PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(4): 1429-1439
https://doi.org/10.14719/pst.4065

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REVIEW ARTICLE

Vegetables grafting: Green surgical fusion to combat biotic and abiotic stresses

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OPEN ACCESS

ARTICLE HISTORY

Received: 07 June 2024
Accepted: 17 September 2024

Available online
Version 1.0 : 15 November 2024
Version 2.0 : 23 November 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE

Janaharshini R, Velmurugan M, Indu Rani C, Venkatachalam SR, Saravanan PA . Vegetables grafting: Green surgical fusion to combat biotic and abiotic stresses. Plant Science Today. 2024; 11(4): 1429-1439. https://doi.org/10.14719/pst.4065

Abstract

Vegetables are considered protective foods with high nutritional value and play an important role in subsistence farming, generating more income. Vegetable crops are highly sensitive to weather fluctuations, which impact their growth, flowering and fruit development and ultimately reduce yield. Grafting has become a viable green surgical option to decelerate conventional breeding approaches to enhance resilience to biotic and abiotic stresses. It is the technique of uniting 2 plants with different genetic backgrounds to create a new one, allowing genetic differences to transfer to the scion. This process offers a better alternative to chemical sterilants in mitigating certain soil-borne diseases in vegetable crops. Solanaceous and Cucurbitaceous vegetable grafting is commercially practiced and has a greater impact in farmers' fields. Grafting is suggested to mitigate environmental changes' negative impact on vegetable quantity and quality by enhancing physiological activities in plants grafted onto rootstocks with potential traits. This method offers insights into stress response mechanisms, improves stress tolerance and enhances vegetable yield and quality. Recent research on vegetable grafting aims to promote sustainable agriculture by offering resilient, high-yielding crop varieties, such as dual-grafted Brimato, suitable for urban and suburban areas. Research is necessary to comprehend the genetic mechanism and physiological process of grafting technology, with a focus on identifying key physiological processes associated with the characteristic features of rootstock.

Keywords

Cucurbits; mechanism; rootstock; solanaceous; stress

Introduction

Vegetables are considered a protective food that is essential and fundamental for human nutrition rich in vitamins, minerals, dietary fibers, antioxidants and phytochemicals. With the ever-increasing world population and increasing demands for nutritious food, ensuring sustainable vegetable production is imperative. Global vegetable yields are severely threatened by soil-borne diseases, abiotic stresses and limited land availability, with soil-borne pathogens causing losses of up to 75 % (1). Additionally, abiotic factors like high temperatures (40 %), salinity (20 %), drought (17 %), lower temperatures (15 %) and other stresses intensify these challenges (2). Though a lot of high-yielding varieties of vegetables developed, their full potential has not yet been harvested because of the stresses. It cannot be solved through the breeding program with ease as most of the genes responsible for resistance are quantitative traits, which are governed by a larger number of genes (3). The use of chemicals will not be a good solution as it does not align with an environmentally friendly approach. Grafting is a green site-specific surgical approach that combats the stresses by exploiting the rootstock's potential.

Grafting is a propagation technique where vascular tissues of 2 plant parts are connected to form a single plant. The rootstock provides anchorage and resistance, while the scion influences photosynthesis, flowering and fruiting. By grafting, the growth and yield of plants are manipulated. Grafting in fruit production has been practiced for centuries, but it is a more recent development in vegetables. At the beginning of the 20th century, the watermelon was grafted onto gourds in Japan to decrease the incidence of fusarium wilt (4-6). In the 1950s, Brinjal (*Solanum melongena*) was the first solanaceous vegetable to be grafted onto scarlet aubergine (*Solanum integrifolium* Lam.). Farmers were made to depend on grafting to control soil-borne diseases and insects due to the altered farming system because of the advent of greenhouse cultivation (7). Solanaceous and Cucurbitaceous vegetables are the most commonly used vegetables. This review explores the role of vegetable grafting in enhancing tolerance to biotic and abiotic stresses, with a focus on the underlying physiological, biochemical and molecular mechanisms contributing to improved crop resilience and productivity under adverse environmental conditions.

Grafting techniques

Grafting Methods

Grafting methods determine the success of a graft. Grafting methods were selected based on labor availability, technical experience, vegetable type, required number of grafts and machine and availability of infrastructure facilities. The 2 types of grafting methods are manual grafting and automated grafting, where robots are employed. The different grafting methods are described below:

One cotyledon splice grafting

One cotyledon splice grafting is referred to as splice grafting or tube grafting where the meristematic region and one cotyledonary leaf of rootstocks are cut at an angle of 35-45 ° and a scion was prepared to match the spliced rootstock. To hold the graft in place, a grafting clip, pin or tape is used. It is used by growers and commercial transplant producers. Pin grafting is similar to this method, which differs by securing the graft union with ceramic pins in place of the clips. Investigation had been carried out on the grafting techniques in cucumber (*Cucumis sativus*), identifying one cotyledon grafting as the most effective method, particularly when the rootstock was already rooted (8). Furthermore, their study demonstrated that pre-grafting treatments with sucrose and anti-transpirants significantly enhanced grafting success. These findings suggest that physiological conditioning of the rootstock and scion before grafting can improve graft compatibility.

