Review Article

A Comprehensive Review on Cucurbit Grafting: A Sustainable Approach to Boost Crop Performance

Abstract: Grafting, which unites the rootstock and scion of a plant, is crucial for combating soil-borne diseases in cucurbitaceous crops such as watermelon, melon, bitter gourd, summer squash and cucumber. Essential due to limited arable land and off-season demand, this technique enhances plant vigour by improving nutrient uptake and providing resistance to soil pathogens, salinity, drought and temperature variations, thereby improving overall yield and fruit quality. Initially implemented in Japan in the late 1990s, grafting significantly affects fruit pH, flavour, sugar content, carotenoids, and texture. Globally, it has been adopted to prevent diseases like fusarium wilt and root-knot nematode. This practice mitigates production losses under adverse conditions and promotes organic, safer vegetables by reducing pesticide residues. Recent advancements in grafting methods and versatile rootstocks further support its widespread use.

Keywords: Grafting, abiotic stress, biotic stress, cucurbits and rootstocks.

1. Introduction: Vegetables are crucial for global food and nutritional security, but their production is challenged by pests, diseases and environmental stresses (Tirupathamma *et al*., 2019). Farmers often rely on agrochemicals, which can be harmful and costly (Colla *et al*., 2010). Grafting, a technique long used in fruit cultivation, is now gaining popularity among vegetable growers for its effectiveness in reducing agrochemical use and managing soil-borne problems. The first vegetable grafting attempt in Japan in the 1920s targeted Fusarium wilt using watermelon grafted onto pumpkin (Leonardi, 2017). Today, grafting is common in cucurbit cultivation, especially in greenhouses in Japan and Korea (Kumar *et al*., 2018). Despite its benefits, grafting is not suitable for all vegetables due to variations in species characteristics. Cucurbits and solanaceous crops are the most commonly grafted (Schwarz *et al*., 2010). Methods such as hole insertion, tongue approach, splice and cleft grafting are used, and automation is being explored to reduce costs (Comba *et al*., 2016). This review examines the role of grafting in improving cucurbitaceous crops.

2. Grafting method: Selection of grafting is done on crop with the help of the farmers experience, the number of grafts required, the motive of grafting and available facilities required for machinery and infrastructure (Lee *et al*., 2010).

2.1 Tongue / approach grafting: Grafting involves using rootstocks and scions of equal size. Although this method requires more labour and space, it results in a high seedling survival rate and is most commonly practiced by small nursery farmers. However, it is not suitable for rootstocks with hollow hypocotyls.

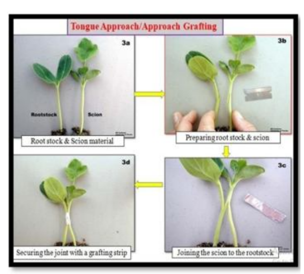

Fig 1: Tongue/Approach Grafting

2.2 Cleft grafting: This method, also known as apical or wedge grafting, involves making a slant cut in the lower stem of the rootstock. The scion, pruned to have 1-3 true leaves, is then placed into the split, and a clip is attached between the scion and rootstock (Johnson *et al*., 2019). This technique is primarily used for solanaceous crops.

Fig 2: Cleft Grafting

2.3 Hole insertion: This method, also known as top insertion grafting, is commonly practiced in China. It is primarily used for watermelon, as the seedlings are smaller than the rootstocks of bottle gourd or squash. For successful transplanting, an optimal temperature range of 21-36℃ is required (Shalaby *et al.* 2022).

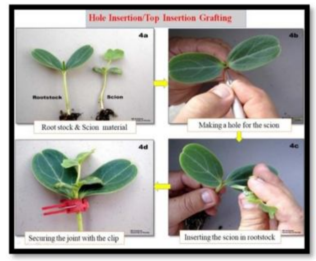

Fig 3: Hole Insertion/Top Insertion Grafting

2.4 Splice/Slant grafting: Splice grafting is a common method for grafting cucurbits, and is also known as one cotyledon splice grafting (OC-SG). It involves joinThe ideal time to graft is when the stem diameters of the scion and rootstock are closest in size. If the sizes are different, line them up along one side to maximize cambial contacting a scion onto a rootstock by making a slanting cut of the same length in both the scion and rootstock, and then fixing the grafted position with a clip. The ideal time to graft is when the stem diameters of the scion and rootstock are closest in size. If the sizes are different, line them up along one side to maximize cambial contact.

