Grafting vegetables for mitigating environmental stresses under climate change: a review

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ABSTRACT

Vegetables are a cornerstone of the human diet, and the importance of vegetables for human health and nutrition cannot be understated. Vegetables are susceptible to a number of biotic and abiotic stressors along with the cumulative pressure of climate change. Climate change is a major driver of the abiotic stress in modern-day vegetable production. Vegetable cropping systems must be resilient to climate change, so that production practices can achieve economic profitability and environmental sustainability. Environmental stressors, such as flooding, drought, and extreme temperatures, pose a severe threat to vegetable crop production, and total crop failures are common. Vegetable grafting, a plant surgical technique that is eco-friendly, rapid, and efficient, is currently the best alternative approach to climate change-resilient plant production that addresses these abiotic stressors. In this review, we document the success of this plant propagation technique using a review of vegetable grafting research results published in the scientific literature.

Key words | climate change, environmental stresses, grafting, vegetables

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INTRODUCTION

Global climate change represents the biggest abiotic threat to plant and human health (Costello *et al.* 2009) and has been given immense consideration worldwide due to its potential impact on agricultural practices (Olesen & Bindi 2002; Baer & Risbey 2008). Increasing agricultural production to meet the dietary preferences of a growing population with limited resources in the face of climate change will require innovative solutions (McMichael *et al.* 2007). Globally, environmental stressors are the primary cause of crop failures and, on average, result in a 50% yield decrease (Reimers 2000). Importantly, vegetable production is prone to a broad spectrum of these abiotic environmental stresses, such as drought, salinity, flooding, and temperature (both low and high) (Moretti *et al.* 2010). Predicted impacts of global climate change on crop production have become a primary focus of the agricultural research community, and the environmental factors related to the lost yield potential of vegetable crops are day length (i.e., photoperiod reduction), water availability, and poor vernalization (Sharma *et al.* 2013).

According to a survey of Kays & Dias (1995), about 392 different vegetables are cultivated globally, representing 70 plant families and 225 genera. Global climate change has a significant impact on vegetable crops due to their succulent nature; vegetables are susceptible to environmental conditions and are affected by both short- and long-term climate changes. Therefore, climate change can impact vegetable crops biochemically, anatomically, morphologically, and physiologically (Fahad *et al.* 2017; Singh *et al.* 2017). Some metals like silicon and biochemicals like phenolic acids help in mitigating the stress imposed by the abiotic factors (Kaushik 2019; Kaushik & Saini 2019; Saini & Kaushik 2019). However, increased mean air temperature and humidity under a changing climate scenario may

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enhance the already presented insect-pest and disease pressure (Chauhan *et al.* 2014).

Food security is also anticipated to be impacted either directly or indirectly by varying climatic conditions (Schmidhuber & Tubiello 2007). For example, the carbon dioxide (CO_2) passing through the leaf stomata at a greater concentration results in the rapid and uniform growth of transplants by affecting the photosynthesis activity (Xu *et al.* 2016). This CO_2 effect could be applied to the healing and acclimatization of grafted transplants in commercial vegetable production. In a study of grafted pepper, transplants were healed and acclimatized following a higher concentration of CO_2 (374 or 1,013 $\mu mol \cdot mol^{-1}$) over 6 days. This influence of CO_2 enrichment resulted in higher CO_2 exchange rates of the grafted pepper transplants. Overall, an increase in photosynthesis and the growth of the pepper were reported (Jang *et al.* 2014).

Climatic vagaries in the form of temperature fluctuations and erratic rainfall affect plant growth and the development of vegetable crops in different ways and cause a drastic reduction in economic yields (Wurr *et al.* 2004; Rao *et al.* 2016). Thus, climate change may be more challenging in vegetable production than other grain or food crops. In order to sustain vegetable production under a global climate change scenario, proper strategies are needed to manage such abiotic stresses. Various strategies were tested, such as breeding resistant cultivars and genetic engineering, but the commercialization of these technological advancements was limited due to the genetic and physiological complexity of abiotic stress resistance traits (Colla *et al.* 2010).

Traditional breeding methods involving large breeding cycles are time-consuming and progress slowly (Atlin *et al.* 2017). A grafting technique based on rootstock and scion compatibilities requires grafting sensitive or susceptible commercial cultivars onto the resistant or tolerant rootstock to manage various environmental stresses (Edelstein 2004; Altunlu & Gul 2012; Nilsen *et al.* 2014). Grafting is an environmentally friendly, efficient, rapid, and integrative reciprocal process in which both scion and rootstock influence the grafted plant (Sakata *et al.* 2007). This technique was first used in watermelon in Japan (He *et al.* 2009). The first scientific report presented results from grafting watermelon plant scion on pumpkin rootstock to avoid fusarium wilt. However, grafting was widely considered as a technique for woody perennial fruit crops in the 1920s and has only more recently been used in cucurbits to manage soil-borne diseases, specifically Fusarium (Davis *et al.* 2008; Bhatt *et al.* 2015).