Apical/ wedge grafting

It is also known as cleft grafting. This method involves decapitating the rootstocks, making a downward slit and inserting a wedge-like scion into the slitted rootstock. A clip or grafting tape is made to secure the scion and rootstock. Solanaceous crops are best-suited for performing wedge grafting. Reports are on the development of an enhanced cleft grafting method for cassava (*Manihot esculenta* Crantz) using a cost-effective wooden healing chamber that increased graft success to 90 % and the success is attributed to precise matching scion and rootstock diameters for optimal cambium alignment and ensuring proper sterilization (9). This method supports improved cassava yields, resilience to abiotic stresses and food security in resource-limited settings.

Tongue approach grafting

The Tongue approach grafting method originated in the Netherlands. In this grafting, the stem diameter of rootstock and scion should be the same, for that, scions are raised a week before rootstocks. The meristematic area and true leaves of rootstocks are decapitated, followed by a downward and upward slanting cut made at 30-40 ° on the rootstock hypocotyl portion and scion respectively and they are fixed, then secured with a specialized clip to hold grafts. Though it has a uniform growth rate and high survival %, this method needs more labor and space, which serves as a limitation. It was reported that bottle gourd rootstocks (*Lagenaria siceraria*) exhibited high compatibility with the cucumber cultivar 'Kalaam' scion, resulting in significantly greater graft success using the splice and tongue approach grafting technique (10). This success was attributed to higher sap content and elevated Soil Plant Analysis Development (SPAD) values.

Hole insertion grafting

This method is performed when the hypocotyls of scions and rootstocks are hollow. This is especially used in watermelon grafts where they are relatively smaller than the rootstocks (usually bottle gourd and squash). This grafting process involves removing the meristematic portion and true leaves of the rootstock, creating a hole using a gimlet, and preparing scions with a narrowing or sharp end so that they will be suitable to insert into the hole of the rootstock. This requires no extra labor for the post-grafting process (11). A grafting technique was devised in watermelon (*Citrullus lanatus*) to suppress the regeneration of the rootstock to less than 10 % in hole insertion grafting by removing the epidermis of the base of the rootstock using a new grafting tool and enhanced the scion growth which reduced the labor need (12).

Mechanical grafting

Now a days, grafting robots are highly used for grafting vegetables. This reduces working intensity and increases survival % and grafting efficiency. In 2021, a semi-automatic grafting model, JFT AI 500 T, was developed, which can graft 1500 plants per hour. A robot programmed for the same diameter might struggle with thicker or thinner stems, which serve as a limitation. A novel flexible clamping device for grafting machines to perform inclined insertion grafting is designed to reduce the damage to rootstock seedlings due to the rigid clamping mechanisms and this is solved by optimizing suction hole diameters, negative pressure levels and surface angles (13).

Brimato

Brimato is a dual or multiple grafting technique developed by the Indian Institute of Vegetable Research (IIVR), Varanasi, to produce two or more fruit-bearing vegetable crops from a single plant using grafting, which will be beneficial for areas where there is a space constraint to growing more vegetables. In this technique, 2 scions, namely Kashi Sandesh, a brinjal hybrid and Kashi Anand, a tomato (*Solanum lycopersicum*) scion, were grafted onto a brinjal rootstock IC 111056 through side/ splice grafting (14).

Best grafting method: According to one report, hole insertion grafting and one cotyledon grafting are suitable for hallow hypocotyl plants and these methods require skilled labors, certain grafting tools and a hardening chamber to get the highest success rate (15). Approach grafting and cleft grafting possess high survival rates, which require more space and labor. Grafting scions are selected based on production, quality of fruit and consumer demand, whereas rootstocks are chosen mainly on resistance to disease, congeniality and versatility to local conditions.

Process in Grafting

Compatible rootstock and scion are essential to produce a successful graft through callus bridge formation, which facilitates the transport of water and mineral nutrition through the vascular bundles. For the process of grafting, the selection of ideal and compatible scion and rootstocks is essential. The scions are sown earlier to obtain the same stem diameter as that of the rootstock during the grafting. The grafting is performed in the early morning or late evening to reduce the transpirational loss, which helps in the better survival of the graft. Then grafts are subjected to healing, and the acclimatization process, during which the callus and vascular bundle formation takes place, and finally grafts are transplanted to the field. Clips, tubes and grafting blades are essential tools in grafting (16). The grafting procedure is schematically represented in Fig. 1.

