E-ISSN: 2618-0618
P-ISSN: 2618-060X
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www.agronomyjournals.com
2025; SP-8(1): 390-397
Received: 09-11-2024
Accepted: 16-12-2024

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Grafting as a sustainable strategy in vegetable crops for enhancing plant resilience to abiotic stresses

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DOI: https://doi.org/10.33545/2618060X.2025.v8.i1Sf.2451

Abstract

In recent era, vegetable grafting is a boon for mitigating the abiotic `stress for getting better yield and quality of vegetable crops. Abiotic stresses, including drought, salinity, extreme temperatures, and nutrient deficiencies, pose significant challenges to vegetable crop production worldwide. Grafting appears to be potentially useful for increasing vegetable crop resistance to toxic elements and preventing contaminants and saline elements from entering the human food supply. Grafted plants also help in mitigating salt stress in saline conditions and plants give better yield in stress conditions. This report provides an overview of the prospects and limitations of grafting as a method of reducing the negative effects of heavy metals, excessive nutrient availability, nutrient deficiency, and alkalinity stress on vegetable crop performance, taking agronomical, physiological, and biochemical factors into account. By enhancing stress tolerance, grafting not only ensures stable yields but also reduces the reliance on chemical inputs, aligning with environmentally friendly and resource-efficient farming practices.

Keywords: Grafting, abiotic stress, resilient, rootstock

Introduction

In the field of horticulture, the cultivation of vegetables has attained significant prominence owing to the substantial economic value and health advantages associated with their products. Vegetables are indispensable components of the human diet, supplying vital nutrients, vitamins, antioxidants, amino acids, and fatty acids (Galili *et al*., 2002) [2]. Nonetheless, vegetable crops exhibit pronounced sensitivity to environmental stressors, including water scarcity, elevated salinity or alkalinity, extreme temperature fluctuations, and the presence of toxic elements. In recent years, considerable efforts have been directed towards mitigating heavy metal uptake and accumulation within the aerial parts of plants. The development of crop varieties capable of restricting the absorption and translocation of heavy metals constitutes an integral aspect of environmentally sustainable practices aimed at yielding clean agricultural products, even in contaminated soils (Alybayeva *et al*., 2014) [3]. However, the breeding process for such varieties is protracted and laborious. Relative to other horticultural crops, vegetable crops display heightened susceptibility to climate change, with salt stress particularly impeding their growth and development at various phenological stages (Giordano *et al*., 2021) [26]. Salinity-induced oxidative stress in vegetables can detrimentally affect both their quality and yield, resulting in a spectrum of biochemical and physiological alterations within the plants (Kashyap *et al*., 2020, 2021) [33, 34]. Grafting is a horticultural technique whereby a segment of one plant (referred to as the scion) is affixed to another plant segment (identified as the rootstock) to engender a novel plant organism. This process facilitates the connection of plant parts, culminating in a genetically composite entity that executes the functions of a singular plant. The rootstocks employed for a designated scion are generally closely related species or wild selections (predominantly within genera) of the scion crop. Instances of natural grafts occurring between distinct plant families have also been documented (Warschefsky *et al*., 2016) [77]. Conventionally, the rootstock is characterized by superior plant vigor and resilience to both biotic (pathogenic organisms) and abiotic (environmental) stressors, while the scion possesses unique qualitative and quantitative horticultural attributes.

Initially, grafting was predominantly applied to fruiting vegetables to bolster resistance against soilborne pathogens (Crino *et al*., 2007) [17]; however, its application has considerably broadened in recent years. Grafting is increasingly utilized to mitigate the detrimental impacts of both biotic and abiotic stressors, thereby expanding its functional scope. It has emerged as a pivotal technique for enhancing plant vigor, augmenting yields, and improving tolerance to stress conditions such as salinity, alkalinity (Colla *et al*., 2010) [13], heavy metal contamination (Kumar *et al*., 2015) [8], extreme temperature variations (Schwarz *et al*., 2010) [60], water scarcity (Rouphael *et al*., 2008) [59], and for enhancing fruit quality.