Currently, many researchers across the world use this grafting technique to improve or increase tolerance to environmental stresses in solanaceous and cucurbitaceous crops (Mohamed *et al.* 2012; Johnson *et al.* 2014) and achieve higher yield and fruit quality (Mudge *et al.* 2009; King *et al.* 2010). Vegetable grafting is now quite a widespread practice in Asia, Europe, and the USA (Witzel *et al.* 2015). Indeed, grafting is useful for combating stresses and results in a better plant ideotype (Figure 1).

However, the latest breeding 'omics' technologies have only targeted tomato and potato, while other vegetables are neglected entirely (Liao & Lin 1996; Kato *et al.* 2001a). In this review article, we discuss the role of vegetable crop grafting for the management of environmental stresses, such as flooding, drought, thermal, and salinity, under a changing climate scenario.

Environmental stress and grafting

Environmental stress, because of a changing global climate, is the primary reason for crop loss or failure. Among the various environmental stressors, extreme temperatures, drought and flooding (due to erratic rainfall), and salinity are the major limiting factors for the sustainable production of agricultural and horticultural crops (Mittler 2006). The severity of these stresses on plants depends on the growth stage, type, and length of exposure to the stress. There are numerous studies describing the use of grafting techniques on different vegetable crops to improve tolerance against a broad spectrum of environmental stresses, and we have summarized the main results in this review article.

Flooding

Excessive moisture due to unpredictable heavy rainfall adversely affects the production of many vegetable crops due to their high sensitivity to flooding, and some vegetables are intolerant of flooded soil conditions throughout their growth and development (Liao & Lin 1996; Kato *et al.* 2001a). High moisture in the soil causes the reduction of

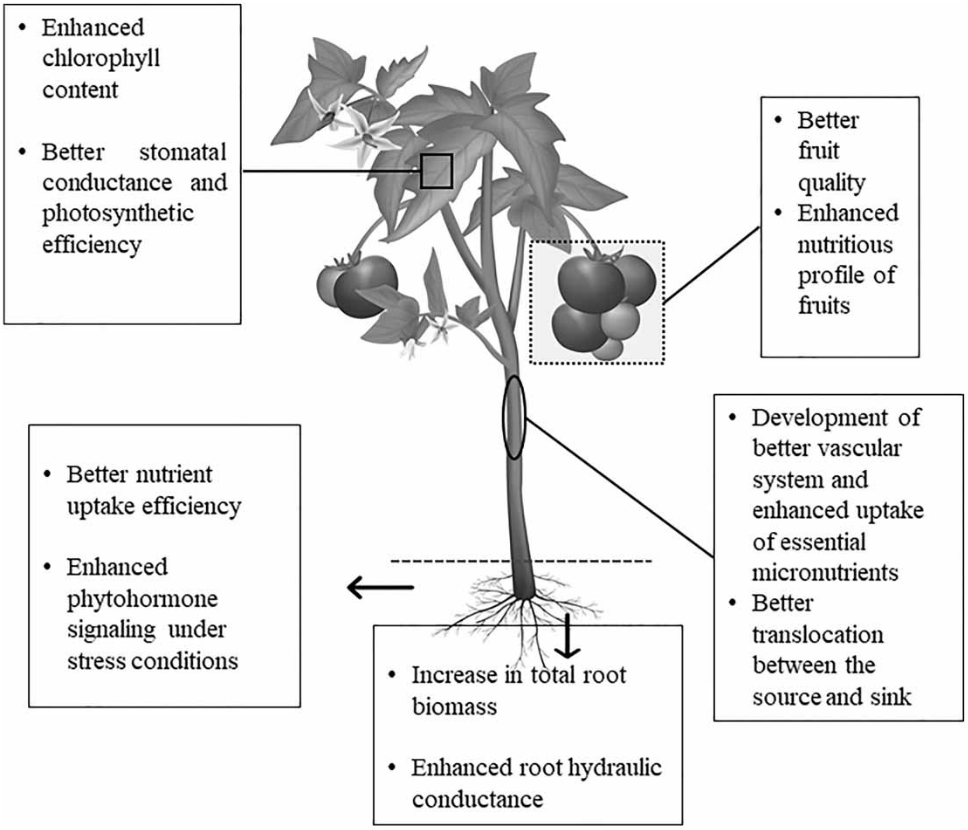

Figure 1 | Illustration of the physiological and morphological benefits of grafted vegetable crops that enable abiotic stress tolerance.