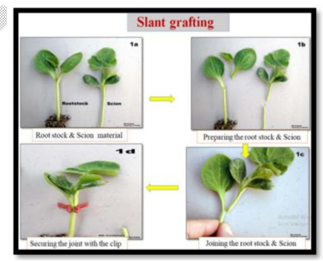

Fig 4: Splice/Slant Grafting

2.5 Pin grafting: In this method, specially designed pins are used to secure the grafted position instead of using grafting clips. It is similar to splice grafting**.**

3. Basic Requirements for Vegetable Grafting:

3.1 Selection of Rootstock and Scion: Grafting is typically performed when plants are at the 2-3 true leaf stage. The selection of rootstock and scion should be based on matching stem diameters.

3.2 Compatibility of Graft: Ensuring graft compatibility reduces the mortality rate even at later growth stages. Successful grafting depends on callus formation between the scion and rootstock, which leads to the formation of vascular bundles (Sanwal *et al.* 2022).

3.3 Grafting Aids: Grafting is facilitated using tools such as grafting clips, tubes, pins, and a grafting blade.

3.4 Screening House: A screening house, constructed with 60-mesh nylon netting, is used to grow seedlings prior to grafting.

3.5 Healing of Grafts: The healing chamber should maintain a temperature of 28-29°C and a relative humidity of 95 per cent for 5-7 days to promote callus formation. This environment reduces light intensity and transpiration, aiding in better attachment of the scion and rootstock.

3.6 Acclimatization of Grafted Plants: After callus formation is complete and the wounded surfaces have healed, the grafted plants should be transferred to a mist chamber or covered with clean plastic in a greenhouse. This helps prevent leaf burning and wilting during the acclimatization process.

4. Current status of vegetable grafting:

Due to the high preference and production of cucurbits and other grafted vegetables in East Asia, this region remains the largest market for vegetable grafting. Watermelon is grown using grafted transplants to varying degrees in Korea (99%), Japan (94%), and China (40%). For solanaceous vegetables, approximately 60-65% of tomatoes and eggplants, and 10-14% of peppers, are cultivated using grafted transplants. In the Netherlands, grafted tomato transplants are used for all soilless tomato production. The popularity of vegetable grafting is rapidly increasing globally, especially in Eastern Europe, North and South America, India, and the Philippines. In China, more than 1,500 industrial nurseries produce grafted transplants, and the international trade of these grafted vegetable transplants is on the rise (Bie *et al*., 2017). Worldwide, cucurbitaceous crops dominate vegetable grafting. However, this technology is still in its infancy in India (Aydin *et al.* 2024).

5. Grafting in cucurbitaceous crops:

Grafting is done to control Fusarium wilt and tolerant to drought and flooding. Currently, in this family watermelon is one crop in which grafting is practiced in the world. There are different grafting methods used in cucurbits are listed in the below Table.1

Table 1: Grafting methods and rootstocks used in cucurbit crops

Scion plant	Rootstock	Method
Cucumber	*Cucurbita moschata, Cucurbita maxima*	Tongue and top insertion method
Watermelon	*Benincasa hispida, Cucurbita moschata, Cucurbita melo, Cucurbita moschata* × *Cucurbita maxima, Lagenaria siceraria*	Top insertion and cleft method and slice grafting
Bitter gourd	*Cucurbita moschata, Lagenaria siceraria*	Top insertion and tongue method
Bottle gourd	*Cucurbita moschata, Luffa sp.*	Top insertion and tongue method.

5.1 Graft compatibility and survival rate:

Graft compatibility is defined as the genetic closeness between rootstock and scion required for a successful graft union, provided other factors such as technique, timing, and temperature is optimal. For instance, inter-generic grafting of highly nematode-susceptible watermelon cultivars ‘Congo’ and ‘Charleston Gray’ onto highly nematode-resistant wild watermelon (*Cucumis africanus*) and wild cucumber (*C. myriocarpus*) rootstocks resulted in a 36% survival rate of the grafts (Pofu and Mashela).

