JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

ADVANCES IN SOLANACEOUS VEGETABLES: A COMPREHENSIVE REVIEW OF METHODS, CHALLENGES AND FUTURE PROSPECTS

Shweta B. Patil*(P. G. Scholar, department of vegetable science college of horticulture, Dr. Balasaheb Sawant Konkan Krishi Vidhyapheeth, Dapoli. Tal. Dapoli, Dist. Ratnagiri, Maharastra.) shwetapatil1813@gmail.com

Dr. Y. R. Parulekar (Head of Department, vegetable science college of horticulture, Dapoli) parulekaryr@gmail.com

Kartikesh D. Bhuwad (P. G. Scholar, department of vegetable science college of horticulture, Dapoli) bhuwadkartikesh@gmail.com

Abstract

India's horticulture sector has witnessed substantial growth, evolving from a focus on cereal production pre-1980s to a planned approach post-1980s. The National Horticulture Mission (2005) drives sustainable development through area-based strategies. Horticulture contributes 28% to India's agriculture GDP and 54% to agricultural exports (2007-08), growing at 3.6% annually. India is the second-largest global producer of fruits and vegetables, producing 146.55 million tons of vegetables and 74.88 million tons of fruits (2010-11).Grafting, originating in Japan to combat soil-borne diseases, enhances crop resilience, yield, and sustainability. It's beneficial for managing bacterial wilt in solanaceous crops like tomato and brinjal. Key grafting success factors include genetic compatibility, similar stem diameters, and controlled healing environments. Post-grafting, high relative humidity (85-100%) and optimal temperatures are critical for 5-8 days until vascular connections form. Healing chambers provide controlled conditions; types include low-cost plastic pouches, plastic boxes, terrariums, and custom-built structures using PVC frames. Institutions like IIHR Bangalore, TNAU Coimbatore, and CSKHPKV Palampur conduct grafting research targeting bacterial wilt resistance. Companies like VNR Seeds Pvt. Ltd. produce grafted seedlings commercially. Grafting addresses challenges in vegetable production, improving crop health and sustainability. Bacterial wilt, caused by *Ralstonia solanacearum*, severely impacts brinjal and tomato; grafting onto resistant rootstocks is a management strategy. India's achievements include grafting research at various agricultural universities and collaborations with international centers like AVRDC. With growing demand for grafted seedlings, the technique holds promise for enhancing agricultural sustainability and productivity in India.

Key words: solanaceous vegetables, Grafting, Bacterial wilt, Healing chamber, Tomato, Brinjal.

Introduction

India's horticulture sector has undergone significant development over the years. Prior to the 1980s, the country's focus was primarily on cereal production, with horticulture taking a backseat. However, between 1980 and 1992, institutional support for horticulture development was consolidated, marking the beginning of a planned approach to the sector's growth. The post-1993 period saw a concerted effort to promote horticulture development through increased plan allocation and the adoption of knowledge-based technologies. The National Horticulture Mission (NHM) was launched in April 2005 as a centrally sponsored scheme to foster holistic growth in the horticulture sector. The mission employs area-based, regionally differentiated strategies to promote sustainable development. The Foreign Trade Policy (2004-09) also emphasized the need to boost agricultural exports, including horticultural products. The horticulture sector plays a vital role in India's agricultural economy, contributing approximately 28% to the Agriculture Gross Domestic Product and 54% to agricultural exports (2007-08). The sector has been growing at an average rate of 3.6% over the last decade. As of 2010-11, India had 8.495 million hectares under vegetable cultivation and 6.383 million hectares under fruit cultivation, producing 146.55 million tons of vegetables and 74.88 million tons of fruits. This accounts for around 14% and 12% of the world's vegetable and fruit production, respectively. India is the second-largest producer of fruits and vegetables globally, after China. The country's annual requirement for fruits and vegetables is estimated to be 74.40 million tons and 175.2 million tons, respectively. With the growing population, the demand for these products is expected to surpass production levels. To address this, India aims to increase horticultural crop production to 300 million tons by 2012, up from 221.43 million tons in 2010-11.The country's substantial production base presents significant opportunities for export. In 2011-12, India exported vegetables and fruits worth Rs. 4801.29 crore, with vegetables accounting for Rs. 3021.74 crore. Key export items include onions, okra, bitter gourd, green chilies, mushrooms, and potatoes, as well as mangoes, walnuts, grapes, bananas, and pomegranates. Major destinations for Indian horticultural products include Bangladesh, UAE, Pakistan, Malaysia, Sri Lanka, UK, Saudi Arabia, and Nepal.