oxygen in the roots of plants by altering photosynthesis and the water potential. It has been documented that grafting has been used by many research groups in various vegetable crops to improve flooding tolerance (Bhatt *et al.* 2015). Tomato is an example of a globally grown vegetable that is sensitive to flooding (Petran & Hoover 2014). Bhatt *et al.* (2015) used the interspecific grafting of tomato to improve flooding tolerance. In this experiment, a commercial tomato cultivar, Arka Rakshak, was grafted onto four eggplant rootstocks, such as BPLH-1, Neelkanth, Mattu Gulla, and Arka Keshav. The results of this study showed that grafting significantly affected yield in flooded and non-flooded conditions. After 5 days of flooding, non- and self-grafted plants died, but two combinations Arka Rakshak/Arka Keshav and Arka Rakshak/BPLH-1 exhibited better performance. It can be concluded from this study that eggplant tolerated flooded soil conditions and may be a suitable grafting rootstock to enhance the flooding tolerance of tomato. Likewise, the World Vegetable Center (AVRDC) recommended EG195 and EG203 eggplant accessions as rootstock for the tomato to enhance flooding tolerance (Black *et al.* 2003).

In a recent study by Bahadur *et al.* (2015), tomato hybrids (Arka Rakshak and Arka Samrat) were grafted onto eggplant rootstocks (IC-354557, IC-111056, IC-374873, and CHBR-2) and exposed to waterlogged conditions. Observations revealed that there were no symptoms of leaf chlorosis or plant wilting and less of a reduction in chlorophyll at all plant growth stages. In contrast, the ungrafted plants experienced 41–100% reduction in chlorophyll content after 96 h of waterlogged stress, while the plants wilted and died 4–7 days after the stress was removed. However, the grafted plants completely recovered from flooding stress within 7–10 days after exposure. So, eggplant rootstocks, namely IC-354557 and IC-111056, improved waterlogging stress tolerance for 72–96 h for the grafted tomato (Bahadur *et al.* 2015).

Furthermore, wild species of eggplant are also used as rootstocks of grafted tomato (Petran & Hoover 2014). In another report, Yetisir *et al.* (2006) found that bitter melon plants grafted onto Luffa rootstocks performed better than ungrafted plants under flooded conditions. Similarly, in watermelon, the commercial cultivar 'Crimson Tide' was grafted onto the *Lagenaria siceraria* SKP (a landrace), and symptoms of chlorosis were observed on both grafted and non-grafted plants, although symptoms were less severe on grafted plants under flooded conditions.

Nevertheless, ungrafted plants accumulated less dry weight than grafted plants under high moisture content; moreover, the decrease in fresh weight of plants was about 180% in ungrafted and 50% in grafted plants compared to the control. Dry weight also decreased by approximately 230 and 80% in non-grafted and grafted plants, respectively. These results suggest that grafted plants exhibited the formation of adventitious roots and aerenchyma tissue after 3 days, but no such observation was made for non-grafted plants under flooded conditions (Liao & Lin 1996; Kato *et al.* 2001a). Along the same lines as the research of Keatinge *et al.* (2014), Kato *et al.* (2001b) conducted a grafting study in waterlogged cucumber and determined that leaf chlorophyll content was enhanced when grafted onto squash rootstocks. However, recently for East Asia, the AVRDC recommended rootstock VI006378 for flood tolerance in tomato, whereas, for eggplant, the recommended rootstocks are VI045276, VI046103, VI034845, VI046104, and VI046101, respectively (Peng *et al.* 2013). Rootstocks can be banked upon under flooding situations for vegetables and other economically important crops (Cattivelli *et al.* 2008; Reynolds & Tuberosa 2008). Additional examples are provided in the Table 1.

Drought

Drought is another serious water stress problem for sustainable vegetable production worldwide, resulting from water deficit under water-limiting conditions. Although breeding and biotechnological interventions have resulted in some new drought-tolerant crop varieties, these advances have been mostly limited to cereal crops (Potop *et al.* 2012). Certainly, water availability is highly affected by climate change which influences crop productivity, specifically that of vegetable crops, and total crop failures are common. Decreased precipitation, along with increased

Table 1 | Examples of top-performing rootstock and scion combinations in vegetable crops under induced flooding stress

