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ROOTSTOCKS IN VEGETABLE GRAFTING: FUNCTIONAL ROLES, MECHANISMS, AND AGRICULTURAL SIGNIFICANCE: A REVIEW

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ABSTRACT

Rootstocks are crucial for the development and performance of grafted plants and vegetable grafting has become a significant sustainable horticultural activity. The rootstock, which makes up the grafted composite plant's root system, directly affects the scion's general physiological control, hormonal signalling and absorption of nutrients and water. Strong and disease-resistant rootstocks significantly enhance resistance to soil-borne diseases such as bacterial wilt, *Verticillium*, *Fusarium* and root-knot nematodes, reducing the requirement for chemical soil disinfestation according to several studies. In addition to controlling biotic-abiotic stress tolerance, which includes resistance to drought, floods, salinity and extreme temperatures are greatly influenced by rootstocks. Improved root architecture and increased hydraulic conductivity in specific rootstocks facilitate better mineral nutrition, photosynthetic efficiency and plant vigour. This ultimately leads to higher yield stability and improved fruit quality characteristics such as size, firmness and shelf life. Rootstocks also influence fruit set, flowering behaviour and scion development patterns through complex root-to-shoot communication pathways. In the context of climate change declining soil health and the need for resource-efficient production methods future research should focus on elucidating the molecular and physiological relationships between rootstock and scion in order to improve rootstock development for targeted stress tolerance and productivity.

Keywords **:** Vegetable grafting, rootstock-scion interaction, soil-borne disease, abiotic stress, nutrient and water uptake, plant vigor, yield stability, root-to-shoot signaling, sustainable vegetable production.

Introduction

Vegetable grafting is a crucial horticultural method that creates a united plant with better performance by joining desirable scions to appropriate rootstocks. To combat biotic and abiotic stressors, poor soil conditions and climate unpredictability, it was first developed in cucurbits and is now widely employed in solanaceous and cucurbit crops. Grafting increases overall plant production and resilience by fusing the vigor and stress tolerance of the rootstock with the yield and quality characters of the scion (Kubota *et al.*, 2008; Bie *et al.*, 2017; Colla *et al.*, 2010). To prevent significant crop losses caused by soil-borne diseases which are worsened by subsequent cropping. Grafted seedlings were first used in vegetable production in Korea and Japan. This practice is rapidly expanding. Vegetable grafting is considered a safe technique for producing organic and eco-friendly vegetable crops. High-quality and better-performing grafted seedlings exhibit increased crop yield and disease resistance. They are also very successful in reducing crop losses caused by unfavorable environmental factors like high soil salinity and low soil temperature, particularly under protected cultivation. In hydroponic agricultural systems, where harmful diseases frequently spread quickly after infection, grafted seedlings are highly preferred (Lee *et al.,* 2010; Schwarz *et al.,* 2010).

Importance and Applications of Vegetable Grafting

Enhancing Biotic Stress Tolerance

Studies have consistently demonstrated that rootstock genotype plays a decisive role in determining resistance responses of grafted vegetables. Tomato scions grafted onto interspecific rootstocks such as Beaufort, Maxifort and Hawaii 7996 (*Solanum lycopersicum* × *S. habrochaites* / *S. peruvianum*) have exhibited high levels of resistance to *Fusarium* wilt, *Verticillium* wilt and bacterial wilt, leading to a significant reduction in disease severity and improved plant survival particularly under biotic stress conditions associated with soil-borne pathogens (Rivard and Louws, 2008; Louws *et al.,* 2010; King *et al.,* 2010). Similarly, cucumbers grafted onto figleaf gourd (*Cucurbita ficifolia*) and bottle gourd (*Lagenaria siceraria*) rootstocks has shown enhanced resistance to root-knot nematodes and *Fusarium* wilt in cucurbit production systems (Colla *et al.,* 2010; Schwarz *et al.,* 2010).

Soil-borne diseases such as *Verticillium* wilt, bacterial wilt, *Fusarium* wilt, corky root and nematode infestations severely constrain vegetable productivity particularly in intensive and continuous greenhouse cropping systems (Lee *et al.,* 2003; Pogonyi *et al.,* 2005). With respect to abiotic stress tolerance, grafting tomato onto vigorous interspecific rootstocks such as Maxifort and Beaufort has been reported to significantly enhance drought tolerance through improved water uptake, increased antioxidant activity and regulated hormonal balance (Albacete *et al.,* 2015; Kumar *et al.,* 2017). Furthermore, grafting pepper scion ‘Nokk wang’ onto resistant breeding lines (PR 920, PR 991 and PR 922) resulted in higher survival rates following inoculation with *Ralstonia solanacearum* and *Phytophthora capsici*, thereby confirming the effectiveness of resistant rootstocks in managing bacterial and fungal diseases (Jang *et al.,* 2012).