A recent study examined production trends, market efficiency, and export competitiveness of vegetables in India, covering 200 crops across eight states. The findings indicate that the area under vegetable cultivation grew at a rate of 4.12%, while production growth rates were 6.48%. This suggests a promising future for the sector. The study reveals that the most common marketing channel for vegetables is the Producer-Wholesaler-Retailer-Consumer channel. The producer's share in the consumer rupee varies significantly across states, ranging from 46% to 100%. The study suggests that most horticultural commodity markets operate efficiently, with the highest marketing efficiency found in the producer-to-consumer channel. To improve marketing efficiency, the study recommends promoting direct marketing models and reducing marketing costs, transportation costs, and labor charges. The analysis of export trends shows a significant increase in fresh vegetable exports, indicating huge potential for growth. The Nominal Protection Coefficient (NPC) for all vegetables is less than 1, indicating that Indian vegetables are competitive in international markets. (Dastagiri *et al*., 2011)

Grafted vegetable production originated in Japan and Korea as a solution to mitigate soil-borne diseases exacerbated by intensive cropping. This practice has gained global traction, offering benefits for organic and sustainable farming by reducing the need for agrochemicals and minimizing residue (Lee *et al*., 2010) uptake. By leveraging grafting technology, farmers can improve crop health, increase yields, and promote environmentally friendly produce. This approach has been recognized for its potential to enhance agricultural sustainability and food safety. Grafting vegetable seedlings is a specialized horticultural technique that originated in East Asia to address challenges posed by intensive farming on limited land. Over time, this technology has been introduced to other regions, including Europe, and has been refined for commercial production. Grafting offers numerous benefits, particularly for crops like tomatoes and brinjals, by enhancing plant resilience, improving yields, and reducing disease susceptibility. As a result, grafting has become an increasingly popular practice globally, providing growers with a valuable tool for sustainable and efficient crop production (Singh *et al*., 2017).

Grafting success hinges on key factors genetic compatibility ensures a strong bond, similar stem diameters facilitate a seamless union, and proper environmental conditions during healing promote vascular connection and overall plant health (kleinhenz, 2011). During the healing process, a critical step is the establishment of a vascular connection between the scion and rootstock, which typically takes 5-8 days. During this period, the scion relies on stored water and cannot absorb water from the rootstock, making careful management of environmental conditions crucial for graft survival and success (Johnson, Kreider, and Miles 2011a). Therefore, reducing scion transpiration is crucial for the grafting survival (Johnson and Miles 2011). To minimize water loss from the scion, a high relative humidity (RH) of 85-100% is recommended. While large commercial operations utilize controlled-environment growth chambers to maintain optimal RH levels, the cost can be prohibitive for small-scale growers. As an alternative, smaller operations often rely on more affordable methods to control humidity and support grafting success (Hassell, Memmot, and Liere 2008; Johnson and Miles 2011). To provide a cost-effective solution for graft healing, growers and researchers use small, covered structures known as healing chambers, which offer a controlled environment for optimal recovery (Johnson and Miles 2011).

Grafting is a valuable technique for fruit vegetables, with tongue, cleft, and splice methods being commonly used. Research has shown that grafting can significantly improve yield, quality, and resilience to stressors like soil-borne diseases, water scarcity, and salinity in crops such as tomato, brinjal, cucumber, and watermelon (Lee *et al*., 2010). The development of new rootstocks with desirable traits compatible with local scions can further enhance the potential of grafting technology (Yassin and Hussen, 2015). As a result, grafting is poised to play a crucial role in future agricultural practices, driven by increasing demand for high-quality grafted seedlings that can improve crop performance and sustainability. This growing demand reflects the technique's potential to address key challenges in vegetable production.