Sl. no.	Rootstock	Scion	Key improved characteristics	Reference
Flooding stress				
1	Luffa (*Luffa cylindria Roem*) cv. Cylinder #2	*Bitter melon* (*Momordia charanthia*) cv. New Known You #3	Slight decrease in photosynthetic rate, stomatal conductance, transpiration, and the activity of RuBisCO	Liao & Lin (1996)
2	Interspecific squash hybrid (*Cucurbita maxima Duchesne* X *C. moschata Duchesne*) cv. Shintosa-ichigou	*Cucumber* (*Cucumis sativus*) cv. Kaga-aonagafushinari	Triggering ethylene biosynthesis resulting in reduction in chlorophyll degradation	Kato *et al.* (2001a, 2001b)
3	*Lagenaria siceraria* (Landrace)	*Watermelon* (*Citrullus lanatus* (*thunb.*) Matsum and Nakai) cv. Crimson Tide	Formation of aerenchyma tissue and adventitious roots and the reduction in the chlorophyll loss under flooded conditions	Yetisir *et al.* (2006)
4	Eggplant (*Solanum melongena*) cv. Arka Neelkanth, Mattu Gulla, BPLH1 and Arka Keshav	*Tomato* (*Solanum lycopersicum*) cv. Arka Rakshak	1. Lesser decline in photosynthetic rate and chlorophyll fluorescence 2. Stomatal conductance and CO_2 concentration 3. Enhanced physiological adaptation and better fruit yield	Bhatt *et al.* (2015)
5	Eggplant (*Solanum melongena*) cv. IC-354557, IC-111056, IC-374873, CHBR-2	Tomato (*Solanum lycopersicum*) Hybrid line cv. Arka Rakshak, Arka Samrat	Less reduction in chlorophyll content and chlorophyll fluorescence yield	Bahadur *et al.* (2015)

mean air temperature, could be the reason for the reduced availability of irrigation water. An upsurge in evapotranspiration would also be anticipated under drought conditions, as vegetables contain about 90% water (Brown *et al.* 1997; Thomas *et al.* 2007, 2011).

Under the scenario of global climate change, water availability and drought stress become critical environmental stressors (Schwarz *et al.* 2010). Therefore, grafting could be used to decrease production losses and increase the water use efficiency (WUE) during water scarcity. This could be accomplished by grafting high yielding susceptible commercial cultivars onto rootstocks capable of reducing the effect of water stress on the shoot. For eggplant, tomato hybrids are popular rootstocks in Europe, including *Solanum* spp., and interspecific hybrids. Similarly, grafting watermelon (*Citrullus lanatus*) onto pumpkin (*Cucurbita moschata*) rootstocks helps reduce the water stress of the watermelon shoots (Davis *et al.* 2008; King *et al.* 2010).

To manage or improve drought tolerance, grafting plants onto tolerant rootstock have been practised in vegetable crops, particularly in solanaceous and cucurbitaceous vegetable crops (Sánchez-Rodríguez *et al.* 2016). For example, a recent study was conducted by Sanchez-Rodriguez and Ruiz (Liu *et al.* 2016) in tomato using a drought-tolerant cultivar and drought-sensitive cultivar to obtain grafted plants in different combinations. Results of this study showed that the antioxidant enzymes varied in fruits of non-grafted and grafted plants under drought stress. In cucumber, it has been documented that grafting improved the WUE by affecting the ABA biosynthesis pathway (Sakata *et al.* 2007) which enhanced plant growth and yield. Osmotic manipulations occurred in accordance with the water stress level when sensitive pepper plants were grafted with the relatively tolerant rootstocks (Penella *et al.* 2014). The parallel study showed that the efficient production of micro- and macronutrients (vitamins and sugars) in the grafted tomato plants resulted in more plant vigor and eventually increased economic yield (Ibrahim *et al.* 2014).

At the genetic level, microRNAs (miRNAs) controlled the growth and development of plants and showed a specific response to various environmental stressors. According to Li *et al.* (2016), scion of watermelon (*Citrullus lanatus*) grafted onto bottle gourd (*Lagenaria siceraria*) or squash (*Cucurbita maxima* × *Cucurbita moschata*) rootstock elicited a change in the expression of more than 40 miRNAs. Furthermore, molecular mechanisms of 17 selected miRNAs in grafted plants under drought stress were studied in recent investigations by grafting cucumber plants onto pumpkin (*Cucurbita moschata*) rootstock. Consequently, the experiment involved mini-watermelon cv. Ingrid, either non-grafted or grafted using rootstock 'PS 1313' (*Cucurbita maxima* × *Cucurbita moschata*), and results pointed out that grafted plants exhibited higher yield, nutritional, and fruit quality-related parameters than non-grafted plants. Whereas no significant difference was observed between grafted and non-grafted plants in gas exchange and leaf water relations. However, even though sensitivity to water stress was similar between grafted and non-grafted plants, the higher marketable yield was recorded with grafting. The results of this study specifically demonstrated the benefit of rootstock 'PS 1313', whereas the use of grafted rootstock plants has been more broadly recommended especially under drought conditions to manage drought stress (Rouphael *et al.* 2008). Another study which compared drought-tolerant rootstocks for watermelon concluded that wax gourd is a better rootstock than bottle gourd under drought-prone conditions (Muneer *et al.* 2016). Apart from these examples of the molecular-level physiological response of grafted vegetables to drought stress, other critical physiological responses, such as changes in stomatal conductance, which increased the WUE and photosynthetic activity, have been documented in the stress-prone environment. In the case of sweet pepper grafted on the rootstock Creonte, López-Marín *et al.* (2017), under a Mediterranean climate, demonstrated that crop total and marketable fruit yield increased by 30 and 50%, respectively. Furthermore, this rootstock maintained 30–60% higher leaf photosynthetic activity and exhibited a significantly higher (10%) WUE. Whereas, for the tomato cultivar Amelia, improved photosynthesis and stomatal conductance were observed when the cultivar Maxifort was used as the rootstock (Chaudhari *et al.* 2017). Therefore, grafting drought-sensitive commercial cultivars of vegetable crops onto vigorous and tolerant/resistant rootstock would be a viable practice for plants in areas prone to water stress. The benefits of grafting demonstrated in the preceding studies included the maintenance of a high capacity for water and nutrient uptake along with the greater WUE under drought conditions. Additional examples of vegetable grafting studies conducted under drought stress are provided in Table 2.

