) Root-growth characteristics contributing to genotypic variation in nitrogen efficiency of bottle gourd and rootstock potential for watermelon. Plants 8:77

Ulas F, Aydın A, Ulas A, Yetisir H (2019b) Grafting for sustainable growth performance of melon (Cucumis melo) under salt stressed hydroponic condition. Eur J Sustain Dev 8:201–210

Ulas F, Fricke A, Stützel H (2019c) Leaf physiological and root morphological parameters of grafted tomato plants drought stress conditions. Fresenius Environ Bull 28(4A):3423–3434

Ulas A, Aydin A, Ulas F, Yetisir H, Miano TF (2020a) Cucurbita rootstocks improve salt tolerance of melon scions by inducing physiological, biochemical and nutritional responses. Horticulturae 6:1–13. https://doi.org/10.3390/HORTICULTURAE6040066

Ulas F, Yetisir H, Ulas A (2020b) Effects of grafting on fruit yield and leaf nutrient contents of pepper (Capsicum annuum L.) inbred lines. Genetika 52(3):1041–1053

Ulas F, Aydin A, Ulas A, Yetisir H (2021a) The efficacy of grafting on alkali stressed watermelon cultivars under hydroponic conditions. Gesunde Pflanz 73:345–357

Ulas F, Erdogdu S, Yetisir H, Ulas A (2021b) Investigation on morphology and physiology of Nitrogen efficiency in different pepper (Capsicum annuum L.) inbred lines. Genetika 53:3

Ulas F, Yetisir H, Ulas A (2021c) Root-growth characteristics contributing to nitrogen efficiency of reciprocally grafted potatoes (Solanum tuberosum L.) under Hydroponic conditions. Gesunde Pflanz: 1–9

Ulas F, Hama Ameen HHHH, Ulas A (2024) Salt stress and its implications in vegetable crops with special reference to the Cucurbitaceae family. Ann Arid Zone 63(4):117–129

Ulas F, Kılıç FN, Ulas A (2025) Alleviate the influence of drought stress by using grafting technology in vegetable crops: a review. J Crop Health

Vidoy-Mercado I, Narváez I, Palomo-Ríos E, Litz RE, Barceló-Muñoz A, Pliego-Alfaro F (2021) Reinvigoration/rejuvenation induced through micrografting of tree species: signaling through graft union. Plants 10:1197. https://doi.org/10.3390/plants10061197

de Vos A, Bruning B, van Straten G, Oosterbaan R, Rozema J, van Bodegom P (2016) Crop salt tolerance under controlled field conditions in the Netherlands, based on trials conducted at Salt Farm Texel. Salt Farm Texel

Wang C-F, Han G-L, Yang Z-R, Li Y-X, Wang B-S (2022) Plant salinity sensors: current understanding and future directions. Front Plant Sci 13:859224

Wang J, Jiang L, Wu R (2017) Plant grafting: how genetic exchange promotes vascular reconnection. New Phytol 214:56–65. https://doi.org/10.1111/nph.14383

Wang M, Liu C, Li S, Zhu D, Zhao Q, Yu J (2013) Improved nutritive quality and salt resistance in transgenic maize by simultaneously overexpression of a natural lysine-rich protein gene, SBgLR, and an ERF transcription factor gene, TSRF1. Int J Mol Sci 14:9459. https://doi.org/10.3390/IJMS14059459

Wang X, Lan Z, Tian L, Li J, Yang G et al (2021) Change of physiological properties and ion distribution by synergistic effect of Ca_2^+ and grafting under salt stress on cucumber seedlings. Agronomy 11:848. https://doi.org/10.3390/agronomy11050848

Wang Y, Zhou J, Wen W, Sun J, Shu S, Guo S (2023) Transcriptome and proteome analysis identifies salt stress response genes in bottle gourd rootstock-grafted watermelon seedlings. Agronomy 13(3):618. https://doi.org/10.3390/agronomy13030618

Wei GP, Yang LF, Zhu YL, Chen G (2009) Changes in oxidative damage, antioxidant enzyme activities and polyamine contents in leaves of grafted and non-grafted eggplant seedlings under stress by excess of calcium nitrate. Sci Hortic 120:443–451