Enhancing drought and salinity tolerence

Grafting onto *Luffa cylindrica* and pumpkin hybrids (*Cucurbita maxima* × *Cucurbita moschata*) has been reported to significantly enhance drought tolerance in cucumber through the induction of stress-responsive gene expression, improved chlorophyll stability and upregulation of antioxidant enzyme activities (Liu *et al.,* 2016). Rootstocks such as *Cucurbita maxima* × *Cucurbita moschata* hybrids, *Lagenaria siceraria* and pumpkin rootstocks effectively restricted Na^+ and Cl^- translocation to the shoot under saline conditions, thereby maintaining ionic homeostasis and photosynthetic efficiency (Rouphael *et al.,* 2008; Colla *et al.,* 2010; Nawaz *et al.,* 2017). Tomato grafted onto *Solanum melongena* and wild *Solanum* rootstocks maintained higher root activity and yield under flooding conditions (Kumar *et al.,* 2017).

Grafting is widely recognised as an effective strategy for mitigating both biotic and abiotic stresses. Cucurbits grafted onto pumpkin rootstocks exhibit enhanced drought tolerance in sandy soils whereas watermelon grafted onto *Lagenaria siceraria* rootstock in heavy or loamy soils shows superior flooding tolerance (Anonymous, 2013). Under irrigation stress, the yield of mini watermelons grafted onto the commercial rootstock PS1313 (*Cucurbita maxima* × *Cucurbita moschata*) increased by approximately 60% compared with ungrafted plants (Rouphael *et al.,* 2008). Cucumber grafted onto Shintoza-type rootstock (*Cucurbita maxima* × *Cucurbita moschata*) also exhibited improved tolerance to copper toxicity and low-temperature stress (Rouphael *et al.,* 2008). In greenhouse production systems, watermelon grafted onto salt-tolerant rootstocks recorded a yield increase of about 81% (Colla *et al.,* 2010). Furthermore, under saline conditions, watermelon cv. Fantasy grafted onto Strongtosa rootstock (*Cucurbita maxima* × *Cucurbita moschata*) showed a marked increase in shoot biomass and leaf area (Goreta *et al.,* 2008).

Overall, abiotic stress-tolerant rootstocks enhance plant performance by improving water relations, ion homeostasis, antioxidant capacity and hormonal regulation whereas disease-resistant rootstocks primarily function by restricting pathogen invasion and activating defence-related signalling pathways. Taken together, these findings indicate that the selection and utilisation of stress-specific rootstocks is one of the most critical factors in maximising the benefits of grafting in vegetable crop production.

Enhancing vigour and yield

Grafting onto *Luffa cylindrica* and pumpkin hybrids (*Cucurbita maxima* × *Cucurbita moschata*) has been reported to significantly enhance drought tolerance in cucumbers by inducing stress-responsive gene expression, improving chlorophyll stability and upregulating of antioxidant enzyme activities (Liu *et al.,* 2016). Rootstocks such as *Cucurbita maxima* × *Cucurbita moschata* hybrids, *Lagenaria siceraria* and pumpkin effectively restrict Na^+ and Cl^- translocation to the shoot under saline conditions, thereby maintaining ionic homeostasis and photosynthetic efficiency (Rouphael *et al.,* 2008; Colla *et al.,* 2010; Nawaz *et al.,* 2017). Tomatoes grafted onto *Solanum melongena* and wild *Solanum* rootstocks maintain higher root activity and yield under flooding conditions (Kumar *et al.,* 2017).

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Enhancing vigour and yield

Grafting is a well-established agronomic technique that significantly enhances the performance and productivity of eggplants. Among the most promising grafting combinations is the use of interspecific eggplant hybrids as rootstocks particularly *Solanum incanum* × *Solanum melongena*, which has demonstrated superior plant vigor and high graft compatibility, both of which are critical determinants of grafting success. This grafting combination is suitable for commercial eggplant production as it is associated with significant improvements in both early and total fruit yield without adversely effects on fruit quality or biochemical composition.