Graft Union Formation

The relationship between stock and scion essential for growth and nutrient uptake. The following are the processes that happen in the graft union establishment: development of callus tissues (from stock and scion), the formation of callus bridges, the development and differentiation of callus cells to form vascular tissue and the formation of secondary xylem and phloem (17). Defoliation decreased scion growth and poor grafted plant survival may result from inadequate or poor callus formation across the stock and scion (18, 19). Callus formation occurs at the union of grafts, which facilitates water and nutrient movement, influencing physiological properties and determining the vascular connection at the rootstock-scion interface.

Factors influencing success rate

Graft compatibility refers to the proper graft union formation, extended life and appropriate functioning of the

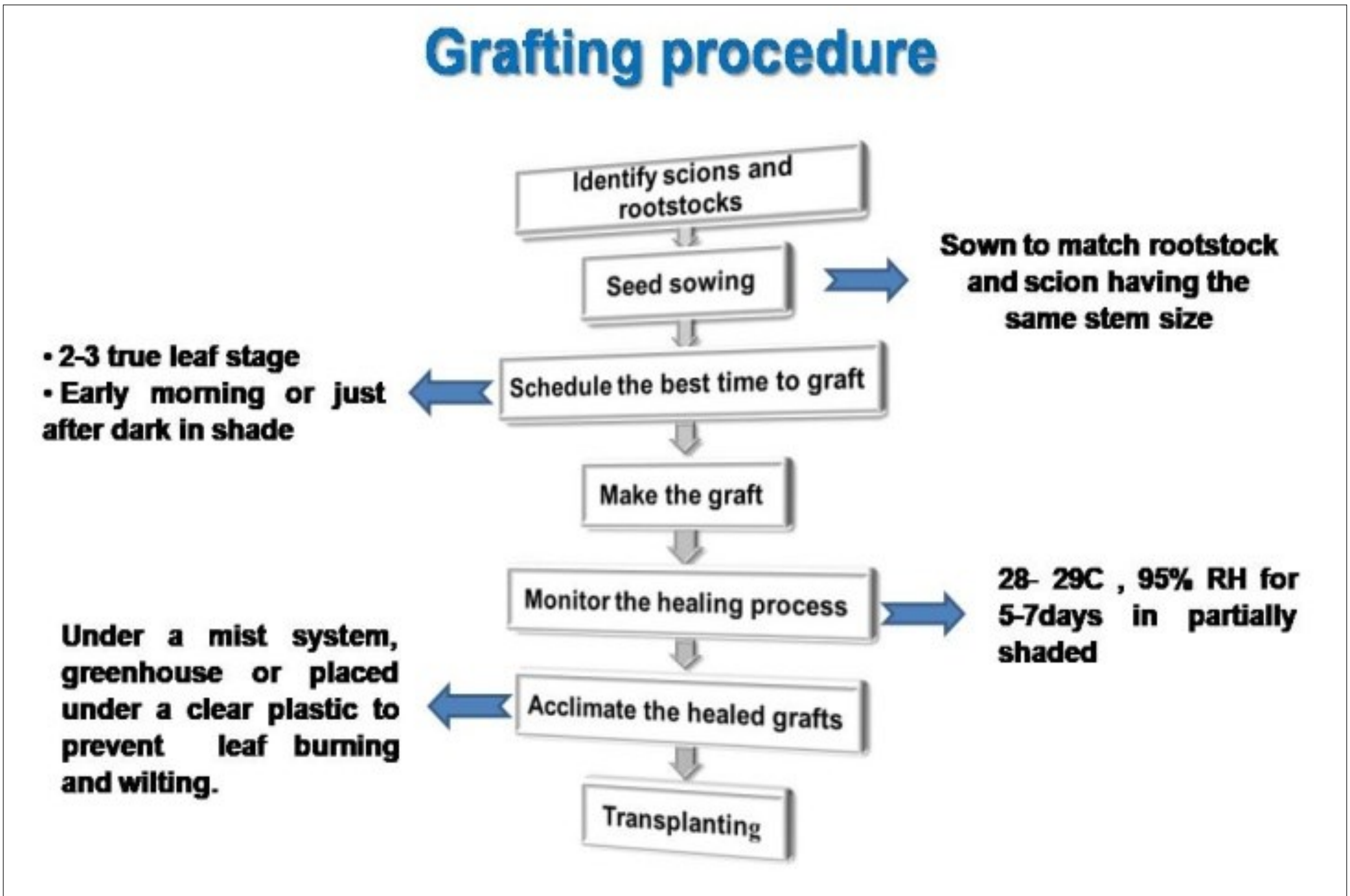

Fig. 1. General grafting procedure in the fruit bearing vegetable crops.