Thermal stress

Temperature extremes can result in vegetable production losses by promoting wilt and necrosis, retarding the rate of truss appearance, and impacting the timing of fruit ripening. Grafting can be used to protect plants from thermal shock and help plants perform even better in terms of yield due to the associated physiological changes in the grafted plant (Rivero *et al.* 2003a). Vegetable crops are highly sensitive to both low and high temperatures. High-temperature conditions are usually seen during the growing season in a tropical environment, while during the winter, spring, and autumn season in the temperate and sub-tropical regions, chilling or low temperature is a serious problem for vegetable production especially for tomato, squash, cucumber, and watermelon.

Furthermore, low temperatures impact seed germination, seedling growth, and plant development resulting in an economic yield loss (Venema *et al.* 2008). For example, in tomato, high temperatures cause significant losses in crop productivity due to decreased fruit set, small fruit size, and lower fruit quality. Similarly, depending on the intensity and length of exposure, low temperature leads to irreversible dysfunction, cell death, and finally plant death. Early fruit yield and quality characteristics are also influenced by temperature. Efforts were made to

Table 2 | Examples of top-performing rootstock and scion combinations in vegetable crops under induced drought stress

Sl. no.	Rootstock	Scion	Key improved characteristics	Reference
Drought stress				
1	PS 1313 (*Cucurbita maxima Duchesne* X *Cucurbita moschata Duchesne*)	Watermelon (*Citrullus lanatus* (thunb.) Matsum and Nakai) cv. Ingrid	Enhanced water and nutrient uptake (N, Mg, and K) and increased CO_2 assimilation	Rouphael *et al.* (2008)
2	Tomato (*Solanum lycopersicum*) cv. Beaufort	Tomato (*Solanum lycopersicum*) cv.M28	Increased total carotenoid and proline content, less reduction in chlorophyll *b* concentration, and increased biomass	Altunlu & Gul (2012)
3	Pepper (*Capsicum annum* L.) cv. Verset	Pepper (*Capsicum annum* L.) cv. Atlante, PI-15225 and ECU-973	Efficient osmotic adjustment was observed resulting in the optimum function of photosynthetic machinery in water stress conditions	Penella *et al.* (2014)
4	Tomato (*Solanum lycopersicum*) cv. Zarina	Tomato (*Solanum lycopersicu*m) cv. Josefina	Development of better radicular system and enhanced uptake of micronutrients like Fe, Cu, N, P, and K	Sánchez-Rodríguez *et al.* (2014)
5	Tomato (*Solanum lycopersicum* L.) cv. Faridah	Tomato (*Solanum lycopersicu*m L.) cv. Unifort	Grafting resulting in more vigorous plants and better fruit quality (increased vitamin C, total soluble salts, and total sugar levels)	Ibrahim *et al.* (2014)
6	Tomato (*Solanum lycopersicum* L.) cv. Jjak Kkung	Tomato (*Solanum lycopersicum* L.) cv. BHN 602	Reduction in aboveground growth and increase in the photosynthetic activity	Nilsen *et al.* (2014)
7	Tomato (*Solanum lycopersicum* L.) cv. Unifort	Tomato (*Solanum lycopersicum* L.) cv. Farida	Increased WUE, growth, and yield were observed in grafted plants	Wahb-Allah (2014)
8	Sweet pepper (*Capsicum annum*) rootstock lines Atlante, Terrano and Creonte	Sweet pepper (*Capsicum annum*) cv. Herminio	High photosynthetic activity, leaf water content, and more stable leaf area and the maintenance of high reproductive/ vegetative ratio	López-Marín *et al.* (2017)
9	Tomato (*Solanum lycopersicum*) cv. Beaufort and cv. Maxifort	Tomato (*Solanum lycopersicum*) cv. Amelia	Improved photosynthesis and stomatal conductance were observed	Chaudhari *et al.* (2017)

develop cultivars with improved thermal stress tolerance using breeding and biotechnology but with limited commercial success since such stresses are genetically complex and plant specific. Therefore, as a rapid and efficient alternative, grafting existing elite commercial cultivars onto selected low-/high-temperature-tolerant rootstocks may be regarded as a viable plant propagation technique.