In India, the production of solanaceous vegetables, especially brinjal and tomato is severely hampered by the bacterial wilt disease (Ramesh *et al*., 2014). There are numerous strains of the bacterial wilt pathogen and it can persist longer in the soil even in the absence of a host hence its management is a very difficult task. The bacterium is quickly transmitted and can enter uninfested areas through water, soil, contaminated plant material, or mechanical means. In brinjal, bacterial wilt may result in yield losses of 30-100% (Ramesh, 2006), or 4-86% (Sabitha *et al*., 2000). In India, many commercial varieties and local cultivars of brinjal show susceptibility to the disease (Gopinath and Madalageri, 1986). A soil borne bacterium *Ralstonia solanacearum* is a causal organism for bacterial wilt. The bacterium get entered into the plant through wounds in the roots caused during transplantation, infestation by nematodes, and through natural wounds. After entering the plant, it quickly grows in the vascular system and fills the xylem components with bacterial cells, obstructing the flow of water. Plant infected with bacterium shows symptoms of yellowing, wilting and dieing rapidly (Huet, 2014). Number of methods, with varying degrees of success, have been reported for managing the bacterial wilt disease, including resistant varieties, soil amendments, soil solarization, grafting on resistant root stocks, bio-fumigants, plant growth-promoting rhizo-bacteria, the use of SAR inducers, and bio-control agents etc. (Phadake, 2012). Out of these the least expensive and most straight forward method of bacterial wilt management is breeding for host resistance (Huet, 2014). Source of bacterial wilt resistance has been reported in many improved varieties and landraces of brinjal (Rakha *et. al*., 2020).

Tomato (*Solanaum lycopersicum* L.), Brinjal (*Solanum melongena* L.) 2n=24 are important solanaceous vegetables consumed commonly by all sections of the society. All these vegetables are popularly cultivated in rice-based cropping system during rabi season in entire konkan region. However, the commercial cultivation of these vegetables poses limitations and one of them is incidence of bacterial wilt disease. Grafting is one possible way in which bacterial wilt resistant tolerant types can be used as rootstock and commercial varieties as scion. Tomatoes are a versatile and nutritious vegetable staple in Indian cuisine, used in a wide range of dishes. Their adaptability and nutritional value make them a key player in the processing industry. Tomatoes are rich in antioxidants, vitamins C and E, and contain beneficial compounds like lycopene and beta-carotene, which provide their characteristic colors (Agarwal and Rao, 2000). They also contain sugars, acids, and tomatine, a compound with antifungal properties, making them a valuable part of a healthy diet (Spooner *et al*., 1993). With their diverse sizes, shapes, and colors, tomatoes are considered a "protective food" due to their unique nutritional profile. Eggplant is a versatile, nutritious vegetable offering numerous health benefits, including supporting digestive health, reducing inflammation, and protecting against chronic diseases due to its richness in dietary fiber, vitamins, minerals, and antioxidants. Its potential medicinal properties, including anti-cholesterol and anti-diabetic effects, make it valuable. Successful grafting requires optimal temperature, humidity, air circulation, and lighting conditions. With its unique flavor, texture, and various sizes, colors, and shapes, eggplant is a popular ingredient in many traditional dishes and cuisines, providing benefits for weight management, healthy blood pressure, and alleviating swelling and joint pain (Khedkar *et al*., 2023).

Thus, in tomato and brinjal for production of healthy grafts thus study effect of healing chamber in production of healthy seedlings of scion and rootstock is required. similarly, the investigation on suitable healthy chamber for healing grafts.

Achievements and Prospects of Grafting in India

a. The pioneering effort in vegetable grafting involved grafting watermelon (*Citrullus lanatus* L.) onto pumpkin (*Cucurbita moschata* L.) rootstock, primarily undertaken in Japan and Korea during the 1920s as a measure to combat fusarium wilt disease (Ashita, 1927; Yamakawa, 1983). This early application showcased grafting's potential for disease management in vegetable production**.**

b. Eggplant grafting began in the 1950s, utilizing Scarlet eggplant (*Solanum integrifolium* L.) as rootstock. This was followed by the adoption of grafting techniques for cucumbers in the 1960s and tomatoes in the 1970s (Lee and Oda, 2003), marking significant milestones in the application of grafting technology for various vegetable crops.

c. In the public sector, grafting research was initiated at IIHR, Bangalore, where Dr. R.M. Bhatt and his team focused on identifying suitable rootstocks for waterlogged conditions. Additionally, the institute organized the first short-term training course on vegetable grafting in 2013 (Kumar *et al*., 2015).

d. Tamil Nadu Agricultural University (TNAU) in Coimbatore has worked on grafting brinjal (eggplant) onto *Solanum nigrum* rootstock.

e. At the NBPGR regional station in Trissur, Kerala, grafting is being practiced in the dioecious crop *Momordica cochinchinensis*, where male plants serve as rootstocks and female plants are used as scions. This approach enables enhanced productivity by grafting female plants onto male counterparts.

f. The Department of Vegetable Science and Floriculture at Chaudhary Sarwan Kumar Himachal Pradesh Krishi Viswavidyalaya, Palampur, is also conducting grafting research, primarily targeting bacterial wilt—a serious constraint in certain regions of the state that hampers the cultivation of Solanaceous vegetables.