graft (20). Success graft union happens when there is more taxonomic affinity and when the rootstock and scion have similar anatomical construction. In this sequential order, intrafamilial < intergeneric < intrageneric < interspecific < intraspecific < interclonal < intraclonal performing grafting is successful (21). According to one report, Chinese pumpkin (*Cucurbita moschata*) and wax gourd (*Benincasa hispida*) have less compatibility with netted melon (*Cucumis melo* var. *cantalupensis*) than Luffa (*Luffa aegyptiaca*) (22). Failure happens when there is a mismatched scion and rootstock, improper grafting procedures due to lack of expertise, grafting during adverse conditions or grafting in diseased planting material (17).

Stress

Any internal or external restrictions that lower a plant's capacity to convert energy from light into biomass and limit its rate of photosynthetic activity are referred to as stress. Plant stress is caused by the way it reacts to changing environmental circumstances. Plants are primarily exposed to two types of stress *viz.,* biotic and abiotic. In contrast to biotic stress, which is caused by biological agents like diseases, pests and abiotic stress refers to the environmental impact that plants experience due to physical or chemical stresses.

Biotic stress

Biotic stress is caused by living entities like pests and diseases, which negatively affect the biomass production of the plant by affecting their morphological, physiological and metabolic processes. Most vegetables face loss due to soil-borne diseases. About 50-75 % of crop loss is due to soil-borne pathogens like *Fusarium* spp., Nematode, *Rhizoctonia* spp., *Verticilium* spp., *Sclerotiana* spp., *Pythium* spp. and *Phytopthora* spp. in a lot of crops (23). Fumigants were commonly employed to combat soil-borne diseases. Now there has been a shift from fumigants to control soil-borne pathogens to grafting due to methyl bromide's ozone-depleting nature, which also poses health risks to humans. Various studies are going on to screen and exploit the rootstocks, which are potentially resistant to the soil-borne pathogens.

Most of the soil-borne pathogens weaken the plant system by root invasion, colonization, disturbing the nutrient uptake and toxin production. The vascular system is most of the pathogen's epicenter to collapse a plant. Reports are on the disease reduction mechanisms by rootstocks (24).

Resistance nature of rootstock either monogenic or polygenic.

Improved water and nutrient uptake by their larger root system, which counterbalances the active root damage during stress.

Shift of microbe population in the rhizosphere area of rootstock.

Root exudates production (25).

Induced resistance due to signal transduction, RNA (Ribonucleic acid) transcript movement, and defense-related phytohormones in the rootstock (26).

Production of callose, phenols, tyloses and gums to limit their colonization in the xylem vessels.

The other mechanisms are the production of anti-oxidant enzymes and stress signaling and hormonal production also help in the limited infestation of the pathogen.

There are various studies carried out to identify the resistant rootstock and identify the mechanism through which the grafted plants tolerate pathogen attack. Root Knot Nematode (RKN) is a sedentary obligate parasite that infests the root and causes galling, limits water and nutrient uptake, ultimately damages plant health, and causes low biomass production. More than 50 % of the yield loss occurs due to nematode infestation in protected houses (27). Reports are on the assessment of the compatibility of various rootstocks with bhendi (*Abelmoschus esculentus*) and found *Hibiscus cannabinus* and *Hibiscus acetosella* were compatible and they performed better in RKN infestation compared to the non-grafted ones (28). The tomato genotypes with the Mi gene and pepper genotypes with the N gene have an inherent potential to control the RKN infestation (29, 30). Cucurbitaceous rootstocks RKVL – 318 and wild species *Cucumis pustulatus* offer resistance to the southern RKN (31, 32).

Fusarium, ascomycotic fungi that can live as chlamydospores without a host or with a specific plant signal, pathogen start their life cycle. The most common host plants are the solanaceous, leguminous and cucurbitaceous families. It had been evaluated for 10 cucurbitaceous rootstocks and 2 scions against the *Fusarium* wilt and found that kumatikai (*Citrulus colocynthis*), African horned cucumber (*Cucumis metuliferus*) and pumpkin (*Cucurbita moschata*) rootstocks were resistant to *Fusarium* wilt, with higher antioxidant enzyme activity in these 3 resistant rootstocks, indicating their potential as effective treatments against the wilt (33). According to one study, the accumulation of the tyloses, which is a parenchymal balloon-like outgrowth formed as a response to pathogen attack in the xylem vessels that limits the pathogen colonization, can be a resistant mechanism in bottle gourd and interspecific hybrid squash varieties (34). Powdery mildew is another devasting biotic stress in gourd families. Grafting-induced water stress triggers a defensive response in the scion, leading to thickened leaf surfaces that restrict water loss and limit fungal growth. This temporary reduction in water availability suppresses powdery mildew growth, resulting in lower colony densities on cucumber scion grafted onto the squash and cucumber rootstocks during the healing period (35).