Wu X, Yuan D, Bian X, Huo R, Lü G, Gong B, Li J, Liu S, Gao H (2023) Transcriptome analysis showed that tomato-rootstock enhanced salt tolerance of grafted seedlings was accompanied by multiple metabolic processes and gene differences. Front Plant Sci 14:1167145. https://doi.org/10.3389/fpls.2023.1167145

Xie J, Lei B, Niu M, Huang Y, Kong Q et al (2015) High throughput sequencing of small RNAs in the two Cucurbita germplasm with different sodium accumulation patterns identifies novel microRNAs involved in salt stress response. PLoS ONE 10:e127412

Xie Y, Tan H, Sun G, Li H, Liang D, Xia H, Wang X, Liao M, Deng H, Wang J, Tang Y (2020) Grafting alleviates cadmium toxicity and reduces its absorption by tomato. J Soil Sci Plant Nutr 20:2222–2229

Yan Lu HX, Tong S (2018) Effects of arbuscular mycorrhizal fungi on photosynthesis and chlorophyll fluorescence of maize seedlings under salt stress. Emir J Food Agric 30:199–204. https://doi.org/10.9755/ejfa.2018.v30.i3.1642

Yang Y, Guo Y (2018a) Elucidating the molecular mechanisms mediating plant salt-stress responses. New Phytol 217(2):523–539. https://doi.org/10.1111/nph.14920

Yang Y, Guo Y (2018b) Unraveling salt stress signaling in plants. J Integr Plant Biol 60(9):796–804. https://doi.org/10.1111/jipb.12689

Yang J, Miao W, Chen J (2021) Roles of jasmonates and brassinosteroids in rice responses to high temperature stress—A review. Crop J 9:977–985. https://doi.org/10.1016/j.cj.2021.02.007

Yildirim E, Turan M, Guvenc I (2008) Effect of foliar salicylic acid applications on growth, chlorophyll, and mineral content of cucumber grown under salt stress. J Plant Nutr 31(3):593–612

Yu J, Chen S, Zhao X, Wang Q, Yang T, Diaz C et al (2011) Physiological and proteomic analysis of salinity tolerance in Puccinelli atenuiflora. J Proteome Res 10:3852–3870. https://doi.org/10.1021/pr101102p

Yuan F, Leng B, Wang B (2016) Progress in studying salt secretion from the salt glands in recretohalophytes: how do plants secrete salt? Front Plant Sci 7:977. https://doi.org/10.3389/fpls.2016.00977

Zhang P, Senge M, Dai Y (2016) Effects of salinity stress on growth, yield, fruit quality and water use efficiency of tomato under hydroponics system. Rev Agric Sci 4:46–55. https://doi.org/10.7831/ras.4.46

Zhang Y, Lai J, Sun S, Li Y, Liu Y, Liang L et al (2008) Comparison analysis of transcripts from the halophyte Thellungiella halophila. J Integr Plant Biol 50:1327–1335. https://doi.org/10.1111/j.1744-7909.2008.00740.x

Zhao C, Zhang H, Song C, Zhu J-K, Shabala S (2020) Mechanisms of plant responses and adaptation to soil salinity. Innovation 1:100017

Zhao FY, Zhang DY, Zhao YJ, Wang WS, Zhang WK, Chen SY (2016a) CRISPR/Cas9-mediated mutagenesis of NHX1 improves salt tolerance in soybean. Plant Cell Tissue Organ Cult 125(3):499–510

Zhao N, Wang S, Ma X (2016b) Extracellular ATP mediates cellular K+/Na+ homeostasis in two contrasting poplar species under NaCl stress. Trees 30:825–837

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6(2):66–71

Zhu J, Bie Z, Huang Y, Han X (2008) Effect of grafting on the growth and ion concentrations of cucumber seedlings under NaCl stress. J Soil Sci Plant Nutr 54:895–902. https://doi.org/10.1111/j.1747-0765.2008.00306.x

Zorb C, Geilfus CM, Dietz KJ (2019) Salinity and crop yield. Plant Biol 21:31–38. https://doi.org/10.1111/plb.12884

Zushi K, Higashijima M (2022) Correlation network analysis identified the key interactions of texture profiles with the sensory, physical, and organoleptic properties of cherry tomato cultivars grown under salt stress. Sci Hortic 293:110754

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.