The benefits of grafting extend beyond the eggplant production. Grafting tomato onto vigorous commercial rootstocks such as 'Efialto', 'Heman' and 'Maxifort' has been reported to significantly increase marketable yield (Djidonou *et al.,* 2017). Furthermore, these rootstocks have been shown to enhance fruit lycopene concentration, a key nutritional attribute due to its strong antioxidant properties.

Similarly, grafting watermelon and melon onto interspecific *Cucurbita maxima* × *C. moschata* hybrids has resulted in substantial yield enhancement in cucurbit crops. Yield increases of up to 84% in watermelon and approximately 44% in melon have been reported compared with non-grafted plants (Martin, 2017; Hollick, 2021). In addition to improving yield, grafting has also been shown to enhance postharvest quality attributes. For instance, grafted watermelon fruits exhibit greater firmness, which is an important determinant of shelf life and marketability, thereby contributing to reduced postharvest losses and improved economic returns (Fallik *et al.,* 2020).

Enhancing morphological characters and processing quality

The physicochemical and sensory attributes of watermelon fruit, including flavor profile, pH, soluble sugar content, flesh colour, carotenoid concentration and textural properties are strongly influenced by rootstock selection. These parameters are key indicators of nutritional quality and consumer acceptability. Rootstocks significantly affect fruit quality by regulating water and nutrient uptake, translocation and metabolic activity within the grafted plant system (Fallik *et al.,* 2020).

Beyond watermelon, substantial evidence indicates that rootstocks also exert a pronounced influence on fruit quality traits in grafted cucumbers. Rootstock choice has been shown to markedly affects fruit shape, rind and flesh colour, texture, firmness, surface smoothness, rind thickness and total soluble solids content (Tan *et al.,* 2022). This highlights the strategic importance of rootstock selection as an effective approach for tailoring horticultural products to meet specific nutritional and market requirements.

In addition to fruit quality grafting also significantly influences flowering behaviour and harvest dynamics. Watermelon plants grafted onto bottle gourd rootstocks (*Lagenaria siceraria*) exhibited earlier initiation of female flowers compared with those grafted onto other rootstocks (Sakata *et al.,* 2007). In contrast, cucumber cultivars grafted onto interspecific squash hybrid rootstocks showed delayed or suppressed flowering. These divergent responses indicate that rootstock-scion interactions play a central role in regulating reproductive development. Overall, grafting enhances plant vigor, physiological efficiency, and nutrient acquisition, which can promote earlier and more uniform flowering and, consequently, a more synchronized harvest. However, the extent and direction of these effects are strongly dependent on the genetic compatibility and functional attributes of the specific rootstock-scion combinations.

Basic Prerequisites for Successful Vegetable Grafting

For accurate vascular alignment, successful graft union formation and minimization of graft incompatibility, the selected rootstock and scion should possess nearly uniform stem diameters (Lee *et al.*, 2010; Kubota *et al.*, 2008). Grafting is generally performed at the two to threetrue-leaf stage when seedlings are physiologically active and exhibit a high regenerative capacity (Oda, 2007; Hassell *et al.*, 2008). Rootstock cultivars should be selected on the basis of genetic purity, vigour, resistance to soil-borne diseases, compatibility with the scion and adaptability to local soil and environmental conditions, whereas scion seeds should be chosen for genetic purity, high viability, yield potential, superior fruit quality and market preference (Kubota *et al.*, 2008; Lee *et al.*, 2010). To prevent contamination and pathogen transmission, all grafting tools including blades and clips must be thoroughly sterilized (Louws *et al.*, 2010). During the healing phase, controlled environmental conditions of 25–30°C, 85–90% relative humidity and low light intensity are essential to promote callus formation and vascular reconnection (Oda, 2007; Hassell *et al.*, 2008). Grafted seedlings are typically maintained in healing chambers and gradually acclimatised over a period of 7-10 days through a hardening process prior to transplanting to ensure high survival rates and proper establishment under field conditions (Kubota *et al.*, 2008; Lee *et al.*, 2010).