Ralstonia solanacearum is a major constraint in the cultivation of solanaceous vegetables. This pathogen blocks the xylem vessels and causes the wilt by producing the substance, Exopolysaccharide (36). Though breeding is an approach, the resistance to bacterial wilt is governed quantitatively, which affects fruit size (29). Grafted vegetables reduce bacterial wilt infection by limiting colonization (37). According to a study, *Solanum sisymbrifolium, Solanum grandiflorum, Solanum capsicoides, Solanum vir-*

ginianum, Solanum hispidum, Solanum sessiliflorum, Solanum stramonifolium and *Solanum torvum* are resistant to bacterial wilt (38). Reports are also on the evaluation of 7 *Solanum melongena,* 2 *S. sisymbrifolium* and 1 *S. torvum* rootstocks onto a green long hybrid scion against bacterial wilt (39). Except, for *Solanum sisymbrifolium*, all other rootstocks showed resistance, especially Haritha, a *Solanum melongena* rootstock that showed superior yield in addition. This may be due to greater compatibility and nutrient flow as belonging to the same species (40). *S. integrifolium* and *S. torvum* showed resistance to soil- borne bacterial wilt infections (41, 42).

Abiotic stress

Abiotic stress refers to adverse environmental factors from non-living sources that affect plant physiology, growth and development, ultimately reducing their biomass production. The common abiotic stresses are waterlogging and drought (water stress), low and high temperature (thermal stress), salinity and toxicity of nutrients. According to another work, about 60-70 % yield gap is attributed to abiotic stress (43). The underlying mechanism that makes the grafts combat biotic and abiotic stresses is presented in Fig. 2.

