Vegetable Science (2024) Vol 51 (Special Issue): 22-33

doi: 10.61180/vegsci.2024.v51.spl.03

ISSN- 0970-6585 (Print), ISSN- 2455-7552 (Online)

www.isvsvegsci.in

REVIEW ARTICLE

Grafting in Tomato for Improving Abiotic Stress Tolerance, Yield and Quality Traits

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Abstract

Tomato (*Solanum lycopersicum* L.) is a major vegetable crop worldwide, however, its production is adversely affected by a wide range of abiotic and biotic stresses at various stages of its cultivation. Abiotic stresses, such as drought, salinity, flooding, extreme temperatures and heavy metals can cause morphological, physiological and biochemical changes in the plant, which ultimately affect crop growth, yield and quality. Among various mitigation strategies, grafting technology has emerged as an effective and alternative tool to slow breeding programs to alleviate various biotic and abiotic stresses. Various studies indicated that increased osmolytes accumulation, synthesis of antioxidant enzymes, improved photosynthesis and vigorous root architecture in grafted tomatoes confer tolerance towards abiotic stresses, besides improving plant growth and fruit yields. Moreover, tomato grafting on suitable rootstocks has also a positive effect on the nutritional qualities of fruits, such as, lycopene, β-carotene, ascorbic acid, proteins, etc.). In this review, we have tried to summarize the adverse effects of abiotic stresses in tomatoes and include all possible recent references related to the response of grafted tomatoes using different intra-and/ or inter-specific rootstocks on improving plant growth, yield and quality and alleviation in various abiotic stresses.

Keywords: Grafting, vegetables, abiotic stress, yield, quality.

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Citation: Bahadur, A. and Kumar, R. (2024). Grafting in Tomato for Improving Abiotic Stress Tolerance, Yield and Quality Traits. Vegetable Science 51(spl): 22-33.

Source of support: Nil

Conflict of interest: None.

Received: 05/08/2023 **Revised:** 09/01/2024 **Accepted:** 18/01/2024

Introduction

Tomato (*Solanum lycopersicum* L.) is a major vegetable crop grown in India with an acreage of 8.41 lakh hectares, and an annual production of 20.33 million tonnes (PIB, 2022). Tomato production faces several constraints, including biotic and abiotic stresses that hamper its production worldwide. Abiotic stresses are the primary cause of crop loss, and worldwide about 50% yield decrease is associated with various environmental stressors (Reimers, 2000). Furthermore, vegetables are more prone to a wide range of abiotic stresses, such as drought, salinity, flooding, and extreme temperatures (Moretti *et al*., 2010). It has been reported that environmental component (E) contributed 71 to 86% to the total variation in tomato yield traits, genotype (G) 1.5 to 10.8%, while the contribution of G × E ranged between 4.3 to 6.7% (Djidonou *et al*., 2020). Tomatoes productivity is limited by various environmental constraints (Table 1; Fig. 1). To overcome these issues, breeding tolerant cultivars is cumbersome, and a time-consuming approach. On the other hand, grafting technology has emerged out an alternative tool of slow breeding programs to alleviate various abiotic stresses effectively (Table 2; Fig 2).

Grafting has been practiced in fruit trees for a long time; however, its application in vegetables is relatively new. Vegetable grafting began in Japan in 1927 wherein

Table 1: Threshold level of abiotic stresses and their impact in tomato

Abiotic stress	*Optimum*	*Threshold level*	*Effect below or above threshold*
Temperature	Mean daily 21–24°C; Standard day/night 25˚C /16°C	Minimum 12°C Maximum 35°C Chilling injury < 15°C	High temperature (32°C and above) impairs pollen and anther development, reduces pollen viability, exerted stigma, low fruit set, size and yield with poor lycopene development; Low temp. (<15°C) reduces growth rate, no. of flowers, fruit set, yield and quality (Vitamin C, TSS and lycopene); Low root-zone temperature (10 ± 2°C) decreases uptake of nutrients and photosynthesis
Salinity	0.25–0.50 dSm^{-1}	2.5 dSm^{-1}	Reduced uptake of water and nutrients; 50% yield losses at 7.5–8 dSm^{-1}
Water deficit (drought)	Field capacity (FC) or 100% ASM or -0.35 to -0.40 bars	Maximum 50% depletion in surface irrigation to 10–15% in drip irrigation	Leaf yellowing and plant wilting, flower and fruit drops, reduction in yield, fruit cracking, blossom-end-rot
Flooding/ waterlogging	Near to FC or 20–25% depletion in ASM	24 hours flooding at high temp. and 48 hours at low ambient temp.	Hypoxia and anoxia: yellowing, wilting, prone to attack of diseases, loss in yield
Relative humidity	65–80% or VPD 4-8 mbars	Minimum 60% Maximum 85%	Excessive RH negatively influences pollen release and distribution on the stigma, blotchy ripening and foliar diseases; Low RH causes loss of pollen viability, poor pollen dehiscence, infertility that leads to small, deformed or hollow fruit, partial wilting and development of blossom-end-rot (BER)
Light	500–800 µmol m^{-2} s^{-1}; standard light intensity 30,000 lux	Minimum 250 Maximum >1200	Low intensity causes low plant growth, leaf area, photosynthesis; high light reduces plant growth, photosynthesis, yield and causes fruit scorching with reduced fruit quality
CO_2	Seedling 800–1000 ppm; Other stages 400–600 ppm	1000 ppm	Low or improved photosynthetic activity, improve plant growth, promote earlier flowering, increase the number of flowers and result in higher yields