Table 2. Different rootstocks used for biotic and abiotic stress in cucurbit crops

Rootstock	Usedfor
Cucumber	
Fig leaf Gourd	Good Fusarium resistance and low temperature resistance
Burr cucumber (*Sicyosangulatus*)	Southern Root-knot Nematode resistance
Interspecific hybrid squash (*Cucurbita maximax C. moschata*)	Fusarium wilt and low temperature resistance
African horned cucumber (*Cucumis metuliferus*)	Excellent fusarium resistance and good nematode tolerance
Cucurbita moschata	“Blooming-less”cucumber fruit.
Cucurbita moschata	Improves stress tolerance
TRC11550 (Intraspecific Hybrid)	Nematode resistance
Ardito/TRC1401	Very strong and uniformrootstock with highly vigorousroot system.
TRC 15NTB4	Resistance to soil-borne diseases and abiotic stress factors.
Watermelon	
Bottle Gourd (*Lagenaria siceraria*)	Fusarium wilt and chilling tolerance
Shintoza	Fusarium wilt and chilling tolerance
Wax Gourd	Greater drought tolerance
Squash (*Cucurbita moschata*)	Resistant to fusarium and low temperature
Pumpkins (*Cucurbita pepo*)	Vigorous root system, resistant to fusarium and low temperature
Watermelon (*Citrullus lanatus*)	Fusarium tolerance, but not resistance
Citron melon	Root knot Nematode
African horned cucumber (*Cucumis metuliferus)*	Excellent fusarium resistance and good nematode tolerance
Interspecific hybrid squash (*Cucurbita maximax C. moschata*)	Resistant to fusarium wilt and vigorous root system ,high temperature tolerance
Ash gourd (*Benincasa hispida*)	Good disease resistance
Summer squash	
Figleaf Gourd (*Cucurbitaficifolia*)	Low soil temperature tolerance
Bitter gourd	
Sponge gourd (*Luffa cylindrica*)	Resistant to fusarium wilt, good tolerance to heat and flooding
Melon	
Squash	Fusarium and low temperature tolerance

(*Cucurbita maxima x C. moschata*)	Fusarium resistance, low and high soil temperature tolerance, and high soil moisture tolerance
Cucurbita pepo	Fusarium resistance, low and high soil temperature tolerance, and high soil moisture tolerance
Melon (*Cucumis melo*)	Fusarium tolerance and good fruit quality
African horned cucumber (*Cucumis metuliferus*)	Fusarium tolerance, low and high soil moisture tolerance and nematode tolerance

5.2 Potential rootstocks for different cucurbitaceous crops:

Watermelon is typically grafted onto rootstocks like *Cucurbita* species, *Citrullus* species and bottle gourd, with primary rootstocks being bottle gourd, interspecific hybrids between *Cucurbita moschata* and *Cucurbita maxima* and wild watermelon. *Cucurbita spp*. rootstocks, particularly interspecific hybrids of *C. maxima* and *C. moschata*, are effective against soil-borne pathogens and abiotic stresses (Sakata *et al.,* 2008). Fig leaf gourd (*C. ficifolia*) is favoured for cucumber due to its compatibility, cold tolerance, and Fusarium wilt resistance, while *Cucurbita* interspecific hybrids are preferred for summer cucumbers for their Fusarium resistance and heat tolerance (King *et al.,* 2010).

5.3 Influence of cucurbit rootstocks to biotic stresses

5.3.1 Grafting against verticillium wilt:

Grafting is commonly used in tomato and brinjal to combat Verticillium wilt, but it's less applied in cucurbits. Grafting improves Verticillium wilt management by boosting root vigor and nutrient uptake (Bletsos *et al.,* 2008). Klosterman (2009) found that reduced infestation is due to the pathogen's poor and slow colonization of vascular tissues and decreased wilt severity is linked to less pathogen colonization. Root exudates from both resistant and susceptible rootstocks inhibit Verticillium growth (Liu *et al.,* 2009). "Crimson Sweet" watermelon grafted onto "Emphasis" and "Strongtoza" rootstocks showed increased resistance to *V. dahliae* (Buller *et al.,* 2013). Grafted watermelon plants had 3.5 times less disease severity compared to non-grafted 'Secretariat' plants (Devi *et al.,* 2020). Effective rootstocks like Pelops, Round, Super Shintoza, and Tetsukabuto also significantly mitigated Verticillium wilt.