g. CSK Himachal Pradesh Krishi Vishvavidyalaya (CSKHPKV) in Palampur has undertaken grafting research and identified optimal rootstocks for crops like brinjal, chili, tomato, potato, and cucurbits, focusing on resistance to bacterial wilt and nematodes.

h. The Department of Vegetable Science at ASPEE College of Horticulture & Forestry, NAU, Navsari, Gujarat, initiated grafting research in 2013–14, focusing on evaluating the feasibility of cultivating brinjal and tomato under the high rainfall conditions of South Gujarat (Kumar *et al*., 2018)

i. Takii Seed India Private Limited is another prominent seed company in India involved in vegetable grafting research and development, as noted by Kumar *et al*., (2015).

j. Recently, researchers at AICRP on Vegetable Crops, Bidhan Chandra Krishi Viswavidyalaya, West Bengal, have begun grafting cultivated brinjal onto highly tolerant wild rootstocks, *Solanum torvum* and *Solanum sisymbriifolium*, to combat bacterial wilt, following extensive cross-inoculation studies with the most virulent strains of Pseudomonas solanacearum (Kumar *et al*., 2018).

k. In the private sector, VNR Seeds Pvt. Ltd., Raipur (Chhattisgarh) has been a pioneer in grafting, collaborating closely with the Asian Vegetable Research and Development Centre (AVRDC), Taiwan. The company has now entered commercial production, providing grafted seedlings to farmers in Chhattisgarh as well as neighboring states based on demand (Kumar *et al*., 2018).

Healing chamber

Principal:

Vegetable grafting can be likened to organ transplantation, necessitating specific post-grafting conditions for success. High relative humidity (RH) and optimal temperatures for about a week post-grafting are critical to minimize scion transpiration until the vascular connection between rootstock and scion is established, restoring water transport (Cary *et al*., 2011) Healing rooms typically maintain temperatures between 15-30°C (±0.5°C precision), RH of 60-90% (±3% precision), and light levels adjustable from 0-5000 lx. (Gregory *et al*., 2015) The entire process from seeding through grafting, healing, and field transplanting spans roughly five weeks. Vascular connections take 5-8 days to form; during this time, the scion can't uptake water via the rootstock, making reduced transpiration vital for graft survival. High RH (85-100%) helps curb scion water loss. Seeding timings and propagation durations adapt to greenhouse conditions and local light intensity.

Mechanism

To prepare the healing chamber for grafted vegetable plants, mist the interior thoroughly with water a few hours before grafting using a hose with a spray nozzle or a handheld spray bottle. Ensure the walls, floor, and ceiling are wetted until water starts accumulating at the bottom. Immediately after grafting, drench the grafted plants with mist until they are dripping wet. Additionally, mist the healing chamber again before placing the grafted plants inside. Once the plants are positioned in the chamber, seal it tightly using clips like clothespins or binder clips to retain moisture. The surrounding greenhouse or location typically has lower relative humidity compared to the healing chamber, so grafted plants should be gradually acclimated to the external environment to prevent stress and mortality. For specifics on acclimating plants from the healing chamber to greenhouse conditions, consult resources like the Extension fact sheet "Vegetable Grafting- Eggplants and Tomatoes" (FS052E).

Types of healing chamber

1. **Low cost plastic pouch:-**

A day prior to grafting, use a hand sprayer to mist the interior surfaces of a suitably sized plastic bag with water, then seal it. This preparatory step helps achieve a relative humidity (RH) of approximately 95% inside the bag before introducing grafted plants. Following grafting, open the bag, insert the potted grafted seedlings, and promptly close it to minimize loss of humidity. If required, additional water mist can be applied inside the bag before placing the plants to ensure adequate moisture levels. Ensuring sufficient bag size allows for tight sealing, crucial for preventing external humidity loss. Resealable plastic bags offer a practical choice as they facilitate easy and effective closure, helping maintain the desired high humidity environment conducive to graft healing.

2. **Plastic box**

A plastic container with a lid, like an empty salad container or storage box, serves as a suitable healing chamber for grafted seedlings. Prepare it by misting water onto the interior walls a day before introducing the grafted plants, then closing the lid to elevate the relative humidity (RH) inside. If necessary, additional misting can be done just before placing the grafted seedlings in the container to ensure adequate moisture. Once the potted grafted plants are positioned inside, promptly seal the container's lid to retain the humid environment, minimizing RH loss. This high-humidity setting supports the graft healing process.