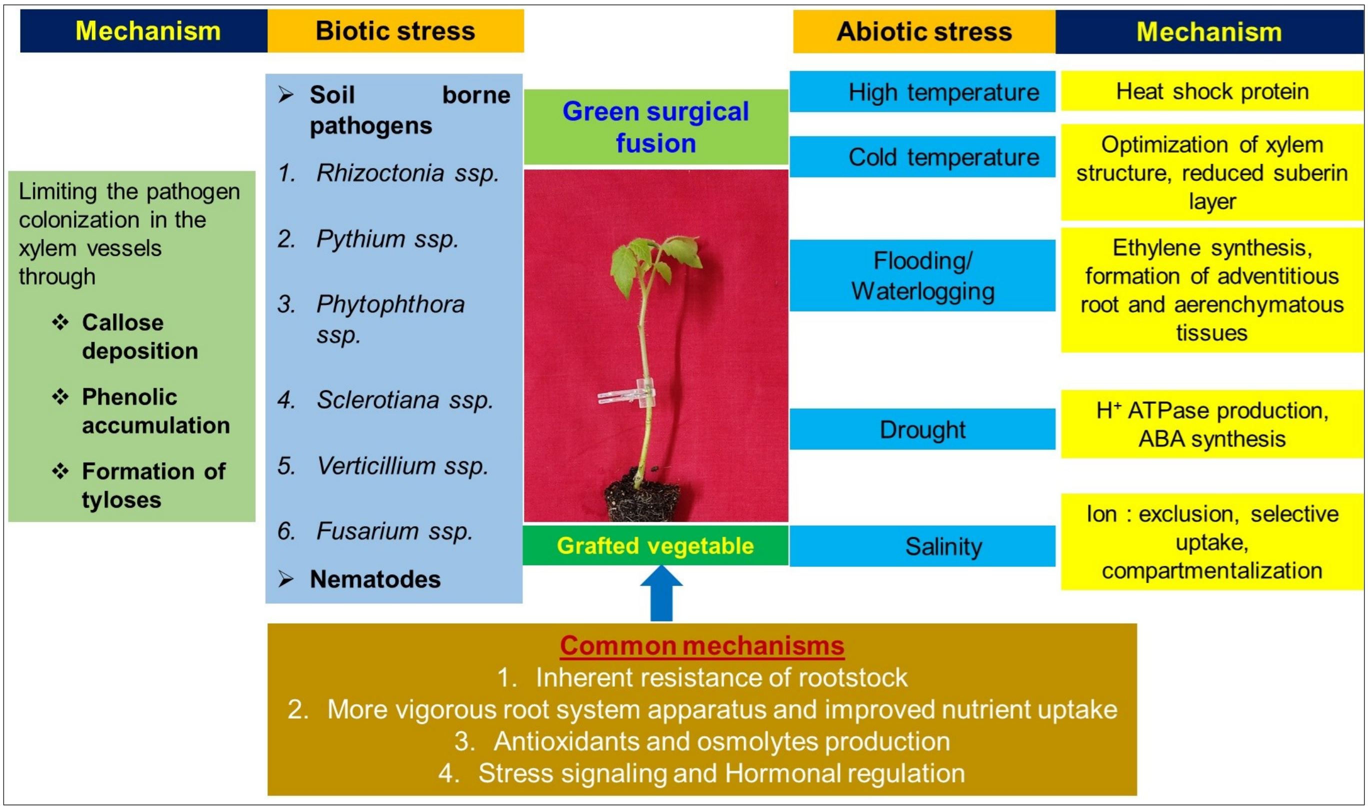

Fig. 2. Underlying tolerance mechanism of grafts to combat biotic and abiotic stress.

Effect of Abiotic stress and tolerance mechanism

Flooding/ waterlogging

Waterlogging is abiotic stress that occurs due to climate change, unpredictable rainfall patterns, soil rich in clay or compacted and poor drainage due to repeated use of machinery, which restricts the exchange of gases between root and atmosphere (44). The shift from aerobic to anaerobic respiration occurs due to the depletion of oxygen in waterlogged soils, resulting in the production of lactic acid, carbon-di-oxide, and reduced root function due to lesser ATP production. The reduced root function causes restricted stomatal conductance, which further affects photosynthesis and respiration ultimately resulting in yield loss (45). In early growth, Solanaceous vegetable tomatoes cannot withstand waterlogging for more than 48 h (46).

Grafted plants produce ethylene in roots under low O_2 partial pressure by triggering a chemical signal in the xylem sap. Ethylene aids in the development of adventitious roots in the subsurface portion of the plant and aids in the acquisition of O_2 from the atmosphere with improved nutritional absorption (47). Ethylene accumulation in submerged plant parts fosters the formation of aerenchymatous tissues, enabling the movement of oxygen from the plant's aerial to submerged sections in the absence of oxygen (48).

It was reported that tolerance to waterlogging in grafted bitter melon (*Momordica charantia* L.) is due to the increased anaerobic respirations in both tap and adventitious roots and the aerenchyma formation in adventitious roots (49). Bitter melon grafted onto luffa (*Luffa cylindrica*) performed better under the waterlogged condition than a self-grafted one. Adventitious roots and aerenchymatous tissues in grafted watermelon were noted earlier (50). Arka Rakshak, a waterlogging susceptible tomato variety grafted onto Arka Neelkanth, a brinjal rootstock, conferred resistance by changing the concentration of sugars and the formation of adventitious roots (51).

Drought

Vegetables are highly susceptible to drought, as more than 2/3rd of the content is composed of water. This affects the physiological and metabolic processes. The reduced water content in the soil makes the leaves close the stomata to reduce the transpiration loss, which increases the leaf temperature and reduces the carbon dioxide uptake. This finally reduces the production of biomass by disturbing the rate of photosynthesis.

Roots will admit the water deficit condition in the soil. In grafted plants, there will be higher H^+-ATPase activity and reallocation of photosynthates to roots, which produces a large and deep root system and ultimately helps in acquiring the water from a deeper soil profile (52). Osmotic stress created during drought will be removed by the accumulation of osmolytes, which helps in regaining the cell turgor and the leaf water potential (53). ABA (Abscisic acid) biosynthesis helps in the reduced transpirational loss and the closure of stomata, which is also an important coping mechanism.

According to one report, *Solanum pimpinellifolium* as rootstock decreases the stomatal conductance when grafted to tomato scion Ramlet and increases the water use efficiency, which is suitable for drought tolerance (54). Grafting cucumber (*Cucumis sativus*) Jinyan No. 4 onto sponge gourd provides resistance to drought by raising the water use efficiency through balancing transpiration and stomata-dependent carbon dioxide assimilation (55).

High temperature

Thermal stresses are of 2 types: high and low-temperature stress. High temperatures cause increased respiration, transpiration and evapotranspiration and ultimately reduce the crop duration and photosynthetic process. In tomatoes, a temperature above 37 °C reduces the pollen formation and its viability, and when it is above 39 °C, colour of the vegetable turns yellow. In chilli, a night temperature above 24 °C ceases the fruit set. In sweet pepper, the growth and yield are retarded when temperature is above 32 °C. The supra optimum threshold temperature is higher in cucurbits than in solanaceous, so above 32 °C temperature affects the solanaceous crop's growth (56).