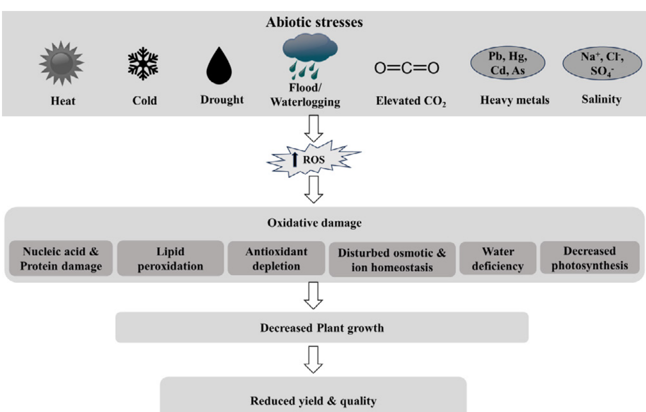

Fig. 1: Abiotic stresses reduce crop yield and quality. Environmental stress factors, such as heat, cold, drought, salinity, and the presence of heavy metals elicit stress responses in plants, including an accumulation of reactive oxygen species (ROS) and subsequent oxidative damage, which ultimately decreases plant growth and thus crop yield and quality

watermelon was grafted on pumpkin to control Fusarium wilt disease. Commercial grafted vegetable production can be traced back between the late 1950s to the early 1960s in Japan and Korea. In both countries, over 90% of watermelon and 75% of cucumber seedlings are grafted onto various rootstocks. In solanaceous vegetables, 20 to 40% of tomatoes are grafted, 20 to 40% of eggplants and 5 to 10% of peppers (Lee *et al*., 2010). Grafting is a unique asexual plant propagation technique that uses a high-yield scion, and a stress-resistant/vigorous rootstock to enhance productivity. The grafted plant combines the characteristics of two different plants. The rootstocks (lower part) used in grafting are usually close relatives or wilds (mostly within the genera) of the scion crop, and have tolerance for biotic (pathogens), abiotic stresses (environmental stress) and plant vigor, whereas the scion (upper part) has some peculiar qualitative and quantitative horticultural traits. Earlier, grafting technology was used mostly for tolerance to soil-borne diseases and nematodes (Rivard *et al*., 2010; Barrett *et al*., 2012), but in recent pasts, it has also been widely used to mitigate the adverse effects of several abiotic stresses such as salinity (Coban *et al*., 2020), thermal stress (Han *et al*., 2019), nutrient absorption and translocation (Savvas *et al*., 2017), heavy metals (Xie *et al*., 2020) and water deficit or drought (Zhang *et al*., 2019). Additionally, improving fruit yield and quality are other advantages exhibited by tomato grafting (Turhan *et al*., 2011; Djidonou *et al*., 2013; Sabatino *et al*., 2021). Besides several benefits of grafting technology, there are some disadvantages in adopting grafting technology

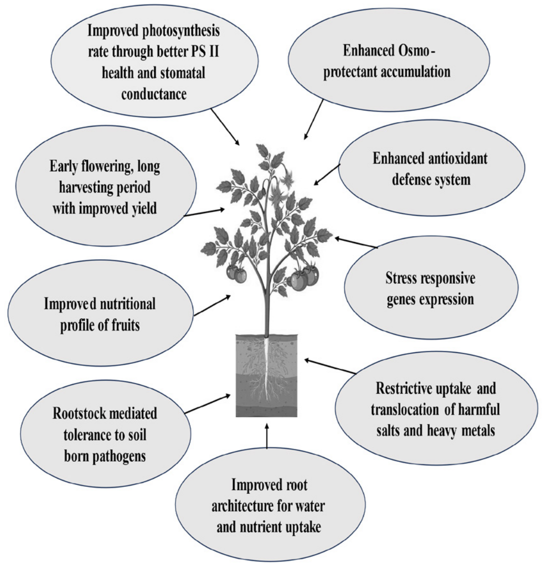

Fig. 2: Strategies to alleviate the impact of abiotic stresses

in vegetable crops (Bahadur *et al*., 2024). A recent study conducted by Bento-Da-Silva (2023) on the status of publications related to grafting reveals that the number of publications on tomato grafting has increased at an annual rate of 8.8% from 1944 to 2020; USA and Spain have the maximum number of published and cited articles on tomato grafting. Grafting technology, however, is not always useful for enhancing the productivity of tomatoes. Grieneisen *et al*. (2018) conducted a meta-analysis of 949 combinations of scion/rootstock of different tomato cultivars, and they reported that grafted tomato yields were not significantly improved in 65% of the combinations, however, an average 37% yield increase was observed overall data evaluated.

Abiotic Stress Tolerance

Temperature stress

Temperature is one of the important environmental factors that affect the productivity of tomatoes. Although tomato plants can grow under a wide temperature regime, however fruit set and productivity are greatly limited when the maximum temperatures (day-time) exceed 32°C and the minimum temperature (night) falls below 21°C (Picken, 1984). In tomatoes, an optimum average day and night temperature requirement for plant growth, fruit set and yield ranges between 21 to 29.5°C and 18.5 to 21°C, respectively (Jones, 2007).