3. **Terrarium**

An empty glass aquarium can serve as an ideal healing chamber (as shown in, offering suitable environmental conditions for grafted seedlings. Preparation involves misting the interior surfaces of the aquarium with water using a hand sprayer a day before grafting, then closing it to elevate the relative humidity (RH). After grafting, position the seedlings inside the aquarium and seal it – either by closing a lid if available, or alternatively, placing the aquarium upside down over the seedlings to create a humid enclosure. This setup helps maintain high RH, fostering conditions conducive to graft union and healing.

4. Facilitate controlled acclimation of grafted plants to external environments post-healing

Plastic storage boxes can serve as healing chambers for grafted plants if they're sufficiently large to accommodate transplant trays. However, using numerous boxes can become costly as grafting production scales up. An alternative is constructing a custom chamber using polyvinyl chloride (PVC) pipes for framing, a plastic tray as the base, and a plastic cover to maintain high relative humidity (RH). For practical management of transplant trays and RH control, it's advisable to keep the structure compact – with a height not exceeding three feet and dimensions of width and length not more than five feet (Johnson, Kreider, and Miles 2011a). Preparation involves misting interior surfaces with a hand sprayer a day before grafting, adding water to the bottom of the chamber, and sealing it to elevate RH. It's crucial to position the transplant trays above the water level to prevent media saturation. This setup supports a favorable humid environment for graft healing while allowing manageable operation.

5. Healing Chamber Construction for Large-Scale Grafting Operations

For large-scale grafting operations, healing chambers can be constructed within a dedicated greenhouse area or above transplant tray benches. Frames can be built using wood or PVC pipes, covered with plastic to enclose the space. Maintaining a water pool beneath the structure provides high relative humidity (RH), removing the necessity for surface misting within the chambers. It's essential to position grafted plant trays above the water level to prevent saturation of the growing media. Preparation involves filling the bottom water pool a day before grafting and sealing the chamber to elevate RH, fostering a conducive environment for graft healing.

Grafting environment condition

1. Temperature

Temperature plays a significant role in graft healing; within an optimal range, higher temperatures can accelerate the process. For the initial three days post-grafting, maintaining suitable high temperatures is crucial. Specific temperature ranges vary by crop: cucumber benefits from 25~28°C daytime and 17~20°C nighttime temperatures; watermelon and melon thrive with 25~30°C daytime and 23°C nighttime temperatures; and tomato does well with 23~28°C daytime and 18~20°C nighttime temperatures. After three days, temperatures can typically be lowered by 1~2°C. Excessive heat may require mitigation through shading and cooling measures. The first three days post-grafting are critical for grafted seedling survival, underscoring the importance of optimal temperature management during this period (Lee *et al*., 2010), (Greathead 2003).

High humidity supports callus formation crucial for graft healing, whereas dry air can hinder this process by causing water loss from the scion. Preparatory steps include saturating the rooting substrate with water pre-grafting. Post-grafting, misting the grafted plants and covering them with a moisture-retaining film is beneficial. For the first 3 days, maintaining air humidity at 90~95% is advisable; from 3 days post-grafting, humidity can be gradually reduced to 85–90% as suitable for promoting successful graft union (Greathead 2003), (Lee. S. G 2007).

Direct sunlight is typically avoided post-grafting to minimize transpiration and prevent scion wilting. Low light conditions favor callus growth, aiding graft survival. Thus, grafted plants are often shaded using sunshade netting initially. After 3~4 days, partial removal of shading can increase light exposure gradually. By 7~10 days post-grafting, normal light management practices can usually be resumed for the grafted seedlings, supporting their acclimatization (Lee et al., 2010), (Greathead 2003), (Lee. S. G 2007). Grafted seedlings require adequate ventilation to supply oxygen for respiration and carbon dioxide for photosynthesis of cambium cells at the rootstock-scion junction. Ventilation should be managed carefully, followed by misting to prevent seedlings from desiccating, thus balancing aeration needs with moisture preservation (Lee, S. G 2007).

Pest and disease incidence significantly impacts grafting success. Grafting environments often involve high temperature and humidity, coupled with tissue injury, which can foster microbial infections and impede healing at the graft union, potentially leading to disease and plant mortality (Lee, S. G 2007). Sucking pests like aphids and whiteflies may target graft junctions and young scion leaves, causing damage and possible viral transmission. Implementing a thorough pest and disease management strategy alongside grafting programs is essential to mitigate these risks and support grafting success (Lee *et al.*, 2010), (Greathead 2003).