Some important grafted vegetables

Solanaceaous vegetables

Tomato

Numerous studies have demonstrated that grafting significantly enhances tomato growth, productivity, stress tolerance and fruit quality and that these responses are strongly influenced by rootstock selection. Extensive research has documented the use of wild and interspecific *Solanum* rootstocks such as *Solanum habrochaites*, *S. peruvianum*, *S. pimpinellifolium*, *S. cheesmaniae* and interspecific hybrids of *S. lycopersicum* × *S. habrochaites* or *S. lycopersicum* × *S. peruvianum* to improve graft compatibility, plant vigour and stress resistance (Ibrahim *et al.*, 2001; Lee, 1994; Oda, 1995; Lee and Oda, 2003). Tomatoes grafted onto *Lycopersicon esculentum* rootstocks exhibit enhanced temperature tolerance and increased boron uptake (Okimura *et al.*, 1986) whereas tomatoes grafted onto *L. hirsutum* do not develop corky root disease. Although susceptible to nematode infection, the tomato rootstock ‘Beaufort’, which carries the Mi resistance gene, performs well in infested soils and is therefore regarded as functionally resistant (Lopez-Perez *et al.*, 2006). In contrast, tomatoes grafted onto *Solanum integrifolium* produce fewer fruits but exhibit higher °Brix, while those grafted onto *S. sisymbriifolium*, *S. torvum* and *S. toxicarium* are not infected by *Verticillium dahliae*, *Fusarium oxysporum* f. sp. *lycopersici* or nematodes and show tolerance to both high and low temperature stress (Oda *et al.*, 1996; Bletsos and Olympios, 2008).

Under both greenhouse and open-field conditions, commercial and experimental rootstocks such as ‘Beaufort’, ‘Maxifort’, ‘He-Man’, ‘Arnold’ and ‘Body’ have been shown to enhance vegetative growth, nutrient uptake and yield (Khah *et al.*, 2006; Marsic and Osvald, 2004; Mohammed *et al.*, 2009; Leonardi and Giuffrida, 2006). By improving plant water relations and mineral balance, grafting tomato onto these vigorous rootstocks increases tolerance to abiotic stresses including salinity and drought (Cuartero and Fernández-Muñoz, 1998; Fernández-García *et al.*, 2004; Campos *et al.*, 2006). Furthermore, depending on the scion-rootstock interaction, fruit quality parameters such as total soluble solids, sugars, organic acids, colour, lycopene content and antioxidant capacity are often maintained or enhanced (Flores *et al.*, 2010; George *et al.*, 2004; Adsule and Dan, 1979). Compatibility evaluations have also indicated that wild *Solanum* rootstocks significantly improve graft survival and success, supporting their extensive utilization in commercial tomato grafting (Ibrahim *et al.*, 2001). Overall, these findings confirm that the full benefits of tomato grafting in terms of productivity, stress tolerance and fruit quality are dependent on the selection of appropriate rootstocks particularly vigorous commercial hybrids and wild *Solanum* species.

Brinjal

Eggplants possess a dense and extensive root system and therefore the rootstock used for grafting should exhibit comparable root characteristics to adequately support scion growth and development. Since the 1920s, eggplant grafting has been widely practiced in Korea and Japan where most of the foundational research on suitable rootstocks has been conducted (Lee, 1994). Eggplant is grafted onto a wide range of rootstocks including hybrids and wild eggplant lines that are resistant to wind stress and soil-borne pathogens (Yoshida *et al.,* 2004; Gao *et al.,* 2001). Among these, *Solanum integrifolium* (syn. *S. aethiopicum* L. Aculeatum group) is considered a suitable *Solanum* species due to its high graft compatibility with eggplant and resistance to bacterial wilt and *Fusarium* wilt (Yoshida *et al.,* 2004) as well as interspecific hybrids such as *S. integrifolium* × *S. melongena*, which combine resistance traits from both parental lines (Milan *et al.,* 1995; Bletsos and Olympios, 2008).

Solanum torvum is one of the most widely used and effective eggplant rootstocks. It has been consistently identified as a superior rootstock due to its strong resistance to bacterial wilt (*Ralstonia solanacearum*), *Fusarium* wilt and *Verticillium* wilt as well as its high graft compatibility and vigorous root system (Honna, 1977; Gousset *et al.,* 2005; Arwiyanto *et al.,* 2015; Ramesh *et al.,* 2016; Miceli *et al.,* 2014). Under both protected and open-field conditions, grafting brinjal onto *S. torvum* has been shown to reduce disease incidence while enhancing plant longevity, vegetative growth and fruit yield (Bletsos *et al.,* 2003; Ioannou, 2001; Singh and Gopalakrishnan, 1997; Moncada *et al.,* 2013).