The objective of this paper is to systematically review contemporary research pertaining to the responses of grafted plants to adverse chemical soil conditions, encompassing nutrient deficiencies, toxic metal concentrations, water deficits and surpluses, as well as extreme pH levels. Additionally, it will scrutinize the agronomic, physiological, and biochemical mechanisms inherent in grafted plants that facilitate tolerance to these unfavorable soil conditions. Ultimately, the review will propose prospective research avenues aimed at further augmenting the role of grafting in vegetable production in the face of abiotic stresses.

Abiotic Stress Tolerance

Vegetable crops are sensitive to a variety of abiotic stresses such as drought, flood, salinity, and low and high temperatures, all of which have a significant impact on plant physiological and morphological growth, resulting in reduced yield. Grafting aids the vegetable crop in mitigating abiotic stresses and provides healthy mechanisms for crop protection.

Heavy metal tolerance

Recent empirical investigations have elucidated the capacity of certain vegetable rootstocks to mitigate the absorption of heavy metals by plants (Savvas *et al.*, 2010; Lux *et al*., 2011) [66, 41]. For instance, vegetables such as tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.), and eggplant (*S. melongena* L.) manifest minimal rates of heavy metal translocation to their respective fruits (Angelova *et al.*, 2009) [4]. The accumulation of cadmium (Cd) within the aerial components of grafted plants exhibits a significant divergence from that within their root systems. Grafting is particularly effective in attenuating the transfer of Cd from the root to the shoot, especially regarding the foliar structures. For example, the concentration of Cd in the leaves of self-grafted specimens was found to be 10% lower than that of non-grafted counterparts, although no notable difference in Cd concentration was detected in the fruits (Kumar *et al*., 2015) [8]. Corresponding findings from unpublished investigations (Ntatsi and Savvas) indicated that grafting cucumber (*Cucumis sativus* L.) can substantially diminish the translocation of nickel (Ni) and lead (Pb) to the aerial parts of the plant. Moreover, research conducted by Rouphael *et al.* (2008) [56] revealed that grafting cucumber onto the commercial rootstock ‘Shintoza’ restricted copper (Cu) uptake and alleviated the adverse impacts of excess Cu on both plant biomass and yield. Nonetheless, the precise mechanisms through which particular rootstocks regulate the uptake and translocation of heavy metals to the shoots remain largely ambiguous. Grafting onto *Solanum torvum* has been shown to reduce Cd accumulation in leaves and increase antioxidant enzyme activity in both eggplant and tomato, compared to non-grafted plants (Kumar *et al.*, 2015) [8]. rafting has been shown to mitigate cadmium (Cd) toxicity through the use of appropriate rootstocks. For example, utilizing wild eggplant rootstocks has been found to enhance tomato growth, increase fruit weight and quality, while simultaneously decreasing Cd concentrations in the aerial parts and fruits of the plant. *Solanum torvum* has been identified as an effective rootstock for improving the quality of tomato fruits and lowering Cd levels under stress conditions (Xie *et al*., 2020) [78]. In the case of pepper plants, the Cd concentrations in immature fruits of grafted specimens were 42% lower compared to self-rooted plants, accompanied by an increase in fruit quantity and overall yield (Morikawa, 2017) [46]. Research on cucurbit vegetables demonstrated that grafting watermelon onto bottle gourd or pumpkin rootstocks improved vanadium (V) stress tolerance by reducing V concentrations in leaf tissues, enhancing chlorophyll content, and upregulating genes associated with antioxidant activity (Nawaz *et al*., 2018) [48]. Grafting represents a highly effective approach for managing heavy metal tolerance in vegetable crops, as it limits the uptake and translocation of toxic metals, thereby safeguarding plant health and promoting yield and quality. These advantages can be attributed in part to the rootstock’s capacity to modulate metal translocation and influence gene expression, thereby enhancing stress tolerance (Yamaguchi *et al.,* 2010) [79].

Salt stress tolerance

Both the rootstock and the scion represent critical elements of the grafting procedure, which enhances the resilience of plants to saline conditions (Etehadnia *et al*., 2008) [22]. This enhanced tolerance is linked to a more vigorous root system that excels in water and nutrient absorption, effectively excludes salt ions, and fosters increased rates of photosynthesis. Grafted plants exhibit greater durability compared to their non-grafted counterparts, as they demonstrate superior osmotic adjustment, hormonal regulation, and oxidative defense mechanisms. While carrots, radishes, peas, onions, and okra are highly sensitive to salinity, crops such as cabbage, cauliflower, broccoli, potatoes, pumpkins, eggplants, and chillies show moderate susceptibility. Conversely, tomatoes, beets, spinach, and summer squash display a moderate level of salt tolerance. Notably, asparagus exhibits a significantly high tolerance to salinity (Shams & Khadivi, 2023) [63].