Enhancing crop productivity and quality through grafting

Grafting is a valuable technique for managing soil-borne diseases in various crops. For instance, it helps control Fusarium wilt in cucurbits (like cucumbers and melons) and bacterial wilt in solanaceous crops (such as tomatoes and peppers). Research has shown that grafting onto resistant rootstocks can effectively combat specific pathogens, including *Fusarium oxysporum* in melons and Phytophthora blight and bacterial wilt in peppers. Studies, such as those by (Jang *et al*., 2012), demonstrate that grafting pepper scions onto resistant rootstocks significantly improves plant survival rates when exposed to pathogens like *Phytophthora capsici* and *Ralstonia solanacearum.* This approach offers a practical solution for disease management in vegetable production.

1) **Tolerance to abiotic stresses:**

Grafting is a valuable technique for enhancing plant resilience to extreme temperatures, making it essential for winter greenhouse production of fruiting vegetables. By utilizing robust rootstocks like figleaf gourd, growers can improve the low-temperature tolerance of crops such as cucumbers, watermelons, melons, and summer squash. Additionally, grafting has been shown to confer tolerance to other environmental stresses, including soil salinity and flooding, as demonstrated by Yetisir *et al*. (2006). This approach enables growers to cultivate crops in challenging conditions, promoting sustainable and productive agriculture practices. Grafting enhances plant survival under low temperatures due to increased levels of linolenic acid, a key fatty acid that helps maintain membrane fluidity and function. Additionally, grafting can improve crop yields under high-temperature conditions, as seen in chili, peppers grafted onto sweet pepper rootstocks (Palada and Wu, 2009). This technique allows growers to leverage the beneficial traits of rootstocks to enhance scion performance and resilience in various environmental conditions. Grafting in tomatoes has been shown to enhance plant productivity in both outdoor and indoor settings. In outdoor cultivation, grafted plants produce more internodes and flowers, while in indoor cultivation, they yield a greater number and total weight of fruits (Voutsela *et al*., 2012). This suggests that grafting can improve tomato plant performance and fruit production in various growing conditions. Drought tolerance (Rivero *et al*., 2007) demonstrated that transgenic tobacco plants can maintain photosynthetic activity and high water content during drought conditions, showcasing a potential strategy for improving crop resilience to water stress. Grafting enhances plant resilience to flooding, as seen in bitter gourd grafted onto luffa rootstock (Liao and Lin 1996). This technique is particularly valuable in lowland tropical regions prone to flooding during hot periods. The AVRDC suggests grafting tomatoes onto specific eggplant rootstocks (EG195, EG203) and peppers onto chili pepper accessions (PP0237-7502, PP0242-62, Lee B) to improve crop performance in such conditions.

2) Influence on fruit quality

Grafting is an effective approach to improve fruit quality under both optimum growth conditions and salinity. The fruit quality of the shoot, at least partially, depends on the root system (Flores *et al*. 2010). In soilless tomato cultivation, grafted plants had higher marketable yield, fruit quality and pH content of fruits depending on rootstocks (Gebologlu *et al.*, 2011). Grafting of eggplant onto *S. torvum* increased the fruit size and had no effect on quality and yield. The fruit size of watermelons grafted to rootstock having vigorous root systems was significantly increased as compared to the fruit from intact plants.

In cucumbers, especially for export, bloom development and external colour are important quality factors. These can be greatly influenced by the rootstock. The grafting technique affects various quality aspects of vegetables. Rootstock/scion combinations should be carefully selected for specific climate and geographic conditions. Appropriate selection can help to control soil borne dis-eases and also increases yield and fruit quality. Sugar, flavour, pH, color, carotenoid content and texture can be affected by grafting and the type of rootstock used (Davis *et al.*, 2008).

3)Encouragement of vigorous growth

The root systems of selected rootstocks are generally larger and more vigorous, enabling them to take up water and nutrients more efficiently than non-grafted plants. In cucumber, such vigorous rootstocks improve water absorption, allowing for reduced irrigation frequency. Similarly, the use of strong rootstocks can significantly lower the need for agrochemical applications. In watermelon cultivation, for example, the application of chemical fertilizers can be decreased to nearly one-half to two-thirds of the recommended dose for non-grafted plants (Salehi-Mohammadi *et al*., 2009).