Low temperature or cold stress

Low temperature is one of the most common abiotic stresses that reduce the productivity of crops (Duan *et al*., 2012), and about 25% of the entire area of the world's land are affected with cold stress (Peel *et al*., 2007). Tomato is considered as cold-sensitive vegetable, and plant growth and development are severely affected below 12°C (Elizondo & Oyanedel, 2010; Ronga *et al*., 2018). Chilling injury in tomato fruit occurs if they are exposed to temperatures of 10°C for longer than 14 days or temperatures of 5°C for about one week. Low-temperature or sub-optimal temperature above the chilling temperature also reduces growth rate, and photosynthesis, and delays the truss appearance and fruit growth. The appearance of injury symptoms depends upon the plant sensitivity, exposed temperature, and duration of cold stress. Cold stress damage in plants may appear after 48 to 72 hours of stress exposure. Cold stress during anthesis induces flower dropping, sterility of pollen, pollen tube distortion, ovule abortion and reduced fruit set, which leads to a reduction in growth and fruit yields. Tomato plant exposed to low temperatures at the vegetative stage, the most noticeable injury symptoms exhibited as stunted seedlings, leaf-hypocotyl wilting, chlorosis and necrosis (Cao *et al*., 2015; Atayee and Noori, 2020), whereas at the reproductive stage, poor pollen viability, low fruit set and yield, and poor fruit quality (vitamin C, TSS and lycopene contents) are the consequences of low-temperature stress (Xiaoa *et al*., 2018). Besides, temperatures below 10°C during flowering also cause hindrance in pollination resulting in catface disorder in fruit. Biochemical and physiological responses such as electrolyte leakage, proline content, chlorophyll contents and photosynthetic rate are also related to low-temperature stress in tomatoes.

Grafting technology has been found an effective tool for coping up low-temperature tolerance in tomatoes. Cold-tolerant rootstocks may overcome limitations in water absorption at chilling temperatures by increasing root hydraulic conductance, decreased induction of cell wall suberin layers, lipid peroxidation and closure of the stomata (Bloom *et al*., 2004). Tomato, rootstocks of the high-altitude accession LA 1777 (*Solanum habrochaites* syn. *S. hirsutum*), KNVF (the interspecific hybrid of *S. lycopersicum* × *S. habrochaites*,), and back-crossed progeny of *S. habrochaites* LA 1778 × *S. lycopersicum* cv. T5 are able to alleviate low root-temperature stress for different scion cultivars of tomato (Bloom *et al*., 2004; Venema *et al*., 2008). Ntatsi *et al*. (2014) also demonstrated that LA 1777 improved low-temperature tolerance (14.6–17°C) in tomatoes (cv. Kommeet) by increasing soluble carbohydrates, amino acids and POD activity in roots with no effect on a number of flowers and fruit production. Similarly, Wang *et al*. (2023) obtained better cold tolerance (4°C) in tomatoes through use LA 1777 rootstock by promotion of jasmonic acid (JA) accumulation in scion, enhanced antioxidant enzyme activity and ROS scavenging potential of scion. Earlier, Suchoff *et al*. (2018) also noticed larger leaf area, fine root length, higher CO_2 assimilation and photosystem II quantum efficiency when tomato plants (cv. Moneymaker) were grafted onto Multifort (*S. lycopersicum x S. habrochaites*) and LA 1777, and exposed to 15°/15°C (day/night) temperatures.