Salinity adversely impacts plant growth and overall development; for instance, in tomato plants, elevated salinity levels result in diminished plant height attributed to shortened internodes and inhibited leaflet growth (Najla *et al*., 2009) [47]. In contrast, grafting enhances the performance of plants under salt stress. A specific example includes the grafting of pepper cultivar "Adige" onto the salt-tolerant rootstock "A 25," which resulted in a 75% increase in yield and a 31% reduction in fruit damage (Penella *et al*., 2016) [53]. Grafted plants typically sustain improved leaf water status. Grafting tomato ("Ikram") onto potato rootstock ("Charlotte") demonstrated potential for salinity tolerance levels reaching 5.0 dS/m, resulting in an enhancement of water productivity by 56.8% (Parthasarathi *et al*., 2021) [52]. This improved salt tolerance is primarily attributed to hormonal regulation—specifically involving ABA, cytokinins, and polyamines—as well as the capacity to regulate Na+ and Cl- accumulation, as evidenced in grafted cucumber plants utilizing pumpkin rootstock, which preserved a higher K+/Na+ ratio (Rouphael *et al*., 2017; Usanmaz & Abak, 2019) [61, 75]. Furthermore, younger leaves exhibited a greater retention of K+ ions, indicating that rootstocks facilitate the exclusion of Na+ while retaining K+ (Sanwal *et al*., 2022) [65].

Additional investigations reinforce the notion that grafting assists plants in overcoming salt stress by enhancing relative water content, elevating antioxidant enzyme activity, and accumulating proline to alleviate oxidative stress and dehydration (Talhouni *et al.*, 2019) [72]. Further studies have illustrated that Cucurbita rootstocks (Nun9075 and Kardosa) significantly improved growth and biomass in melons subjected to salt stress by fostering physiological responses (increased leaf area and enhanced photosynthesis), biochemical responses (reduced leaf proline and MDA levels), and nutritional responses (lower leaf Na+ levels and ion leakage, alongside increased K+ and Ca++ content) (Ulas *et al.*, 2020) [74]. Overall, grafting emerges as a highly effective strategy for alleviating the detrimental impacts of salinity on plant growth, yielding considerable improvements in both yield and stress resilience across a variety of crop species.

Waterlogging or flooding stress

The advancement and efficiency of crops that are susceptible to flooding are significantly compromised by the occurrence of waterlogging or inundation, primarily due to its detrimental effect of inducing hypoxia as a result of sluggish gas diffusion in aqueous environments, alongside the consumption of oxygen by both plant root systems and microbial populations. One approach to mitigate this predicament involves the grafting of sensitive plant species onto rootstocks that exhibit flood tolerance, or alternatively, the cultivation of crops that possess inherent flood resilience (Bahadur *et al.*, 2015, 2016; Bhatt *et al.*, 2015) [8, 6]. The phenomenon of waterlogging tolerance in grafted tomato and watermelon cultivars has been correlated with the enhanced formation of adventitious roots and the development of aerenchyma tissue (Bahadur *et al.*, 2015) [8]. In numerous vegetable species, the practice of grafting onto appropriate rootstocks is regarded as an effective strategy to alleviate the adverse consequences associated with flooding. For example, research has demonstrated that tomato plants can endure waterlogging for a duration of 4 to 6 days when grafted onto aubergine rootstock (Bahadur *et al.*, 2015, 2016; Bhatt *et al.*, 2015) [8, 6, 10].