Low-temperature tolerance of the rootstock is one of the most desirable traits for vegetable production in the greenhouse during winter or early spring. den Nijs (1980) conducted a grafting experiment to manage low temperature by taking four advanced breeding lines and *Cucurbita ficifolia* as the rootstock in the Netherlands. This experiment illustrated that grafted plants performed outstandingly in terms of survival, longevity, and fruit quality compared to non-grafted plants under low-temperature conditions. This study was carried forward by Horvath *et al.* (1983) with the observation that cucumber plants grafted on *C. ficifolia* rootstock enhanced trans-hexadecenoic acid in phosphatidyl glycerol, which helps with low-temperature tolerance in plants. In Morocco, *C. ficifolia* is also the preferred rootstock for cucumbers and is an excellent rootstock for low soil temperature tolerance, particularly for spring production in winter (Besri 2008). The cultivated tomato is highly sensitive to suboptimal and chilling temperature throughout its growth and development stages. To increase tolerance to low-temperature stress in tomato, the grafting of high yielding commercial and susceptible cultivars onto tolerant rootstock is considered as a rapid technique. For instance, the tomato cultivar Moneymaker was grafted onto the *Solanum habrochaites* accession (LA) 1777 of the wild tomato to study the effect of low temperature by Venema *et al.* (2008). The authors determined that grafting tomato onto wild tomato rootstock exhibited the high relative growth rate of shoots and higher root mass ratios under low temperature as compared to selfed and non-grafted plants. Therefore, the results of this study document the wild tomato *Solanum habrochaites* accession (LA) 1777 as another rootstock option when managing suboptimal root zone temperature in tomato and other solanaceous vegetable crops. Additional studies in tomato also revealed the role of resistant rootstock in maintaining an optimal level of hydraulic and stomatal conductance during temperature-related stress (Bloom *et al.* 2004). Furthermore, such effects are known to be much weaker in grafted compared to non-grafted plants, directly reflected in higher biomass production. The results of this study suggested the practical use of grafted plants under extremely high-temperature conditions. Furthermore, the same research groups in the separate study explained that heat stress in both grafted and non-grafted tomato plants increased phenylalanine ammonia lyase (PAL) activity, increased total phenols, and increased *o*-diphenols, decreased polyphenol oxidase (PPO), and guaiacol peroxidase (GPX) activities and decreased dry weight. However, the influence of stress was reduced in grafted compared to non-grafted tomato plants (López-Marín *et al.* 2013). Better performance of grafted plants in thermal stress conditions can also be attributed to better RuBisCO activity and higher photosynthetic efficiency (Zhou *et al.* 2007). In the case of pepper, studies were conducted to test the behavior of non-grafted and grafted cultivar Herminio plants onto three rootstocks (Atlante, Create, and Terrano) under shaded and non-shaded conditions. The grafted plants performed better than non-grafted under both conditions. About 40% more leaf area was recorded in plants grafted onto Atlante rootstock than the other combinations but found neutral for Atlante. Grafting onto Creonteeli resulted in no significant effect on leaf biomass. However, there was a 30–50% greater total and marketable fruit yield produced by grafted plants under non-shaded and shaded conditions compared to the non-grafted plants. Thus, the rootstock Creontemay is more effective at overcoming thermal stress when grafted to sweet pepper (del Amor *et al.* 2008). The additional studies conducted by del Amor *et al.* (2008) and Colla *et al.* (2008) also documented that sweet pepper-grafted plants produced higher marketable yields under Mediterranean climatic conditions.

For tomato cultivation, high day and night temperatures influence fruit setting, resulting in yield loss. A study associated with high-temperature stress was conducted to test grafted plants of tomato under high-temperature stress. The plants of heat-sensitive tomato cultivar ‘UC 82-B’ were grafted onto the heat-tolerant tomato cultivar rootstock ‘Summerset’ and the eggplant cultivar rootstock ‘Black Beauty’. The results indicated that plants grafted onto the Black Beauty rootstock exhibited significantly more chlorophyll fluorescence at late fruiting stage, greater leaf area, and lower values of electrolyte leakage than non-grafted 'UC 82-B' at 37/27 °C (day/night), whereas no positive effect of grafting on total yield was reported by Abdelmageed & Gruda (2009). Recently, Muneer *et al.* (2016) demonstrated as many as 87 cellular proteins of tomato were responding to temperature fluctuation. Additional studies evaluating the use of vegetable grafting to manage thermal stress are provided in Table 3.