Table 2: Grafting technology for abiotic stress tolerance in tomato

Stress	*Rootstock*	*Tomato scion cultivar*	*Improved feature with mechanism*	*Reference*
Drought/water deficit	Zarina and Josefina (tomato)	Zarina and Josefina	Higher SOD and CAT activities, and decreased in ROS, MDA and DHA concentration in leaves	Sánchez-Rodríguez *et al*. (2014)
	Beaufort and Multifort (*Solanum lycopersicum* x *S. habrochaites*)	Florida 47	Higher number of fruits and weight, enhanced water and nutrient use efficiency, increased yield (27-30%)	Djidonou *et al*. (2013)
	Josefina (tomato)	Zarina	Drought tolerance by the changes in antioxidant enzyme activities (SOD, CAT) and reduced AsA, MDA DHA content	Sanchez-Rodrigues *et al*. (2014)
	RILs derived from the wild *Solanum pimpinellifolium*	Tomato hybrid TT-115	Induced low biomass and water use, improved fruit yield (40%) and WUE	Cantero-Navarro *et al*. (2016)
	Beaufort, Maxifort and *Solanum pimpinellifolium*	Ramellet	Increased stomatal conductance, photosynthesis and WUE with Beaufort Maxifort rootstocks	Fullana-Pericàs *et al*. (2018)
	Beaufort (*Solanum lycopersicum* x *S. habrochaites*)	Durinta	Increased tomato yield by 40.4- 100.7% with water saving of 25% over non-grafted; improved TSS, Vit C and nutrient content in fruits	Abdulaziz *et al*. (2017)
	Reciprocal grafting of Procera and Micro-Tom (tomato)	Procera and Micro-Tom	Maintained plant growth, modulation in stomatal conductance and WUE, upregulation of drought-tolerance-related gene	Gaion *et al*. (2018)
	606 (drought tolerant tomato)	112 (drought sensitive)	Alleviated phytotoxicity and oxidative damage by regulating antioxidant enzymes under drought stress	Zhang *et al*. (2019)
	Solanum pennellii and *S. peruvianum*	HM 1823	Higher LWP, RWC, photosynthetic rate and WUE with lower MDA and proline content	Alves *et al*. (2021)
	TD1, GS and GF (tomato)	Momotaro	Improved drought tolerance by altered gene expression and regulation of plant hormones, stress response and cell proliferation	Fuentes-Merlos *et al*. (2022)
	Solanum lycopersicum × *S. pennellii* derivative RF4A and RF39	F1 6242	More conservative in water uses with higher plant water status through better stomatal regulation. Higher level of PSII efficiency, signifying better photosynthetic efficiency	Khapte *et al*. (2022)
Waterlogging/ flooding	IC 111056, IC 354557 (brinjal)	Arka Rakshak, Arka Samrath	Better survival up to 4 days of waterlogging; less reduction in CCI, Fv/Fm, better physiological and biochemical adaptation	Bahadur *et al*. (2015, 2016)
	Arka Neelkanth (brinjal)	Arka Rakshak	Plant survival up to 6 days flooding; lesser reduction in photosynthetic parameters; better physiological adaptation and yield	Bhatt *et al*. (2015)
	Maxifort and Beaufort (*S. lycopersicum* x *S. habrochaites*) (tomato)	Dreamer	Better photosynthesis, root biomass and growth performance by buffering negative effect of root hypoxia	Mauro *et al*. (2020)
Cold and chilling	LA 1777 (*Solanum habrochaites*)	Moneymaker	Improved relative growth of shoot and root biomass at low root zone temp (15°C)	Venema *et al*. (2008)
	LA 1777 (*Solanum habrochaites*)	Kommeet	increasing soluble carbohydrates, amino acids and POD activity in roots with no effect on no. of flowers and fruit mass at low temp. (14.6–17°C)	Ntatsi *et al*. (2014)
	Multifort and LA 1777 (*S. lycopersicum x S. habrochaites*)	Moneymaker	Larger leaf area, fine root length, and higher CO_2 assimilation and photosystem II quantum efficiency at 15°/15°C Day/Night temp.	Suchoff *et al*. (2018)
	060112 (tomato)	060911	Resistant rootstocks/scion (060112) displayed the lowest chilling injury index with the lowest electrolyte leakage and higher content of soluble sugar and proline	Han *et al*. (2018)
	LA 1777 (*Solanum habrochaites*)	LA 4024, Spr8 mutant, Castlemart	Better cold tolerance (4°C) by promotion of JA accumulation in scion, enhanced anti-oxidant enzyme activity and ROS scavenging potential	Wang *et al*. (2023)

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High temperature/ Heat stress	Rx-335 (tomato)	Tmknvf2	High tolerance in grafted plants with enhanced enzymatic (PAL, PPO, GPX) activities and leaf dry weights at average daily temp. of 35°C	Rivero *et al*. (2003b)
	Summerset (Tom) and Black Beauty (brinjal)	UC 82-B	Better tolerance at 37/27°C Day/ night temp. on brinjal rootstock, High PS II efficiency (Fv/Fm), leaf area, no. of pollen grains	Abdel-mageed & Gruda, (2009)
	B-blocking (tomato)	Super Sunload, Super Doterang	Rootstocks defend against temp. stress by modifying their physiological and proteomic responses to establish a new cellular homeostasis including ion binding /transport, photosynthesis and protein synthesis at high and low 30/15°C (D/N) temperatures	Muneer *et al*. (2016)
	Maxifort (*S. lycopersicum* x *S. habrochaites*)	Tomato	Rootstocks improved heat tolerance and reduced the heat stress-responsive enzymes	Leskovar *et al*. (2022)
	Maxifort (*S. lycopersicum* x *S. habrochaites*)	Celebrity	Thermos-tolerance (38/30°C, day/night) by Increased leaf APX, root SOD and CAT, and decreased root POD, lower chlorophyll: carotenoid ratios and higher total leaf soluble proteins	Lee *et al*., (2023)
Salinity	Zhezhen No. 1	Hezuo903	Improved the photosynthesis activity with higher Gs, PSII efficiency and WUE under saline conditions (100 and 150 mM NaCl); increased antioxidant system and decreased lipid peroxidation	He *et al*. (2009)
	Maxifort and Arnold (*Solanum lycopersicum* x *S. habrochaites*)	Cuore di Bue	Higher capacity to modulate shoot Na^+ partitioning by increasing Na^+ accumulation in older leaves and reducing in younger and active leaves; Maintenance of higher K^+/Na^+, Ca^{2+}/Na^+, and Mg^{2+}/Na^+ ratios	Di Gioia *et al*. (2013)
	Unifort (*Solanum lycopersicum* × *S. habrochaites*)	Farida	High plant growth, yield and WUE by exclusion Na+ and Cl- under saline condition (EC 4.5 dS m^{-1}). Lower fruit quality (Vit. C and TSS)	Wahb-Allah. (2014)
	Hasankeyf (Tobacco)	Elazig	High leaf and shoot growth, enhanced proline content and antioxidant activity (APX and CAT)	Iseri *et al*. (2015)
	Maxifort	Buran and Berberana	Less fruit weight reduction, and no change in total phenols, flavonoids, ascorbate and lycopene content in the fruits of grafted plants at 6.95 dSm-1 salinity	Koleška *et al*. (2018)
	Tom 174 (tolerant), Tom 121 (susceptible)	Tom 174, Tom 121	Ameliorating leaf osmotic adjustment of the sensitive genotype under salt stress (50 mM NaCl). Reduced yield loss with improved fruit size, total dry matter content and vitamin C content	Coban *et al*. (2020)
	LA1995, LA2711, LA2485, LA3845	Bark	Based on molecular, physiological and agronomical traits, all 4 rootstocks exhibited better performance under salinity stress (100 and 200 mM NaCl) with enhanced plant shoots, root growth, fruit yield and fruit quality (Vit. C, firmness and TSS)	Abdeldym *et al*. (2020)
	Charlotte (potato)	Ikram (tomato)	Un-changed in total plant dry mass of tomato, improved salt tolerance (saline water with 5 EC dS/m) and water productivity through distinct changes in dry mass allocation and mineral-compartmentalization	Parthasarathi *et al*. (2021)
	IC-111056 and IC-354557 (brinjal)	Kashi Aman	Improved relative water content and chlorophyll SPAD index along with higher proline and antioxidant enzyme activities, rootstocks mediated the partitioning of toxic saline ions in the scions with irrigating EC 6 and 9 dS m-1 saline water	Sanwal *et al*. 2022