Waterlogging frequently results in a reduction of chlorophyll content in cucumbers; however, grafting onto squash rootstocks has been found to prevent this decline (Kato *et al.*, 2001) [35]. In addition, the grafting of cucumber onto "Ferro" and "Cobalt" (*Cucurbita maxima* × *Cucurbita moschata*) significantly enhanced tolerance to severe flooding (lasting 15 days) by maintaining higher leaf water potential, optimizing potassium absorption, and elevating photosynthetic rates (Haghighi & Khosravi, 2022) [29]. A study conducted by Peng *et al.* (2020) [54] elucidated that grafting improved the resistance of bitter melon to waterlogging by elevating the activities of anaerobic respiration enzymes (such as pyruvate dehydrogenase, alcohol dehydrogenase, and lactate dehydrogenase) in both taproots and adventitious roots, as well as by expanding the aerenchyma in adventitious roots. Grafted watermelon cultivar "Crimson Tide," when grafted onto Lagenaria siceraria SKP (Landrace), exhibited diminished chlorophyll loss in comparison to non-grafted watermelons subjected to waterlogging stress (Yetisir *et al.*, 2006) [80].

The grafted tomato hybrid Arka Rakshak, when grafted onto aubergine rootstocks (IC354557 and IC-111056) and subjected to waterlogging for a period of 72 to 96 hours, demonstrated a lesser decrease in chlorophyll fluorescence yield (Fv/Fm) and chlorophyll concentration index (CCI) as compared to non-grafted plants, which experienced a reduction of 39.6 to 41% in Fv/Fm and a decrease of 41 to 100% in CCI following 96 hours of exposure, as reported by Bahadur *et al.* (2015) [8]. Furthermore, grafted tomato plants that were exposed to waterlogging for up to 96 hours exhibited negligible impacts on physiological, biochemical, and yield-related parameters including CCI, chlorophyll a, chlorophyll b, total chlorophyll content, chlorophyll fluorescence yield (Fv/Fm), catalase (CAT), superoxide dismutase (SOD), proline levels, and fruit yields (Bahadur *et al.*, 2016) [6]. Tomato plants grafted onto aubergine rootstock (Arka Neelkanth) were also able to recover from 6 days of submergence stress during their reproductive phase, as evidenced by enhanced gas exchange rates, leaf water potential, and chlorophyll fluorescence (Bhatt *et al.*, 2015) [10]. Grafting has been recognized as a promising technique for augmenting waterlogging tolerance across various vegetable crops by facilitating improved physiological and biochemical responses to flooding conditions.

Water deficit

Plant water potential and turgor pressure are adversely affected by drought conditions or water scarcity, which in turn disrupts essential physiological processes. This phenomenon significantly threatens global food security, influencing both agricultural output and the quality of produce (Bahadur *et al.*, 2023) [7]. Notable consequences of drought stress include diminished fruit setting in tomatoes and chilies, fruit cracking in tomatoes and cabbages, nitrate accumulation in root crops and watermelons, alongside bitterness and deformities in cucumbers. To mitigate yield reductions and enhance water use efficiency (WUE), it is feasible to graft high-yielding vegetable cultivars onto rootstocks that alleviate the adverse effects of water stress on the aerial parts of the plant (Coskun, 2023; Padilla *et al.*, 2023) [15, 51].

Cantero-Navarro *et al.* (2016) [11] investigated the application of grafting using recombinant inbred lines (RILs) derived from the wild tomato species *Solanum pimpinellifolium*, aiming to enhance WUE in tomatoes through root-based hormonal modulations. Their findings indicated that specific rootstocks, which led to a reduction in biomass and water consumption, could enhance fruit yield and WUE by as much as 40% in comparison to self-grafted specimens. This suggests that the regulation of shoot biomass via rootstock can facilitate water conservation without compromising tomato productivity within greenhouse environments. The utilization of cherry tomatoes as a rootstock contributed to improved plant growth and yields under conditions of moderate to severe drought stress, attributable to an augmented root system, enhanced uptake of phosphorus and potassium, and a reduction in electrolyte leakage (Sadeghi *et al.*, 2023) [63].

Padilla *et al.* (2023) [51] posited that peppers subjected to severe water stress (induced by 48 hours of Polyethylene Glycols, PEG) could benefit from the application of the drought-resistant rootstock "Niber," which improved water retention and WUE by facilitating stomatal closure and increasing the synthesis of protective phytohormones such as salicylic acid (SA), jasmonic acid (JA), and abscisic acid (ABA). Moreover, drought-tolerant plants exhibited elevated activity levels of antioxidant enzymes including ascorbate, glutathione reductase (GR), and ascorbate peroxidase (APX), as well as decreased concentrations of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) (Bahadur *et al.*, 2011) [6]. To attain drought resistance, it was essential for grafted cucumbers to have their stress-responsive gene expression regulated alongside the modulation of their antioxidant enzyme activity (Shehata *et al.*, 2022) [70].