4)Enhanced output

In soil-based cultivation, grafting has been employed as an effective method to enhance crop yields (Kacjan-Marsic and Osvald, 2004). For example, tomato cv. Monroe grafted onto the rootstock Beaufort produced significantly higher yields. Both greenhouse and open-field studies have shown that grafted plants consistently outperform non-grafted ones in terms of productivity (Khah *et al.,* 2006). Tomato plants grafted onto Heman and Primavera also demonstrated superior yields under both conditions. Moreover, grafted plants exhibited improved water-use efficiency along with yield gains. Research conducted in Korea and Japan reported yield increases ranging from 25% to 50% in grafted tomato, melon, pepper, eggplant, and watermelon when compared to their non-grafted counterparts.

Techniques of vegetable grafting

Various grafting methods are utilized in fruit-bearing vegetable crops. In tomato and eggplant, cleft and tube grafting are the most common practices. For cucurbits, particularly cucumber, the tongue approach technique is generally adopted. In watermelon and melon, the slant-cut grafting method has recently gained popularity due to its simplicity, and it was primarily designed to support robotic grafting. The following section outlines these techniques in detail:

1)Cleft and tube grafting

The seeds for the rootstock are sown 5–7 days before the scion seeds. When the scion reaches the four-leaf stage, its stem is cut straight across, leaving 2–3 leaves on the stem. Similarly, the rootstock, at the four- to five-leaf stage, is cut straight across with 2–3 leaves remaining. The scion is then shaped into a wedge, which is inserted into a cleft cut made at the top of the rootstock. The graft union is secured using a plastic clip, and the tray containing the grafted plants is then moved to a suitable place for healing.

2)Tube or Japanese Grafting

This grafting technique is designed for vegetable seedlings grown in plug culture. It allows small plants in plug trays to be grafted two to three times faster than traditional methods. Smaller seedlings also enable more plants to be accommodated in healing chambers or acclimation rooms. To graft, cut the rootstock just below the cotyledons at a 45° angle or sharper. Prepare the scion with a matching hypocotyl width, making the cut at the same angle about 5–10 mm below its cotyledons. Place a grafting tube halfway over the cut end of the rootstock hypocotyl, then insert the scion into the tube so that is cut surface aligns precisely with that of the rootstock. Finally, move the tray containing the grafted seedlings to a healing area for up to seven days.

3)Tongue Approach Grafting:

In this method, cucumber seeds are sown 10–13 days before grafting, and pumpkin seeds 7–10 days prior, to ensure that the scion and rootstock hypocotyls have uniform diameters. The shoot apex of the rootstock is removed to prevent its growth. The hypocotyls of both scion and rootstock are cut to interlock with each other, and the graft is held in place using a plastic clip. The scion's hypocotyl is allowed to heal for 3–4 days, after which it is gently crushed between the fingers. Three to four days following this, the hypocotyl is cut off using a razor blade.

4)Slant-Cut Grafting

This grafting method is simple to perform and has gained popularity. It was primarily developed for robotic grafting. When cutting the rootstock cotyledon at an angle, it is essential to remove the first leaf and any lateral buds.

5)Hole Insertion/Top Insertion Grafting

This is the most commonly used grafting method in cucurbits. It is best suited for scion and rootstock with hollow hypocotyls. To ensure a high success rate, relative humidity should be kept around 95%, and the temperature should be maintained between 21–36 °C until transplanting. With this method, a single person can produce 1,500 or more grafts per day.

6)One Cotyledon/Splice Grafting

This method has recently been adopted by commercial seedling nurseries and is suitable for most vegetable crops (Sakata *et al*., 2006). To promote successful graft union formation, the grafted plants should be kept in darkness at 25 °C with 100% humidity for three days. This technique was developed specifically for robotic grafting of cucurbits.

7)Pin Grafting

Pin grafting is similar to splice grafting, but instead of using grafting clips, specially designed pins are used to secure the graft in place. These pins are made of natural ceramic, allowing them to remain on the plant without causing any issues.

Challenges in vegetable grafting

a) This method is labor-intensive and demands skilled, specially trained personnel.

b) Proper timing is essential for sowing rootstock and scion seeds.

c) A controlled environment is necessary to ensure successful graft healing.

d) Grafting may raise the risk of pathogen transmission, particularly from seed-borne pathogens in the nursery. Additionally, workers carrying out grafting in greenhouses and growth chambers often experience heat stress and discomfort, especially during the months of April–June and September–October (Marucci *et al.*, 2012).