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Heavy metal	Maxifort, Unifort (*Solanum lycopersicum* × *S. habrochaites*)	Ikram	Higher fruit yield, shoot and root biomass and leaf area esp. on Maxifort. Low Cd and higher Ca, Mg, Fe and Cu uptake at 25–50 µM Cd level	Kumar *et al*. (2015)
	Maxifort, He-Man (*Solanum lycopersicum* × *S. habrochaites*)	Caramba	More accumulated arsenic in roots, and only small amount translocated to shoots and fruits when plant irrigated with arsenic-enriched nutrient solution (100 µg·L^{-1})	Stazi *et al*. (2016)
	Solanum torvum (wild brinjal)	Tomato	Rootstock reduced Cd accumulation by 72% in tomato leaves grown in soils containing 2 mg kg^{-1} Cd.	Yuan *et al*., (2019)
	Solanum torvum and Totosga (wild brinjal), and Banzhen 18 (tom.)	Zhongyanhong 6 (tom.) and Hongyu (cherry tom.)	Significant reduction of Cd in grafted plants and fruits in Cd-contaminated soil (10 mg kg^{-1})	Xie *et al*. (2020)
	Red cherry 5-5-1-1, RTY-3-2	Red cherry 5-5-1-1, RTY-3-2	Root Cd content in grafted plants increased by 53–54%. Improved root, stem, leaf and shoot biomass	Wang *et al*. (2023)
	USP 16 (tom.)	USP 15	Improved Cd tolerance (35 µM $CdCl_2$) index and reduced translocation and accumulation of Cd in leaves	Lupp *et al*. (2023)

Hight temperature or heat stress

In Mediterranean regions, wherein summer temperatures are usually high (35–45°C), tomato production is severely affected with reduced yield and poor fruit quality. Its availability in these regions is adversely suffering during May to July. Furthermore, the anticipated impact of global warming and climate change in the next few decades, its productivity in these areas will suffer greatly. It has been predicted that due to heat stress, the acreage of tomatoes in tropical conditions will be reduced drastically during 2050–2100, especially in open field conditions (Silva *et al*., 2017). Gautier *et al*. (2008) reported that an increase in ambient temperature from 21 to 26°C, the total carotene content in fruits reduced, whereas the lycopene content does not affect. Further, an increase in temperature from 27 to 32°C reduces the ascorbate and lycopene content significantly. In tomatoes, the male function is more sensitive to heat stress damage than the female parts (Hoshikawa *et al*., 2021). The most sensitive stage is early stamen development (anther meiosis) which occurs about 10 days before anthesis. Heat stress thereafter, impairs tapetum function which inhibits micro-gametogenesis. High temperatures also affect pollen viability, pollen release and transfer over stigma, pollen tube growth, and fertilization, resulting in poor fruit set and yields (Sato *et al*., 2006, Pressman *et al*., 2007). A few degrees increase (say 1°C) above an average daily temperature of 25°C can greatly impair reproductive organs, such as pollen viability and female fertility, resulting in a drastic decrease or total failure in fruit setting (Peet *et al*., 1997; Sato *et al*., 2006; Firon *et al*., 2006). Plants activate stress-responsive mechanisms, such as shifts in protein synthesis (e.g., heat shock proteins), detoxification, osmo-protection and stabilization of enzymes and membranes during heat stress (Karkute *et al*., 2021).