High temperature: Elevated temperatures can significantly influence vegetable cultivation, especially in hot (semi)arid regions and in lowland tropical areas during the hot-wet and hot-dry seasons. For instance, Solanaceous vegetables may be unable to thrive at temperatures exceeding 35 °C, whereas Cucurbitaceous vegetables exhibit a lesser degree of susceptibility. The adverse effects of high temperatures encompass stunted growth, diminished photosynthetic activity, increased respiration rates, a shift in nutrient allocation towards reproductive organs, osmotic and oxidative stresses, reduced absorption of water and ions, and cellular desiccation. In response to stress conditions, plants engage stress-responsive mechanisms such as osmoprotection, detoxification processes, enzyme and membrane stabilization, along with alterations in protein synthesis (e.g., heat shock proteins) (Karkute *et al.*, 2021) [32].

In a comparative analysis of non-grafted plants under 37/27°C (Day/Night) conditions, Abdelmageed and Gruda (2009) revealed that the aubergine rootstock (cv. Black Beauty) and the heat-tolerant tomato cultivar Summerset exhibited significantly enhanced chlorophyll fluorescence, increased leaf area, and elevated fresh and dry biomass, in addition to a higher pollen grain count and reduced electrolyte leakage. However, they did not observe any positive effects of grafting on yield or reproductive attributes. Moreover, high temperatures (35°C and above) promote the biosynthesis of phenolic compounds in tomato plants while mitigating oxidation. Notably, grafted tomato cultivars sustained less damage from elevated temperatures in comparison to their non-grafted counterparts. The grafting of eggplants onto tomato rootstocks results in diminished electrolyte leakage at supra-optimal temperatures, indicating reduced membrane damage and improved solute, ascorbic acid, alongside lower proline concentrations.

Low temperature

Chilling and less-than-ideal winter temperatures pose problems for vegetable growing in cold or moderate areas. Melons, capsicum, eggplant, cucumber, tomatoes, and other chill-sensitive fruits and vegetables do best at 8 to 12°C (Criddle *et al.*, 1997) [16]. Many tropical and subtropical crops might suffer from physiological anomalies that, depending on the intensity and length of the exposure, can result in cell death and total plant mortality when exposed to temperatures below this range. During the vegetative growth phase, suboptimal temperatures mainly impede the creation of new leaves and the expansion of existing leaves.

Since root systems have received much of the attention in low-temperature research, chilling-sensitive species may experience water stress as a result of reduced water intake (Ahn *et al.*, 1999) [1]. According to Ahn *et al.* (1999) [1], fig-leaf gourd (*Cucurbita ficifolia*) and bur cucumber (*Sicos angulatus*) are potential rootstocks for cucumber in suboptimal conditions. The ideal root temperature for fig-leaf gourd is approximately 15°C to 6°C lower than that of cucumber roots. According to Liang *et al.* (2023), the use of pumpkin and ridge gourd rootstocks can counteract the negative effects of low temperatures (8°C) on bitter gourds by preserving gas exchange, osmotic balance, and improved metabolism of sucrose and nitrogen.

Furthermore, by modifying physiological characteristics, mobile mRNA profiles, and transcriptomic and metabolomic alterations in both aboveground and underground tissues, pumpkin rootstock can mitigate early cold stress in cucumber seedlings (Liu *et al.*, 2022) [39]. According to Ropokis *et al.* (2019), grafting pepper (cv. Sammy) onto 'Robusto' and 'Terrano' rootstocks boosted overall fruit output by 39% and 34%, respectively, in comparison to self-grafted controls, even though low temperatures can cut pepper yields by 33-50%. Additionally, in low temperatures, grafted plants demonstrated improved water usage efficiency (WUE) and increased uptake of K, Ca, Mg, and N. According to Kaleem *et al.* (2023), rootstocks prolong the shelf life of melons and preserve post-harvest fruit quality throughout storage. In particular, after 7 days of room storage, Tianzhen No. 2 rootstock had reduced titratable acidity (0.21%), malic acid (0.84 mg/g), and total phenolic content (15.96 mg/g) without exhibiting any weight loss. In contrast, after 28 days of cold storage, Yinguang rootstock-grafted melon fruits showed lower levels of malic acid (0.97 mg/g) and total phenolic (15.31 mg/g), but greater amounts of sucrose (169.30 mg/g) and total soluble solids (15.4°).