Potential rootstocks begin to accumulate compatible osmolytes (proline, valine, soluble sugars etc) in high temperatures. These osmolytes are essential for controlling osmotic functioning and shielding tissues in the cell from elevated temperatures by preserving membrane stability, water balance in the cell and redox potential. The potential rootstocks will produce the antioxidant to reduce the effect of reactive oxygen species, thus preventing the crop from oxidative stress and increasing photosynthetic activity. Heat shock protein also helps in repairing the damaged protein in the stress condition. Cucurbits are susceptible to high temperatures. Cucumber grafted onto Sponge gourd (*Luffa cylindrica*) increased the high-temperature tolerance (57). $SQ60F_1$ is a commercial rootstock that imparts heat tolerance when the cucumber is grafted onto it. The World Vegetable center recommended rootstocks of chilli *Capsicum annuum* 'Toom-1' and '9852-54', *Capsicum chacoense,* and *Capsicum frutescens,* which produced high yields under heat stress (58). The Brinjal rootstocks EG195 and EG203 were suggested for tomato production in conditions of high warmth and moisture (59).

Cold temperature

Cold temperature/ low temperature is a serious threat to biomass production in vegetables as it adversely affects the metabolic processes and the cellular components. Low temperature (below minimum) causes membrane damage, necrosis, chlorosis, alterations in cytoplasm viscosity and changes in enzyme activity, all of which cause the plant to die. Loss of compartmentalization results from intracellular organelles' integrity being compromised by cold stress. Additionally, it reduces and impairs general metabolic activities, protein building and photosynthesis. Low temperature increases the viscosity of water and causes changes in the xylem vessels, which leads to decreased hydraulic conductance and this result in reduced nutrient absorption by roots. The other effects of low-temperature stresses are decreased production and upward movement of phytohormones. The threshold temperature for most vegetables is 8-12^{0}C, below which metabolic activities decrease and physiological disorders happen.

Increased H^+-ATPase enzyme activity in grafted plants maintains the acidic apoplastic environment, activating the cell wall's expansion protein to aid in breaking the cellulose's H-bond and encouraging growth of the cell and extension of the root (52). Rootstock exhibits excellent hydraulic conductivity due to its optimized xylem structure, enhanced root growth development, and specialized root architecture (including surface area and length). Reduced suberin layer helps in the transport of water during cold stress and antioxidant production, ABA, cytokinin production helps in scavenge the free electrons in the ROS (Reactive oxygen species) and prevents the plant from lipid, protein and DNA (Deoxyribonucleic acid) damage (60). Cucumber scion grafted onto the figleaf gourd (*Cucurbita ficifolia*) rootstock produced the lowest electrolyte leakage possible due to the antioxidant defense system when exposed to low temperature (61).

Salinity

NaCl in water or soil in arid and semi-arid conditions can negatively impact vegetable productivity (62). This condition causes an imbalance in the ions, which results in stress due to osmotic pressure and ionic damage which helps in the production of reactive oxygen species. 50-70 mM of NaCl is injurious to tomatoes and cucumbers, whereas 20 mM is to pepper.

Restricting the transfer of sodium ions and in certain situations, chloride ions to the shoot and accumulating them in the roots are the common mechanisms of tissue tolerance in grafted plants. In grafted plants, a greater concentration of osmolytes and suitable solutes in the leaf cells' cytosol can prolong the life span of plants and prevent senescence of the leaves. A potential antioxidant defense system that lowers the damage by oxidative stress is essential for improving grafted plants' resistance to salt. Furthermore, hormone stimulation might make it possible for grafted plants to respond to salt more effectively. The grafted plants' ability to tolerate salt at the leaf and/or root levels may be influenced by the aforementioned factors (62).

The salinity stress imparted by tomato scion was grafted onto the potato rootstock as the rootstock, can compartmentalize the minerals and allocate more dry matter accumulation (63). *Cucurbita maxima* x *Cucurbita moschata* serves as a potential rootstock to alleviate the salinity by reducing the sodium content in soil but maintaining the chlorine in the leaf (64). Grafting chilli 'Adige' onto *Capsicum chinense* Jacq. ECU-973 and *Capsicum baccatum* var. *pendulum* increased the yield of chilli under saline conditions, which was mainly due to decreased ion deposition and ion selectivity (65). The potential rootstock to combat the stresses is furnished in Table 1.

Table 1. Potential rootstocks against biotic and abiotic stresses.