Brinjal as a rootstock for tomatoes may confer some degree of resistance to thermal stress (Rivero *et al*., 2003a), because brinjal is better adapted to hot arid climates and it may be a potential rootstock at supra-optimal soil temperature. Abdelmageed and Gruda (2009) reported that heat tolerant tomato cultivar 'Summerset' and the brinjal rootstock 'Black Beauty' showed higher values of chlorophyll fluorescence (Fv/Fm), leaf area, leaf fresh and dry weight, number of pollen grains with lower values of electrolyte leakage than non-grafted plants at 37/27°C (day/night) temperatures, however it could not register any positive effect on reproductive traits including yield. Similarly, Rivero *et al*. (2003b) reported that grafting tomato on heat-tolerant rootstock 'RX-335' decreased H_2O_2 concentration significantly as evidenced by lower oxidative stress at high temperatures due to catalyzing H_2O^+ by synthesis of antioxidant enzymes, such as glutathione peroxidase (GPX) and catalase (CAT). High temperatures (35°C and higher) also promote phenolic buildup in tomato plants by accelerating biosynthesis and preventing oxidation. Muneer *et al*. (2016) observed that 'B-blocking' rootstocks of tomato alleviated the high and low (30/15°C, D/N) temperatures stress by modifying physiological and proteomic responses to establish new cellular homeostasis including ion binding /transport, photosynthesis and protein synthesis in scion cultivars (Super Sunload, Super Doterang). Recently, Lee *et al*. (2023) demonstrated that thermos-tolerance (38/30°C, day/night) in tomatoes was achieved by Increased leaf APX, root superoxide dismutase (SOD) and catalase (CAT), and decreased root POD, lower chlorophyll: carotenoid ratios and higher leaf soluble proteins with use of maxifort rootstock (*S. lycopersicum* x *S. habrochaites*).

Drought or water deficit stress

In recent pasts, unpredictable drought is the most significant element affecting global food security. Water-deficit conditions may also be observed in areas with adequate water due to uneven precipitation. Drought or water deficit severely affects the plant's physiological processes, because of reduced water potential and cell turgidity. A rise in the solute concentration in the soil environment due to drought stress results in an osmotic flow of water out of plant cells. This causes the concentration of solutes in plant cells to rise, which lowers the water potential and interferes with membranes and cell functions including photosynthesis. Vegetables consist of more than 90% water, and drought stress at any stage greatly influences vegetable productivity and quality. In tomatoes, drought stress may cause 50% reduction in yield (Ximénez-Embún *et al*., 2018). Soil moisture deficit at critical growth stages such as active growth, flowering and fruit enlargement greatly reduces vegetable production and product quality (Bahadur *et al*., 2023). Some significant effects of drought stress include in tomatoes are; low fruit set, fruit splitting, cat-face, blossom-end-rot, and poor yields and quality. Under soil-moisture deficit conditions, grafting of high-yielding vegetable cultivars onto tolerant rootstocks can lessen the impact of water stress and is an effective strategy to reduce yield losses and increase water use efficiency (WUE) (Coskun, 2023; Padilla *et al*., 2023).

In tomatoes, Sadeghi *et al*. (2023) exposed plants to moderate and severe drought stress (6–9 days) grafted on different solanaceous rootstocks. It was observed that cherry tomato as rootstock mitigated the adverse effect in scion plants with enhanced plant growth and yields mainly because of vigorous root system, improved uptake of P and K in leaves and roots, and reduction in electrolyte leakage. During stress, it was noticed that the plants activate stress-responsive mechanisms, such as shifts in protein synthesis (e.g., heat shock proteins), detoxification, osmo-protection and stabilization of enzymes and membranes (Karkute *et al*., 2021). Fuentes-Merlos *et al*. (2022) reported that drought tolerance in tomatoes was improved with use of tomato rootstocks 'TD1', 'GS' and 'GF' mainly due to altered gene expression and regulation of plant hormones, stress response and cell proliferation. Khapte *et al*. (2022) reported better tolerance in tomatoes by using *Solanum lycopersicum* × *S. pennellii* derivative rootstocks- 'RF4A' and 'RF39'. These rootstocks expressed more conservatively in water uses with higher plant water status through better stomatal regulation, higher PSII efficiency and better photosynthetic efficiency.

Flooding or waterlogging stress

Flooding or waterlogging conditions cause oxygen starvation in plants due to the slow diffusion of gases in water and from oxygen consumption by microorganisms and plant roots. It has been reported that the flooding problem in tomatoes may be solved by grafting onto tolerant rootstocks, particularly brinjal. Bahadur *et al*. (2015, 2016) and Bhatt *et al*. (2015) achieved 4 and 6 days of waterlogging tolerance in tomatoes, respectively with the use of different brinjal rootstocks. Various physiological, biochemical and yield parameters such as, CCI, chl. a, chl. b and total chl. content, chlorophyll fluorescence yield (Fv/ Fm), photosynthetic rate, CAT, SOD, proline, fruit yields, etc were not much affected in tomato plants exposed to waterlogging conditions (4–6 days) when grafted onto brinjal rootstocks. Similarly, Mauro *et al*. (2020) also found better photosynthesis, root biomass and growth performance by buffering the negative effect of root hypoxia at low root zone oxygen (2–3 mg L^{-1} for 30 days) when tomato (cv. 'Dreamer') was grafted over inter-specific rootstock 'Maxifort' and 'Beaufort' (*S. lycopersicum* x *S. habrochaites*).

Salinity stress

Salinity is the most serious abiotic stress stress and poses a great threat to agricultural productivity. Globally, about one-third of irrigated land is affected with salinity stress and, it is anticipated that by 2050, more than 50% of the world's cultivated land will be affected by soil salinity (Roșca *et al*., 2023). Salinity occurs when there is an excessive accumulation of salts (Na^+, Cl^- and SO_4^-) in the soil or irrigation water. The increase of these salts in soil or irrigation water causes a reduction in the water potential of the root medium, leading to a water deficit in plants. Besides, excess levels of salts can cause ion toxicity and nutrient imbalance, particularly of K^+, Ca^{2+} and Mg^{2+} by disturbing their uptake and/or transport to the shoots (Sholi, 2012).