Plant growth and yield

In various cucurbitaceous species, including cucumber, musk melon, and watermelon, the application of grafting technology has demonstrated significant benefits. In comparison to *ungrafted* specimens, the grafting of the watermelon cultivar Fantasy onto the Strongtosa rootstock (*Cucurbita maxima* × *C. moschata*) resulted in enhanced salinity tolerance as well as a reduction in the decline of shoot weight and leaf area. Similarly, Huang *et al.* (2009) [31] reported that three squash hybrids (*Cucurbita maxima* × *C. moschata*) exhibited superior fruit yields of 4.6 dS m−1 when two cultivars of musk melon were grafted onto them. Grafting has been shown to augment various yield parameters in tomatoes, including the number of fruits per truss, overall fruit production, fruit index, and individual fruit weights (Turhan *et al.*, 2011) [73]. For example, the grafting of the Moneymaker cultivar onto Radja or Pera rootstocks at a concentration of 50 mM NaCl resulted in a 40% increase in tomato fruit yield, as noted by Martinez-Rodriguez *et al.* (2008) [44]. At the same salinity level, Estan *et al.* (2005) [21] reported that grafting the Jaguar scion onto the identical rootstock led to an 80% increase in yield. Moreover, under conditions of saline stress, the aubergine cv. Suqiqie, when grafted onto the wild relative Solanum torvum, exhibited enhanced growth performance (Liu *et al.*, 2007) [39]. Comparable results were observed by Cansev and Ozgur (2010), who indicated that grafting hybrid cucumber onto the P 360 (*Cucurbita maxima* × *Cucurbita moschata*) and Arican-97 (*Cucurbita maxima* Duch.) rootstocks resulted in increases in total yield and earliness by 20-100% and 54-154%, respectively, in cv. Assos F1, and by 53-120% and 87-209%, respectively, in cv. Marathon F1. According to Crinò *et al.* (2007) [17], melon plants grafted onto Cucurbita interspecific hybrid rootstocks, especially on "RS 841," yielded fruits that were 24% heavier than those from ungrafted plants and those grafted onto Cucumis melo rootstocks. Farhadi *et al.* (2016) [23] found that the yield of hybrid cucumber was significantly diminished when utilizing various commercial Cucurbita interspecific hybrid rootstocks, with reductions of 44% on Ghalyani, 73% on 913, and 35% on 64-19 rootstocks. Chawda (2021) [12] documented considerable enhancements in the yield and growth of muskmelon and cucumber when Summerfit, an interspecific hybrid of snap melon and acidulous melon, served as the rootstock. Moreover, research conducted on grafted cucumbers in soilless substrates revealed that fruit output increased by 24% due to the grafted plants' larger stems and extended root systems (Maršić & Jakše, 2010) [43].

Fruit quality

The assessment of the quality of vegetable fruits designated for fresh consumption is predicated upon various criteria, including visual characteristics (size, shape, color, and absence of defects), firmness, texture, flavor (incorporating sugars, acids, and aromatic volatiles), and health-related constituents (such as minerals, vitamins, and carotenoids), while simultaneously minimizing the presence of undesirable substances, including heavy metals, pesticides, and nitrates. The process of grafting influences the quality of vegetable fruits by modifying their physical attributes, flavor profiles, and the concentrations of health-promoting compounds, notably vitamin C, carotenoids, and minerals (Rouphael *et al.,* 2010) [13]. Furthermore, it serves as an effective strategy for enhancing nutritional quality and bio-fortification. Specifically, aubergine grafted onto Solanum torvum, when subjected to iodine treatment, exhibited enhancements in protein, potassium, iron, and zinc levels by 22.9%, 7.2%, 20%, and 2.4%, respectively, along with a 53% increase in marketable yield (Consentino *et al.,* 2022) [14]. In addition, research conducted by Sabatino *et al.* (2021) demonstrated that grafting tomatoes onto cherry tomato rootstock and administering selenium (at concentrations of 2.0 and 4.0 μmol Se $L{-1}$) resulted in improvements in the firmness of the fruit, as well as increases in soluble solids, polyphenols, total carotenoids, ascorbic acid, lycopene, and selenium content. A comparative analysis of grafting utilizing KOTOBI as the rootstock revealed a positive impact on shelf-life extension, achieving an enhancement of up to 6 days relative to non-grafted plants (Mahbou *et al*., 2022) [42]. In a similar vein, grafting onto Ferro and RS841 rootstocks was found to augment post-harvest quality after a 21-day storage period at 7°C, as indicated by findings pertaining to watermelon (Özdemir *et al*., 2016) [49]. Notably, the fruit maintained its superior quality even subsequent to an additional 7 days at 21°C in contrast to ungrafted specimens.