5.3.2 Grafting against fusarium wilt:

Grafting is more effective for managing Fusarium wilt in cucurbits compared to solanaceous crops. In watermelon cultivation, interspecific hybrids and rootstocks like "Shintoza" and "Super Shintoza" (*C. maxima* × *C. moschata*) improve tolerance to Fusarium and Verticillium wilt, enhancing fruit size and yield (Gaion *et al.,* 2018). For cucumbers, rootstocks such as fig leaf gourd and ISHc 'Shintoza' offer resistance to Fusarium and environmental stress. Bitter gourd grafted onto *C. colocynthis, C. metuliferus,* and *C. moschata* exhibits reduced Fusarium wilt, with these rootstocks being the most effective (Gaion *et al.,* 2018).In 2021, Reyad *et al.* conducted an experiment at Cairo

University in Giza, Egypt, and found that cucumbers grafted onto *Cucurbita maxima* and *C. moschata* exhibited greater resistance to Fusarium wilt.

5.3.3 Grafting against root-knot nematode:

Commercial cucurbits lack natural resistance to root-knot nematodes (RKN), necessitating resistant rootstocks (Cohen *et al.,* 2007). Root-knot nematodes cause galls that impair water and nutrient uptake, leading to poor plant and fruit quality. Grafting cantaloupes onto *C. moschata* and *C. metuliferus* rootstocks reduced galling, with *C. metuliferus* showing moderate resistance (Pradhan *et al.,* 2017). "Strongtosa" and "Shintosa" rootstocks significantly increased yields (Al-Debei *et al.,* 2011). *Citrullus colocynthis* and *Cucumis metuliferus* were identified as resistant rootstocks for cucumbers (Punithaveni *et al.,* 2015; Thangamani *et al.,* 2018). Despite their tolerance, some common rootstocks are vulnerable to nematode buildup and should be used cautiously.

5.4 Influence of cucurbit rootstocks to abiotic stresses

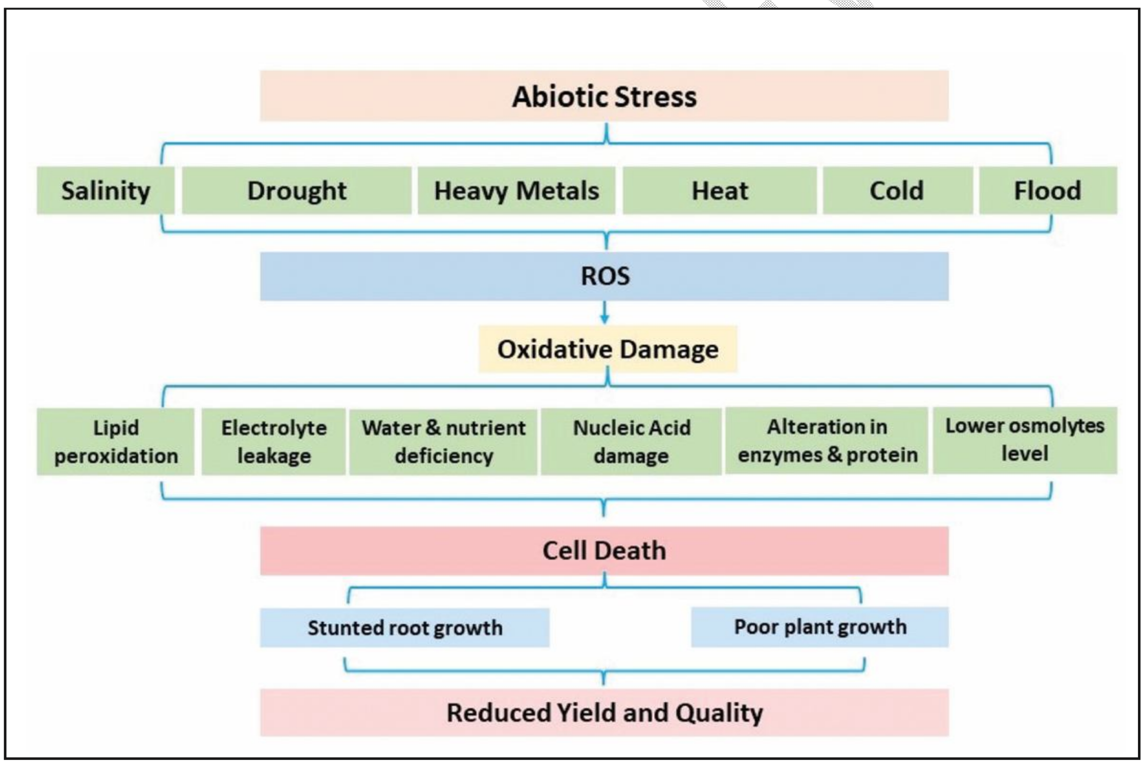

Figure 5. Impact of abiotic stresses on plant physiology, growth and productivity