Grafting technology is known to improve the plant growth and yield of fruit and vegetables under saline conditions. Martinez-Rodriguez *et al*. (2008) noticed an improvement in tomato fruit yield by 40% when 'Moneymaker' was grafted onto either Radja or Pera at 50 mM NaCl; whereas in another study about 80% yield increase was noticed using same the rootstock with different scion ('Jaguar') at the same salt concentration (Estan *et al*., 2005). Furthermore, Fu *et al*. (2022) conducted a grafting study in tomatoes using 11 commercial rootstock genotypes of tomatoes against tolerance to low temperature (10–15°/ 10-5°C Day/night temperatures) and high salinity level (175 mM). They reported that grafting increased tomato yields by 14.6 to 17.2% as compared to non-grafted, however, rootstock genotype did not affect the fruit quality (acidity and TSS), but increased lycopene and ascorbic acid contents significantly. Water salinity also poses problems in tomato production. Such study in tomatoes was conducted by Sanwal *et al*. (2022) by using brinjal rootstocks 'IC-354557' and 'IC 111056'. They reported 20.3 and 49.1%; and 24.41 and 55.9% higher fruit yields over un-grafted tomatoes, respectively to irrigating plants with moderate (EC 6 dS m^{-1}) to high (9 dS m^{-1}) saline water. The tolerant rootstocks mediated the partitioning of toxic saline ions in the scions by promoting higher Na^+ accumulation (24%) in the older and lower leaves than in the active younger leaves (14%) of the grafted plants. Earlier, Di Gioia *et al*.

(2013) also recorded a higher capacity to modulate shoot Na^+ partitioning by increasing Na^+ accumulation in older leaves with reduced accumulation in younger and active leaves and maintaining higher K^+/Na^+, Ca^{2+}/Na^+, and Mg^{2+}/Na^+ ratios in tomato plants grafted over Maxifort and Arnold (*Solanum lycopersicum* x *S. habrochaites*). Tomato grafted on salt-tolerant rootstock 'Tom 174', ameliorating the leaf osmotic adjustment of the sensitive genotype under salt stress (50 mM NaCl) with a significant reduction in yield loss and improvement in fruit size, total dry matter content and vitamin C content (Coban *et al*., 2020).

Heavy metal stress

Heavy metals on agricultural land are not only dangerous for plant growth but also to the environment and human health. Heavy metals, like cadmium (Cd), arsenic (As), lead (Pb), mercury (Hg) and nickel (Ni) have been introduced to agricultural ecosystems through a number of sources, such as industry, reclaimed wastewater, and soil amendments. These sources may result in excessively high levels of NO_3, SO_4, $H_2PO_4^-$, K^+, Ca_2^+, Mg_2^+, and metallic micronutrients (e.g., Cu) in soil. Grafting of vegetables on suitable rootstocks can reduce the entry of heavy metals and excessive trace mineral buildup in aerial portions of the plant, hence cause negative impacts on crop performance and human health. Savvas *et al*. (2009) observed restricted transport of Cu to the leaves and the roots of tomato (cv. 'Belladona') grafted on He-Man rootstock (*Solanum lycopersicum* × *S. habrochaites*). Similarly, Kumar *et al*. (2015) also reported higher fruit yield, shoot and root biomass and leaf area with a lower level of Cd, and higher Ca, Mg, Fe and Cu uptake at 25 to 50 µM Cd level in tomato (cv. 'Ikram') grafted on inter-specific rootstock 'Maxifort'. *Solanum torvum* as a rootstock also reduced the Cd uptake in tomato plants significantly when grown in Cd-contaminated soils (Yuan *et al*., 2019; Xie *et al*., 2020). In tomatoes, Cd alleviation has also been reported by Wang *et al* (2023) and Lupp *et al*. (2023) by grafting on tolerant rootstocks through maximum retention in the root system, and lesser uptake and transport of Cd in scion plants.

Fruit yield and Quality parameters

In fruit vegetables, an improvement in plant growth and yield was observed in several graft combinations. Yield performance varies with the specific rootstock/scion combinations and with the conditions of a given production system. Grieneisen *et al*. (2018) evaluated 949 heterograft treatments (rootstock/scion of different cultivars), and they concluded that grafted plant yields were not significantly higher in 65% of the cases, yet they averaged a 37% yield increase for all data. Khah *et al*. (2006) noticed 32.5, 12.8, 11.0 and 11.1% higher fruit yield in big red tomatoes grafted onto Heman and Primavera (hybrid tomatoes) than the un-grafted in the greenhouse and the open-field, respectively. Tomato grafted on brinjal rootstocks ('EG-203' and *Solanum torvum*) demonstrated better growth and yield than controls, as Latifah *et al*. (2021) established a significant positive relationship between yield, plant growth parameters, and photosynthetic organs, expressed by higher production, greater scion diameter, longer roots, and increased relative growth rate, leaf area ratio, and net assimilation rate of grafted plants compared to the non-grafted plants. Similarly, the grafting experiment on tomato conducted by Chandanshive *et al*. (2023) showed that tomato grafted over wild brinjal rootstock (*S. torvum*) significantly increased the fruit weight, number of fruits per plant and yields over ungrafted control. The grafted plants also expressed no incidence of fusarium wilt with 57 days of extended crop duration. Martinez-Rodriguez *et al*. (2008) observed an improvement in tomato fruit yield (around 40%) when Moneymaker was grafted onto either Radja or Pera compared to self-grafted at 50 mM NaCl, whereas Estan *et al*. (2005) also noticed an increase of 80% in the yield using the same rootstock with different scion (Jaguar) at the same salt concentration. In tomato, fruit yield, fruit index, number of fruits/truss and fruit weights were improved by grafting (Turhan *et al*., 2011).