The well-being of humans is contingent upon the intake of essential nutrients, including vitamin C, carotenoids (such as lycopene and β-carotene), and minerals encompassing calcium, magnesium, phosphorus, potassium, and iron. Certain studies have indicated that grafting has no discernible effect on the vitamin C content (Barrett *et al*., 2012) [9], while other investigations have reported diminished vitamin C levels in tomatoes. Gisbert-Mullor *et al.* (2020) highlighted significant increases in lycopene and volatile compounds in fruits grafted onto the Niber rootstock, thereby emphasizing the critical role of the rootstock and scion combination in enhancing fruit yield and marketable quality in peppers. According to Proietti *et al*. (2008) [56], grafting watermelon onto the hybrid rootstock PS 1313 (*C. maxima* × *C. moschata*) resulted in a 40% augmentation in lycopene concentration, while grafted mini-watermelon plants exhibited elevated levels of dehydroascorbate and total vitamin C by 13% and 7%, respectively, in comparison to ungrafted counterparts. Davis *et al.* (2008) [18] reported that the grafting of watermelon led to a 20% increase in both lycopene and total carotenoid concentrations. Conversely, tomatoes grafted onto Beaufort F1 and Maxifort F1 demonstrated a reduction in vitamin C content ranging from 14% to 20% when compared to ungrafted controls, as elucidated by DiGioia *et al*. (2010) [19].

According to Riga *et al*. (2016) [57], grafted tomatoes cv. Brigeor had a 48% higher lycopene content than non-grafted plants, and self-grafted Jack had a 39% increase. However, they also observed that grafting onto Alligator rootstock resulted in a 32% decrease in amino acids and a 16.5% reduction in protein content, while grafting onto Primed rootstock produced a 19% increase in total essential amino acids and a 17% increase in tomato fruits. Pogonyi *et al*. (2005) [55] discovered that fruit quality parameters of tomato cv. Lemance had lower concentrations of soluble solids, carbohydrates, and organic acid when grafted onto the Beaufort rootstock in comparison to ungrafted plants.

Conclusion

In conclusion, grafting technology has emerged as an invaluable instrument for the enhancement of growth, yield, and quality of various vegetable crops, particularly in the context of stress conditions such as salinity, drought, and extreme temperature variations. By employing compatible rootstocks, cultivators can augment salinity tolerance, enhance water utilization efficiency, and alleviate the adverse effects of sub-optimal environmental circumstances. The advantages of grafting encompass not only yield improvement but also enhancements in fruit quality, nutritional composition, and post-harvest attributes. Nevertheless, the ramifications of grafting can exhibit considerable variability contingent upon the specific rootstock-scion combinations, in addition to environmental determinants. The reactions of grafted plants to both deficient and excessive external concentrations of nutrients and heavy metals are influenced by the genotypes of both the scion and the rootstock, as well as the physiological interplay between the rootstock and scion. Ongoing investigation into these interactions will be crucial for the optimization of grafting methodologies and the maximization of resilience and productivity in vegetable crops, ultimately contributing to the advancement of global food security and sustainability.

Author Contribution

PP, KY, and RF conceptualized the review topic, designed the framework, and conducted the primary literature search. VR, HB, and NY analyzed the selected studies and drafted the methodology and review results sections. IA and JS provided critical revisions, supervised the overall process, and approved the final manuscript. All authors contributed to the final review and approved the manuscript for submission.

Conflict of Interest

The authors declare no competing interests.

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