5.4.1 Cold/heat:

Temperature extremes can hinder vegetable production by delaying flowering and fruit ripening. Using low-temperature tolerant rootstocks for grafting superior cultivars offers a quick alternative to lengthy breeding processes (Schwarz *et al*., 2010). For example, watermelon is grafted onto "Shintosa" rootstocks to hasten planting in cool weather, while fig leaf gourd and bur cucumber are used to enhance cold resistance in cucumbers (Padilla *et al.*, 2023). Grafted cucumbers on squash rootstocks can better endure adverse conditions, and luffa rootstock-grafted cucumbers can tolerate heat stress (Gaion *et al*., 2018).This was reflected in better growth parameters, higher chlorophyll and proline levels, reduced ROS and lipid peroxidation, increased antioxidant enzyme activities (especially CAT and GPX), and elevated expression of Calvin cycle enzymes (Lu *et al*., 2021).

5.4.2 Drought:

Drought significantly impacts global crop productivity and quality. Grafting high-yielding varieties onto drought-tolerant rootstocks can mitigate water stress effects and improve water use efficiency. For example, mini-watermelons grafted onto the commercial rootstock PS 1313 (*Cucurbita maxima* × *Cucurbita moschata* hybrid) yielded 60% more marketable fruit under drought conditions (Gaion *et al*., 2018). In cucumbers, grafting drought-tolerant rootstocks increased commercial yield, enhanced defense gene expression, and improved various physiological parameters such as chlorophyll content, photosystem II efficiency, and antioxidant enzyme activity, while reducing electrolyte leakage and stress markers (Shehata *et al*., 2022).

5.4.3 Soil salinity:

Soil salinity affects up to 20% of irrigated land and 7% of global land (Shahid *et al*., 2018). For instance, grafting watermelon onto bottle gourd significantly improves salt tolerance (Yang *et al*., 2013).Grafting cucumber onto pumpkin (*Cucurbita moschata*) enhances salt tolerance, with grafting onto "Chaojiquanwang" rootstock reducing Na concentration in the scion by limiting Na transport (Huang *et al*., 2014). Additionally, grafting cucumber onto highly salt-tolerant Luffa rootstocks improves salinity tolerance and fruit quality (Guo *et al*., 2023). *Cucurbita maxima x C. moschata* may mitigate the adverse effects caused by the combination of saline soil and heat stresses. Rootstocks improved salinity tolerance in crops, as demonstrated by Usanmaz *et al.* (2019) in North Cyprus, Turkey. Using four commercial cucumber rootstocks (TZ148 F1, RS841 F1, Nun9075 F1 and Avar F1) and two local *Cucurbita moschata* landraces (Local-1 and Local-3) under three different salinity levels, the study found that grafted crops had higher growth and yield than non-grafted ones.A study by Usanmaz and Abak (2019) found that cucumbers grafted on *Cucurbita moschata* L. rootstocks (Nun 9075, TZ148, and Local-3) showed increased salinity tolerance under an EC of 5.0 dSm-1. The RS841 rootstock enhanced tolerance at both 5.0 and 7.5 dSm-1 by reducing Na+ accumulation in leaves.

5.4.4 Flooding:

Many vegetable crops are highly sensitive to flooding caused by heavy rainfall, with some unable to tolerate waterlogged conditions (Singh *et al*., 2020). Grafting has been shown to improve flooding tolerance in various crops (Bhatt *et al*., 2015). For example, watermelon grafted onto landrace *Lagenaria siceraria* showed reduced chlorosis under flood conditions. In contaminated soils, watermelon cv. Arava grafted onto *cucurbita* rootstocks exhibited lower levels of harmful heavy metals. Interspecific hybrids (*C. maxima* × *C. moschata*) and certain melon cultivars like Proteo grafted onto hybrids (Dinero, Magnus, RS841, Shintoza, Strongtosa) have been found to reduce heavy metal uptake, with RS841 being particularly effective in maintaining productivity and reducing arsenic transfer to fruits (Allevato *et al*., 2019). In cucumber, waterlogging causes a reduction of chlorophyll content in leaves, however, no reduction in chloro phyll was observed after grafting onto squash root stocks