Other promising wild rootstocks include *Solanum sisymbriifolium*, *S. aethiopicum*, *S. macrocarpon*, *S. incanum* and *S. stramonifolium*, which improve nutrient uptake and plant vigour while conferring resistance to nematodes, bacterial and fungal wilts and high temperature stress (Daunay, 2008; Hayati *et al.,* 2005; Gisbert *et al.,* 2011a, 2011b; Wang *et al.,* 2007; Singh *et al.,* 2019). Furthermore, related species and interspecific eggplant hybrids have been reported to function as efficient rootstocks for enhancing fruit quality and yield stability (Sabatino *et al.,* 2016; Sabatino *et al.,* 2018). Physiological investigations have also indicate that appropriate rootstocks improve water relations, hormonal signalling and mineral uptake at the graft union, thereby contributing to enhanced tolerance to biotic stress and high temperature conditions (Kato and Lou, 1989; Aloni *et al.,* 2010; Leonardi and Giuffrida, 2006).

Overall, the available evidence demonstrates that grafting brinjal particularly onto *Solanum torvum* and other wild *Solanum* species represents a scientifically validated and commercially viable strategy for controlling bacterial wilt, improving productivity and stabilising yields in stress-prone production systems.

Pepper

Grafting has emerged as an essential agronomic strategy for enhancing pepper growth, productivity and tolerance to both biotic and abiotic stresses. Numerous investigations have demonstrated that appropriate rootstock selection improves nutrient uptake, disease resistance, salinity tolerance and overall plant vigour. Among the most widely used and effective pepper rootstocks are *Capsicum chinense*, *C. baccatum*, *C. annuum* hybrids and interspecific rootstocks such as ‘Criollo de Morelos 334’ (CM334) (Chung and Choi, 2002; Oka *et al.,* 2004; Yang *et al.,* 2010). These rootstocks confer resistance to major soil-borne pathogens including *Phytophthora capsici* and *Ralstonia solanacearum* (Semi *et al.,* 2010; Kim *et al.,* 2010; King *et al.,* 2008; Tran and Kim, 2010). Grafting also enhances tolerance to abiotic stresses such as salinity and nutrient imbalance through improved ion exclusion of Na^+ and Cl^- and increased efficiency of mineral nutrient uptake (Chung and Choi, 2002; Edelstein *et al.,* 2011; Savvas *et al.,* 2010; Ruiz *et al.,* 1997).

Under diverse environmental conditions including low night temperatures and heavy metal stress, rootstock choice significantly influences vegetative growth, fruit set, yield and fruit quality (Jang *et al.,* 2008; Rivero *et al.,* 2003; Davis *et al.,* 2008). Recent breeding programs in Korea and worldwide have focused on the development of multiple disease-resistant rootstocks that combine resistance to bacterial wilt, *Phytophthora* blight and nematodes while maintaining high compatibility with commercial pepper cultivars (Yang *et al.,* 2010; King *et al.,* 2010). Overall, grafting pepper onto vigorous and resilient rootstocks such as CM334, *Capsicum chinense*, *C. baccatum* and interspecific hybrids is a scientifically validated approach for improving fruit quality, yield stability and stress tolerance.

Chilli

Under protected cultivation systems, grafting chilli and sweet pepper (*Capsicum annuum* and related species) onto resistant rootstocks has been shown to enhance resistance to soil-borne diseases, promote vegetative growth and increase productivity. Several studies have evaluated local chilli genotypes as potential rootstocks. When grafted with bell pepper scions, *Capsicum annuum* rootstock lines such as CRS-1, CRS-2, CRS-8, CRS-11 and CRS-15 consistently reduced the incidence of bacterial wilt (*Ralstonia solanacearum*) and root-knot nematode infestation. This resulted in significantly higher biomass production, earlier flowering and increased fruit yield compared with non-grafted and self-grafted plants.

Commercial sweet pepper scions grafted onto CRS-8, CRS-1 and CRS-15 rootstocks exhibited superior yield performance and enhanced disease resistance. These rootstocks, derived from different *Capsicum* species such as *C. annuum* and *C. frutescens*, are associated with improved nutrient accumulation and elevated antioxidant enzyme activity, indicating increased tolerance to biotic stress.

Furthermore, *Capsicum annuum* and *C. frutescens* accessions have been identified as suitable rootstocks for improving productivity under nematode pressure due to their moderate to high resistance to root-knot nematodes (*Meloidogyne* spp.) (Oka *et al.,* 2009). Field evaluations conducted in tropical environments have also demonstrated that grafting sweet pepper onto disease-resistant chilli rootstocks substantially reduces the incidence of bacterial wilt and *Phytophthora* blight, thereby increasing marketable yield (Wu *et al.*, 2012).