Salinity stress

About 7% of the world area and close to 20% of the arable irrigated land are affected by soil salinity (Shahid *et al.* 2018). Climate change stimulates salinization, and therefore, the amount of saline land has been predicted to increase under climate change scenarios (Shrivastava & Kumar 2015). Salinity negatively affects plant production and growth. In order to overcome the impact of salinity and the use of saline soils for vegetable crop production, several strategies have been proposed. Several of the procedures that aim to reclaim saline soils are only a temporary cure and are relatively expensive to implement (Machado & Serralheiro 2017). Similarly, breeding for salt-tolerant vegetable crops has also been considered, but the complex polygenic trait that evokes salt tolerance requires several cycles of plant breeding (Ashraf *et al.* 2008).

The use of resistant genotypes as the rootstocks was deemed to be an easy and efficient technique for improving crop tolerance to salt stress (Koevoets *et al.* 2016). In the past decade, studies have investigated the salt tolerance of grafted vegetable crops and most of the studies have concluded that grafting is a highly efficient way to improve salt tolerance (Colla *et al.* 2010). Interspecific hybrid rootstock has improved the salt tolerance of the grafted tomato plants (Di Gioia *et al.* 2013). When bottle gourd was used as a rootstock, the salt tolerance capacity of watermelon plants improved several-fold (Yang *et al.* 2013). In the case of muskmelon, Orsini *et al.* (2013) found that interspecific squash rootstock (*Cucurbita*

Table 3 | Examples of top-performing rootstock and scion combinations in vegetable crops under induced thermal stress

Sl. no.	Rootstock	Scion	Key improved characteristics	Reference
Thermal stress				
1	Tomato (*Solanum lycopersicum*) cv. RX-335	Tomato (*Solanum lycopersicum*) cv. Tmknvf2	1. Increased PAL activity 2. Decreased PPO and GPX activity 3. Decrease in dry weight 4. Increase in total phenols and *o*-diphenols	Rivero *et al.* (2003b)
2	Tomato (*Solanum lycopersicum*) cv. LA1778	Tomato (*Solanum lycopersicum*) cv. T5	Root hydraulic conductance and stomatal conductance were maintained in grafted plants	Bloom *et al.* (2004)
3	Figleaf Guard (*Cucurbita ficifolia Bouché*)	Cucumber (*Cucumis sativus*) cv. Jinyan No. 4	Lesser reduction in the carboxylation activity and RuBisCO activity resulting in comparatively higher CO_2 assimilation	Zhou *et al.* (2007)
4	Tomato (*Solanum habrochaites*) breeding line LA1777	Tomato (*Solanum lycopersicum*) cv. Moneymaker	1. Higher root mass ratio 2. High total leaf carbon concentration	Venema *et al.* (2008)
5	Tomato (*Solanum lycopersicum*) cv. Summerset and Eggplant (*Solanum melongena*) cv. Black Beauty	Tomato (*Solanum lycopersicum*) cv. UC 82-B	1. Larger leaf area, more leaf fresh and dry weight 2. Higher chlorophyll fluorescence 3. More pollen grains/flower	Abdelmageed & Gruda (2009)
6	Figleaf Guard (*Cucurbita ficifolia*) and Luffa (*Luffa cylindrica*) cv. Xiangfei	Cucumber (*Cucumis sativus*) cv. Jinyan No. 4	1. Higher biomass production and CO_2 assimilation capacity 2. Decrease in lipid peroxidation and protein oxidation	Li *et al.* (2014)

Table 4 | Examples of top-performing rootstock and scion combinations in vegetable crops under induced salinity stress