Stress	Crop	Rootstock	References
		Biotic Stress	
Bacterial wilt	Tomato	*Solanum pimpinellifolium*	(68)
	Brinjal	*Solanum torvum*	(41)
Fusarium wilt	Brinjal	*Solanum torvum*	(41)
	Cucumber	*Cucumis ficifolia*	(69)
Nematode	Tomato	*Solanum peruvianum*	(70)
	Brinjal	*Solanum torvum*	(71)
		Solanum khasianum *Solanum toxicarium*	(72)
		Solanum integrifolium	(73)
	Sweet pepper	*Capsium annuum* 'AR-96023'	(30)
	Musk melon	*Cucumis pustulatus*	(32)
	Water melon	Shintoza	(74)
Verticillium wilt	Brinjal	*Solanum torvum* *S. sisymbrifolium*	(75)
		Solanum integrifolium	(42)
Powdery mildew	Chilli	*Capsicum baccatum* *C. chinense* *C. frutescens*	(76)
		Abiotic stress	
Drought	Tomato	*Solanum pennelli*	(77)
		Solanum chilense	(78)
	Brinjal	*S. elaeagnifolium*	(79)
Salt	Tomato	*S. pennelli*'	(80)
		S. cheesmanii	(81)
	Watermelon	TZ-148	(82)
	Cucumber	*C. moschata* Chaojiquanwang'	(83)
Flooding	Brinjal	*S. macrocarpon*	(84)
High temperature	Cucumber	*Luffa cylindrica*	(85)
Cold temperature	Cucumber	*Cucurbita ficifolia*	(86)
	Cucumber	*Sicos angulatus*	(87)

Transgrafting

Transgrafting is a grafting method/ new plant breeding technique in which one among the scion and rootstock will be transgenic whereas the other will be non –transgenic (66). It has been gaining momentum in grafting in recent days to combat biotic and abiotic grafts. One such transgenic graft is to combat the heat stress by grafting the transgenic rootstock in which the LeFAD7 gene is silenced, which is known to be the fatty acid denaturase gene, with non - transgenic scions. They exhibited tolerance and that may be due to the change in fatty acid composition (67).

Challenges

Sensitization of grafting techniques to enhance stress tolerance in field workers is a difficult task.

Grafting requires skilled laborers, and it is a labor-intensive process.

Requires controlled conditions for healing and effective grafting robots.

During the summer months, workers face heat stress and discomfort when grafted in a greenhouse and growth chamber.

Time management is required for sowing the seeds of rootstocks and scions to obtain the uniform stem diameter.

Overgrowth of transplants under field conditions significantly affects the yield and quality of fruits.

Graft incompatibility happens at the initial stages of transplanting. Root suckers are produced during the healing process.

The use of two plant seeds and cutting instruments may increase the risk of seed-borne pathogen spread in grafting.

Future prospects

Creation of rootstocks with strong root systems, resistance to diseases carried by the soil, and the capacity to stimulate more shoot vigor—all of which would boost yield.

The fundamental need for vegetable grafting has necessitated the selection of appropriate rootstocks with disease resistance, besides exhibiting tolerance to abiotic stressors.

It is also important to encourage the use of biotechnological technologies in India for the development of rootstock.

Production and distribution of healthy, uniformly grafted seedlings at affordable prices are crucial for wider adaptability, especially in countries with little knowledge.

Conclusion

The main aim of grafting is to boost yield, particularly as a result of intense pressure from nematodes and soil-borne diseases as well as unfavorable climatic factors. Future research should help advance nursery management techniques and grafting technology to guarantee growers receive high-quality grafted transplants. The management of nurseries requires a lot of labor and manual grafting has less efficacy. To increase grafting efficacy and lower labor costs, researchers must concentrate on creating and promoting facilities, tools, and automatic grafting robots. Seed-priming processes should be improved for better germination, uniformity and seedling vigor. The creation of databases, software programs, mobile apps and crop simulations of grafted plants will help farming communities and nursery managers to choose the best cultivars for the scion and rootstock in addition to offering instructions for best management techniques. Vegetable grafting still has certain issues, but overall, the benefits of grafting exceed the drawbacks; therefore, grafting will remain a popular and well- accepted technique to mitigate stresses.

Acknowledgements

We gratefully acknowledge the technical help provided by Sindhuja K and also express our sincere thanks to the Department of Vegetable Science and Dean, School of Post Graduate Studies, Tamil Nadu Agricultural University, Coimbatore, for their support.

Authors' contributions

RJ conceptualized the manuscript, collected literature and drafted the manuscript. MV revised the manuscript and processed the images. CIR, SRV and PAS contributed to editing the manuscript. All authors reviewed and approved the final version.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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