Overall, these findings indicate that grafting sweet pepper and chilli onto resistant rootstocks particularly genotypes of *Capsicum annuum* and *Capsicum frutescens* represents a promising and effective strategy for managing soil-borne diseases, enhancing yield and improving plant performance under protected cultivation systems.

Watermelon

Grafting has emerged as a highly effective strategy for enhancing watermelon productivity worldwide as demonstrated by extensive research conducted over the past several decades. As an alternative to chemical soil fumigation, grafting watermelon onto vigorous and disease-resistant rootstocks such as *Cucurbita maxima* × *C. moschata* and *Lagenaria siceraria* significantly reduces losses caused by soil-borne diseases particularly *Fusarium* wilt (Tateishi, 1927; Cohen *et al.*, 2007; Kubota *et al.,* 2008; Sakata *et al.,* 2007). Numerous studies have shown that grafted watermelon plants develop stronger root systems, improved water and nutrient uptake, enhanced tolerance to abiotic stresses such as salinity, drought and low soil temperature (Colla *et al.*, 2006; Aloni *et al.,* 2010; Marguerit *et al.,* 2012). Consequently, under both stress and nonstress conditions, grafted plants frequently exhibit superior vegetative growth, higher yield and improved yield stability (Taylor *et al.,* 2008; Galinato *et al.,* 2016; Devi *et al.,* 2020).

Advances in grafting techniques, healing chamber management and automation have markedly improved graft survival rates and economic feasibility (Lee *et al.*, 2010; Hassell *et al.*, 2008; Kurata, 1994; Dabirian and Miles, 2017). Investigations on fruit quality indicate that although certain rootstocks may influence internal quality attributes and mineral composition, grafting generally maintains acceptable sweetness, texture and sensory properties, thereby emphasizing the importance of appropriate rootstock-scion combinations (Barrett *et al.*, 2012; Devi *et al.*, 2020). Economic analyses consistently demonstrate that despite the higher initial cost of grafted transplants, their use is economically justified in high-value cropping systems and disease-infested soils becaus due to increased marketable yield, reduced chemical inputs and extended plant longevity (Taylor *et al.,* 2008; Galinato and Gallardo, 2017).

Among watermelon rootstocks, commercial hybrids such as TZ-148 and RS-841 (*Cucurbita maxima* × *C. moschata*) are widely utilised. Open-pollinated rootstocks include *Cucurbita moschata*, *C. maxima* and *Lagenaria siceraria*. Common hybrid rootstocks include Strong Tosa, Gold Tosa and P360 (*C. maxima* × *C. moschata*) as well as Skopje, Emphasis, 216 and FRG (*Lagenaria* spp.). The watermelon cultivar Crimson Tide reportedly to exhibit approximately 65% graft survival on *Cucurbita* rootstocks and about 95% survival on *Lagenaria* rootstocks. Grafted plants are characterized by early flowering, rapid vegetative growth and increased fresh biomass production (Yetisir and Sari, 2003).

Overall, available evidence confirms that watermelon grafting represents a scientifically validated and economically viable approach for improving sustainability, productivity and stress tolerance in modern watermelon production systems.

Muskmelon

Grafting muskmelons (Cucumis melo L.) onto suitable rootstocks has been shown to significantly enhances yield, fruit quality, and resistance to soil-borne diseases such as *Fusarium* wilt. Grafting cultivars ‘ZT105’ and ‘ZT401’ onto interspecific squash rootstocks (*Cucurbita maxima* × *C. moschata* SZ12) and muskmelon rootstocks (ZT1, T1, and YZ9) increased yield by up to 27%, while reducing disease incidence from more than 20% in non-grafted plants to as low as 0–3% in grafted combinations (Hishida *et al.*, 2025). Similarly, grafting the cultivar ‘Samsoori’ onto the squash hybrid rootstock ‘Ace’ improved total fruit yield by approximately 23.5% without adversely affecting soluble solids content (Mohammadi *et al.*, 2015). Physiological investigations indicate that grafting onto interspecific *Cucurbita* rootstocks enhances fruit development and sugar translocation through increased leaf photosynthetic rate, chlorophyll concentration and carbohydrate metabolism (Lu *et al.*, 2011).