Vegetable fruit quality is determined in terms of appearance (size, shape, color and absence of defects), firmness, texture, flavor (sugars, acids and aroma volatiles) and health-related compounds (minerals, vitamins and carotenoids) with less undesired compounds such as, heavy metals, pesticides, and nitrates. Grafting is known to affect the quality of fruits in vegetables, including physical properties, flavor and contents of health-related compounds (mainly vitamin C, carotenoids and minerals) (Rouphael *et al*., 2010). Vitamin C and carotenoids such as lycopene and β-carotene, as well as minerals such as phosphorus, potassium, magnesium, calcium, and iron, are crucial molecules for human health. In some studies, grafting did not have any effect on the vitamin C content (Barrett *et al*., 2012), while in others it reduced the amount of vitamin C in tomatoes (Turhan *et al*., 2011; Nicoletto *et al*., 2013). The results obtained by Sora *et al*. (2019) showed that tomato grafting on the suitable rootstock ('Emperador') has positive effects on the nutritional quality of fruits compared with ungrafted tomatoes. Tomato grafted on 'Emperador' had a very good fruit quality i.e., 82.3 and 86.8% extra and first quality fruits, respectively. Buajaila *et al*. (2022) reported that grafting of tomato 'Panzer' on one of three tomato rootstocks 'Estamino', Maxifort' and 'DRO138TX' had a significant effect on plant growth, nitrate-N content in leaves, total and marketable fruit yields than non-grafted plants; however, the grafting did not affect the fruit quality (acidity, β-carotene and lycopene content). According to Di Gioia *et al*. (2010), vitamin C content in tomato fruit grafted onto Beaufort and Maxifort dropped by 14 to 20% when compared to the ungrafted treatment. Fernández-García *et al*. (2004) reported that tomato fruits from grafted Fanny had doubled the lycopene concentration of ungrafted plants. Riga *et al*. (2016) observed 48% increase in lycopene content in grafted tomatoes cv. Brigeor than in non-grafted plants, whereas self-grafted Jack registered 39% increase in lycopene content. They also reported that relative to nongrafted plants, Alligator rootstock resulted in a reduction of 32% amino acid and 16.5% in protein content, while primed induced an increase of 19% in the total essential amino acids and 17% in the protein content in tomato fruits.

Conclusion

Abiotic stresses (low and high temperatures, drought, salinity flooding and heavy metal) are the major causes of reduced yield and quality in tomatoes, as they greatly affect several physiological and biochemical processes like reduced photosynthetic activity, altered metabolism and enzymatic activity, thermal injury to the tissues, reduced pollination and fruit set etc. Grafting is an efficient rapid alternative tool to the relatively slow breeding methodology for enhancing environmental-stress tolerance in tomatoes. The use of appropriate tolerant rootstocks improves crop growth, yield and quality in tomatoes which confer resistance against abiotic stresses. Graft compatibility is a key factor in the success of grafting so future studies should be focused on this aspect.

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सारांश

टमाटर की खेती सम्पूर्ण विश्व में वृहद् पैमाने पर की जाती है। टमाटर के उत्पादन को कीट एवं रोग व्याधियों के अलावा बहुत से वातावरणीय कारक जैसे सूखा, अत्यधिक या कम तापमान, बाढ़, मृदा लवणता, इत्यादि बहुत हद तक प्रभावित करते हैं। प्रजनन एवं जैव-प्रौद्योगिकी के माध्यम से इन विकारों के प्रति सहनशील किस्में विकसित करना एक कठिन एवं अधिक समय वाली प्रक्रिया है। ग्राफ्टिंग के माध्यम से टमाटर में बहुत सी व्याधियों एवं प्रतिकूल वातावरणीय कारकों से छुटकारा पाया जा सकता है। इसके लिए उचित मूलवृन्त की पहचान करना आवश्यक है। टमाटर में यह देखा गया है कि कुछ जातीय एवं अन्तर्जातीय मूलवृन्तों के प्रयोग से जड़-जनित बीमारियों, वातावरणीय कारकों के अतिरिक्त उपज एवं गुणवत्ता में बढ़ोत्तरी पायी गयी है। इसके अतिरिक्त विशिष्ट प्रकार के ग्राफ्टेड पौध जैसे-पोमैटो, ब्रिमैटो इत्यादि का उत्पादन करके लाभ कमाया जा सकता है, जिसमें दो सब्जियों का उत्पादन ग्राफ्टिंग माध्यम से एक ही पौधे में लिया जा रहा है। इस लेख के माध्यम से ग्राफ्टिंग तकनीक से टमाटर में प्रतिकूल वातावरणीय प्रभावों के साथ-साथ उत्पादन एवं गुणवत्ता में बढ़ोत्तरी पर उपस्थिति शोध पत्रों को प्रस्तुत किया गया है।