Sl. no.	Rootstock	Scion	Key improved characteristics	Reference
Salinity stress				
1	a) Macis (*Lagenaria siceraria* Standl., Nunhems Zaden, The Netherlands) b) Ercole (*Cucurbita maxima* Duchesne X *Cucurbita moschata* Duchesne, Nunhems Zaden, The Netherlands)	Watermelon (*Citrullus lanatus*) cv. Tex	Increased total soluble solid content, dry matter, and sugar content	Colla *et al.* (2006)
2	a) Black seeded figleaf gourd (*Cucurbita ficifolia* Bouché) b) Chaofeng Kangshengwang (*Lagenaria siceraria* Standl.)	Cucumber plant (*Cucumis sativus* L.) cv. Jinchun No. 2	Grafted plants possessed significantly higher scion dry weight, more soluble sugars and micronutrient content	Huang *et al.* (2010)
3	*Cucurbita* hybrid rootstocks (*Cucurbita maxima* Duch. X *Cucurbita moschata* Duch.) ‘P360’ and ‘PS13132’	a) Melon (*Cucumis melo* L.) cv. Cyrano b) Cucumber (*Cucumis sativus* L.) cv. Akito	1. Lesser reduction in the leaf area index in grafted plants. 2. Smaller effect of salinity on the net photosynthetic rate (P_N) and stomatal conductance (g_s) in grafted individuals	Rouphael *et al.* (2012)
4	*Cucurbita* hybrid rootstock (*Cucurbita maxima* Duch. X *Cucurbita moschata* Duch.) ‘PS1313’	Cucumber (*Cucumis sativus* L.) cv. Akito	Relatively higher chlorophyll content (SPAD index), better net assimilation rate, and higher nutritional value	Colla *et al.* (2012)
5	a) Cucumber (*Cucumis sativus* L.) cv. Affyne b) *Cucurbita* hybrid rootstock (*Cucurbita maxima* Duch. X *Cucurbita moschata* Duch.) ‘P360’	Cucumber (*Cucumis sativus* L.) cv. Ekron	1. Higher PSII photochemical activity 2. Lesser reduction in chlorophyll content (SPAD index)Better GPX activity resulting in the enhanced antioxidant system	Colla *et al.* (2013)

(*continued*)

Table 4 | continued

Sl. no.	Rootstock	Scion	Key improved characteristics	Reference
6	Interspecific tomato hybrid rootstocks (*Solanum lycopersicum* X *S. habrochaites*) 'Maxifort'. 'Arnold' & 'Armstrong'	Tomato (*S. lycopersicum* L.) cv. Cuore di Bue	Higher fruit juice Na^+ content	Di Gioia *et al.* (2013)
7	Chaofeng Kangshengwang (*Lagenaria siceraria* Standl.)	Watermelon (*Citrullus lanatus*) cv. Xiuli	Increase in the total biomass and NO_3^-	Yang *et al.* (2013)
8	Interspecific squash rootstock (*Cucurbita maxima* Duch. X *Cucurbita moschata* Duch.) 'RS841 improved'	Melon (*Cucumis melo* L.) cv. Brennus and London	1. Improved plant biomass and leaf area 2. Enhanced ion partitioning resulting in the selective uptake of K^+ 3. Better stomatal regulation under salt stress conditions	Orsini *et al.* (2013)
9	Pumpkin (*Cucurbita moschata* Duch.) cv. Chaojiquanwang	Cucumber (*Cucumis sativus* L.) cv. Jinchun No. 2	1. Relatively higher activities of dehydroascorbate reductase, ascorbate peroxidase, and glutathione reductase were observed in the chloroplasts of grafted plants providing better H_2O_2-scavenging capacity 4. Enhanced net CO_2 assimilation and transpiration rates	Zhen *et al.* (2011)
10	a) *Capsicum chinense* Jacq. 'ECU-973' *Capsicum baccatum* L. var. *pendulum* 'BOL-58'	Pepper (*Capsicum annum*) cv. Adige	2. Lesser negative impact on the nitrate reductase activity, photosynthetic rate, and lipid peroxidation	Penella *et al.* (2014)

maxima × *Cucurbita moschata* Duch.) increased salt tolerance, along with plant biomass and leaf area, in the grafted muskmelon compared to non-grafted control plants. Additional studies evaluating vegetable grafting to manipulate salt tolerance are provided in Table 4.

CONCLUSION AND FUTURE RECOMMENDATIONS

In summary, grafting scion and rootstock of genetically diverse vegetable crops with the goal of mitigating environmental stressors predicted under a changing global climate scenario have been documented in the scientific literature as a promising technique. New research should be conducted to evaluate and test elite diverse germplasm as a source of the viable rootstock. However, realizing the full potential of the grafting methodology is based on several factors, such as the appropriate selection of scion and rootstock, the geographical location, scion–rootstock communication, and the reciprocal effect of the shoot and root system. Additional research is needed to develop automated grafting platforms which scale-up this technique, so that grafting can become an integral component of modern vegetable crop production. Only then can progress in modern simulation and automated grafting techniques for the production of grafted plant material become more economically accessible to vegetable farmers. Moreover, vegetable grafting is followed in the developed parts of the world owing to the updated knowledge of the farmers regarding the modern vegetable production technology.

Vegetable grafting will help growers to deal with climate change and to overcome the unsustainable vegetable production practices which result in soil degradation and the rapid depletion of natural resources. In the future, research involving the development of grafting technologies ideal for the stable, year-round, and economical production of seedlings is required, so that this technology becomes more accessible to farmers in every part of the world.

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