Further studies have demonstrated that pumpkin varieties (Arka Chandan and Arka Suryamukhi), bottle gourd cultivars (Arka Bahar and Samrat) and sponge gourd cultivars (Phule Komal and Phule Prajakta) exert a strong influence on fruit yield, biochemical attributes and disease resistance in grafted muskmelon. Certain rootstocks have been found to be particularly effective during the kharif and summer seasons (Hishida *et al.*, 2025). Collectively, these findings indicate that interspecific squash hybrids and compatible muskmelon rootstocks are highly effective in improving muskmelon productivity when appropriate scion–rootstock combinations are employed.

Cucumber

In both greenhouse and field production systems, grafting cucumber onto appropriate cucurbit rootstocks has been shown to enhance vegetative growth, yield, fruit quality and tolerance to environmental stresses. Rootstocks such as bottle gourd (*Lagenaria siceraria*), interspecific squash hybrids (*Cucurbita maxima* × *C. moschata*) including Ferro and Super Shintosa, and other native cucurbit species such as ridge gourd (*Luffa operculata*) and bitter gourd (*Momordica charantia*) consistently outperform non-grafted plants in terms of vegetative vigour and yield traits (El Beltagi *et al.*, 2023; Kurum and Padem, 2025). For example, compared with non-grafted controls, grafting onto Ferro rootstock significantly increased cucumber plant height, early fruit production and total fruit yield during both summer and winter seasons, while bottle gourd rootstock improved fruit dry matter and total soluble sugars under specific conditions (El Beltagi *et al.*, 2014). Grafting onto *Luffa operculata* rootstock has been reported to enhance vegetative growth, yield and salinity tolerance by reducing Na^+ translocation to the shoot and increasing net photosynthesis, vitamin C content and soluble sugars under greenhouse conditions (Luffa rootstock study, 2022).

Grafted cucumber plants often exhibit higher survival rates, earlier flowering and improved morphological traits including vine length, leaf number and stem diameter, which collectively promote increased fruit set and overall productivity (MDPI, 2021; Kurum and Padem, 2025). In comparison with non-grafted counterparts, grafting onto *Cucurbita maxima* × *C. moschata* and *Lagenaria* rootstocks frequently results in greater fruit weight and number per plant, enhanced water and nutrient uptake and improved postharvest quality (MDPI, 2021; El Beltagi *et al.*, 2014).

Overall, evidence indicates that grafting cucumber onto vigorous and compatible cucurbitaceous rootstocks particularly *Lagenaria siceraria*, interspecific squash hybrids such as Ferro and Super Shintosa, and *Luffa operculata* effectively improves plant vigour, yield, fruit quality and tolerance to environmental stresses, highlighting the critical importance of selecting rootstocks tailored to specific production objectives (Guo *et al.*, 2023).

Bottle gourd

Owing to its vigorous root system, high graft compatibility and tolerance to abiotic stresses and soil-borne diseases, *Lagenaria siceraria* is among the most widely used and effective rootstocks for watermelon. Rootstocks such as ‘Emphasis’, ‘Hiyari’, ‘Belo’ and accessions BG-11 to BG-13 have been reported to enhance plant growth, nitrogen use efficiency and overall survival. Grafting onto *L. siceraria* has been shown to increase tolerance to *Fusarium* wilt, *Pythium* spp. and salinity while simultaneously improving biomass accumulation and fruit yield (Karaca *et al.*, 2012; Yetisir and Karaca, 2018; Morales *et al.*, 2023).

Other important cucurbits

Grafting studies on minor cucurbits such as bitter gourd (*Momordica charantia*), sponge/summer gourd (*Luffa* spp.) and ridge gourd (*Luffa acutangula*), in addition to major cucurbits like cucumber and watermelon, indicate that these species can both serve as rootstocks and benefit from grafting under specific conditions. Research on bitter gourd has shown that grafting onto vigorous cucurbit rootstocks such as pumpkin (*Cucurbita moschata*) and sponge gourd (*Luffa cylindrica*) improves graft success, vegetative growth and yield compared with non-grafted plants, highlighting the potential of these rootstocks to enhance the performance of minor cucurbits (Tamilselvi and Pugalendhi, 2017). Studies on cucumber scions have investigated indigenous cucurbit landraces-including bottle gourd (*Lagenaria siceraria*), ridge gourd (*Luffa acutangula*), sponge gourd (*Luffa aegyptiaca*) and pumpkin (*Cucurbita pepo*) as alternative rootstocks. Results indicate that grafting onto these minor cucurbits can enhance morphological, physiological and yield traits under stress conditions such as salinity by improving biomass accumulation, photosynthetic efficiency and antioxidant activity relative to non-grafted plants (Abbas *et al.*, 2024; Nat Sci Reports, 2023).