5.5 Influence of cucurbit rootstocks on qualitative and quantitative characters:

Grafting is widely used by farmers to enhance fruit yield and plant vigour by improving water and nutrient uptake (Lee *et al*., 2010). Rafting enhances yield by improving root systems, photosynthesis, and disease resistance. For instance, cucumber cv Kalaam grafted onto *Lagenaria siceraria* rootstocks showed superior vegetative growth, fruit yield, and quality compared to other rootstocks (Noor *et al*., 2019). Similarly, grafted cucumbers on pumpkin rootstocks produced 27 per cent more marketable fruit per plant and yielded 8.4 kg per vine under copper toxicity (Rouphael *et al*., 2008).Pugalendhi *et al*. (2019) found that grafted bitter gourd plants yielded 63.2% more than self-rooted plants. Similarly, Tamilselvi and Pugalendhi (2017) and Tamilselvi *et al*. (2015) reported that *Palee F1* grafted onto *Cucurbita moschata* produced more fruit and higher fruit weight per vine compared to other combinations. Watermelon grafted onto *Lagenaria* and *C. maxima* rootstocks resulted in 24 per cent and 27 per cent firmer fruits, respectively, and had rind thicknesses 21 per cent and 17 per cent higher than ungrafted plants (Proietti *et al*., 2008). This increased rind thickness, while generating more waste, improved postharvest handling and injury prevention.Melons grafted onto interspecific hybrid rootstocks (*Cucurbita maxima* × *Cucurbita moschata*) experienced severe premature internal decay.

Watermelon grafted onto bottle gourd rootstock produces female flowers early in the crop's lifecycle. In contrast, pumpkin, bottle gourd, watermelon, and wax gourd grafted onto ‘Shintosa’-type rootstock showed delayed flowering. Flowering time significantly affects harvest timing and produce quality (Sanket *et al.,* 2017).Lecholocholo *et al.* (2020-21) conducted an experiment in South Africa to study the effect of rootstocks on the quality and volatile constituents of cantaloupe and honeydew melons. Using Kickstart and Carnivor rootstocks (a cross between sweet melon and watermelon) grafted with four melon cultivars, they found that grafted fruits had higher soluble sugar-to-titratable acidity ratio, higher pH, increased fruit firmness, and higher ascorbic acid content compared to non-grafted controls.

6. Certain challenges associated with grafting:

Grafting poses challenges such as the need for skilled labour and post-graft care for 7 to 10 days.Many rural farmers lack knowledge about rootstock-scion compatibility, which is essential for successful grafting. Achieving good synchronization, germination rates, and graft success is crucial but often difficult (Sen *et al*., 2018). Maintaining ideal conditions for temperature, humidity, and light is challenging in open fields, and grafting increases disease risks, especially from nursery infections (Maurya *et al*., 2019). Additionally, consistent supply and high cost of rootstocks and grafting tools are significant issues for large-scale production.

7. Future prospects:

Grafting boosts plant performance and supports off-season vegetable production, and it can be a key element in Integrated Pest Management for organic farming. Despite its benefits, grafting is labour-intensive and time-consuming, and the availability of planting materials for widespread use is limited. However, the growing focus on organic and sustainable farming presents a significant opportunity for this eco-friendly technique. There is a need to develop more efficient grafting methods, both manual and mechanical, and to identify, collect, and conserve indigenous and wild rootstocks that are better suited to local conditions, rather than relying solely on exotic sources.

8. Conclusion:

Many countries have adopted this technique, achieving higher profits through healthy rootstocks. Rootstock-scion compatibility is crucial for successful grafting, but the mechanisms behind graft union formation need further study. While grafting addresses issues like pest and disease susceptibility, soil salinity and drought, and promotes organic farming, it remains labour-intensive and requires skilled handling. Recent advances in automated grafting robots have improved efficiency, but challenges such as disease transmission and limited tool availability still need to be addressed. Developing better breeding techniques to enhance rootstock-scion compatibility is essential.

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