Physiological investigations further demonstrate that grafting cucumber onto *Luffa* rootstocks can enhance drought tolerance by modulating abscisic acid dynamics and stomatal sensitivity, thereby improving water-use efficiency and stress resilience (PubMed, 2016). Although some minor cucurbits may be incompatible with specific scions-for instance, melon grafted onto *Luffa* or bitter gourd exhibits anatomical graft barriers-combinations within closely related cucurbit groups can succeed when appropriately matched (Frontiers Plant Sci, 2021). Consequently, with careful assessment of scion-rootstock compatibility, minor cucurbits such as *Luffa* species, ridge gourd and sponge gourd represent promising rootstocks for other cucurbit crops, offering improved growth, stress tolerance and yield potential.

Okra

Grafting in okra (*Abelmoschus esculentus* L.) has shown potential, although it remains less studied than other vegetable crops, particularly for controlling root-knot nematodes and enhancing stress tolerance. Studies indicate that intergeneric rootstocks from closely related Malvaceae species, including kenaf (*Hibiscus cannabinus* L.) and roselle (*Hibiscus sabdariffa* L.), are compatible with okra scions and may serve as effective rootstocks (Silva, Versuti and Braz, 2022; Andrade *et al.*, 2019). Grafting onto *H. sabdariffa* achieved high graft survival (~100%) and produced vegetative growth and yield comparable to self-grafted and non-grafted okra in greenhouse trials using the cultivar 'Santa Cruz 47', indicating strong compatibility and potential production benefits (Andrade *et al.*, 2019; Silva *et al.*, 2022). In contrast, grafting onto cotton (*Gossypium barbadense* L.) resulted in incompatibility, causing wilting and plant mortality soon after transplantation, emphasising the importance of selecting rootstocks with close taxonomic affinity to okra (Silva *et al.*, 2022).

Further studies using okra rootstocks have demonstrated that grafting drought-sensitive scions onto drought-tolerant genotypes (e.g., NS7774) substantially improves drought tolerance by increasing biomass, photosynthetic activity under water deficit, chlorophyll content and leaf water status compared with non-grafted plants (PMC, 2024). These physiological enhancements suggest that suitable okra rootstocks may confer abiotic stress tolerance and disease resistance.

Overall, despite the limited research on okra grafting, current evidence indicates that drought-tolerant okra genotypes can serve as effective rootstocks to enhance stress tolerance, while *H. sabdariffa* and *H. cannabinus* are promising for improving disease resistance, including management of root-knot nematodes. Optimizing graft combinations for productivity and resilience will require continued research using diverse Malvaceae rootstocks and okra breeding lines.

Table : Grafting methods and rootstocks used in vegetable crops

Scion Plant	Rootstock	Method
Eggplant	*Solanum torvum* *S. sissymbrifolium* *S. khasianum*	Tongue and cleft method Cleft method Both tongue and cleft methods
Tomato	*L. pimpinellifoium* *S. nigrum*	Only cleft methods Tongue and cleft methods
Cucumber	*C. moschata* *Cucurbuta maxima*	Hole insertion and cleft method Tongue method
Water melon	*Benincasa hispida* *C. moschata* *c. melo* *C. moschata* X *C. maxima*	Hole insertion and cleft method Hole insertion and cleft method Cleft grafting Hole insertion and cleft method
Bitter gourd	*C. moschata* *Lagenaria siceraria*	Hole insertion and cleft method Hole insertion
Bottle gourd	*C. moschata*, *Luffa sp.*	Hole insertion and cleft method

(**Source**: Kumar A.B. and K. Sanket)

Conclusion

Rootstocks provide a robust root system to the scion and play a key role in enhancing crop yield and quality. Their vigorous root structure allows for increased absorption of water and nutrients from nutrient-deficient soils, offering greater adaptability under challenging environmental conditions. Commercial vegetable crops, due to their widespread cultivation and high nutritional demand, have the potential to serve as rootstocks for mitigating various biotic and abiotic stresses. In contrast, many minor or underutilized vegetables have received little or no attention as rootstocks. These minor vegetables are often cultivated in resource-limited regions where environmental pressures are high, yet they are successfully grown in small populations under largely unmanaged conditions. Therefore, there exists considerable potential to identify promising and suitable rootstocks from both major and minor crops to improve scion adaptation, compatibility, yield, and overall vegetable quality in future horticultural systems.

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