Present scenario of vegetable grafting

1. Introduction to Vegetable Grafting

Vegetable grafting involves joining the shoot system of one plant (scion) with the root system of another (rootstock) to combine desirable traits such as disease resistance, stress tolerance, and improved yield. It has become an essential technique in modern horticulture, especially for high-value crops like tomato, cucumber, eggplant, watermelon, and melon.

2. Current Adoption and Usage

Vegetable grafting has transitioned from experimental research to commercial-scale adoption, particularly in Asia (Japan, Korea, Taiwan, Thailand) and increasingly in Europe and North America. In India, awareness about grafted seedlings is growing among commercial nurseries and progressive farmers, though adoption is still limited by cost and technical requirements. Private seed companies and agricultural research centers have started supplying grafted seedlings to farmers. For example: VNR Seeds Pvt. Ltd., Raipur has initiated commercial production of grafted seedlings in collaboration with the Asian Vegetable Research and Development Centre (AVRDC), Taiwan. ICAR and State Agricultural Universities (SAUs) are promoting grafted vegetables through demonstration trials and farmer awareness programs.

3. Popular Crops for Grafting

Solanaceae family- Tomato, eggplant, chili, Cucurbitaceae family- Cucumber, watermelon, melon, pumpkin, Other crops- Capsicum, zucchini, and squash. The choice of rootstock depends on soil-borne pathogen resistance, tolerance to abiotic stresses (salinity, drought, high temperature), and compatibility with scion cultivars.

4. Techniques in Practice

Splice or Tongue Grafting- Widely used for seedlings in plug trays, Cotyledon Grafting- Increasingly adopted for robotic or high-throughput nursery operations, Pin Grafting- Uses specialized ceramic pins instead of clips to hold grafts. These methods are being refined for mechanization, reducing labor dependency and improving success rates.

5. Advantages Driving Adoption

Resistance to soil-borne pathogens, such as Fusarium, Verticillium, Pythium, and Phytophthora. Improved abiotic stress tolerance, salinity, drought, and temperature extremes. Enhanced growth and yield, stronger root systems support vigorous vegetative and reproductive growth. Fruit quality improvement- Grafting can improve fruit size, firmness, and shelf life.

6. Challenges and Limitations

Labor-intensive and skilled work requires trained personnel for high success rates. Time-sensitive coordination rootstock and scion seed sowing must be synchronized. Controlled environment requirement: Healing chambers and acclimatization rooms are necessary to maintain high humidity and temperature. Grafted seedlings are more expensive than non-grafted ones. Health risks in nurseries: Workers may face heat stress in summer months, and improper hygiene can spread pathogens in dense nurseries.

7. Commercial and Institutional Support

Increasing support from government schemes, agricultural universities, and private seed companies is helping reduce cost barriers. Training programs for nurseries and farmers improve skill levels for grafting operations. Research is focusing on developing disease-resistant rootstocks suited to local conditions.

8. Future Prospects

Wider adoption is expected with mechanized grafting techniques, such as robotic grafting systems. Expansion into new crops beyond tomato and cucumber is likely as rootstock breeding progresses. Integration with sustainable and organic farming systems is increasing interest among farmers aiming to reduce chemical pesticide use.

Essential requirements for vegetable grafting

Grafting is an essential horticultural method in vegetable cultivation that combines two different plant varieties to create a superior plant. This technique allows growers to incorporate desirable traits from both varieties—such as disease resistance, higher yields, or improved tolerance to environmental stresses—into a single plant. The process involves joining two main parts: the rootstock, which forms the root system, and the scion, which develops into the above-ground portions including stems, leaves, and fruits (Garner, 2013). Successful grafting, however, can be challenging and depends on certain prerequisites. These prerequisites include the compatibility of the plants, suitable environmental conditions, and the use of proper grafting techniques. The following sections discuss these factors in detail.

1. Criteria for Rootstock and Scion Selection

Choosing an appropriate rootstock and scion is essential for successful grafting. Ensuring that the stems of both plants are similar in size is critical for a proper union and overall compatibility. Additionally, grafting is most effective when the plants have developed 2–3 true leaves, as this stage provides the most favorable conditions for successful graft formation (Garner, 2013).

2. Rootstock-Scion Compatibility

Graft compatibility plays a vital role in the success of the grafting process. When the rootstock and scion are well-matched, plant mortality is greatly minimized, even during later stages of growth. Compatibility promotes rapid callus development at the junction of the scion and rootstock, which in turn facilitates the formation of vascular bundles, ensuring the proper functioning of the grafted plant (Garner, 2013).

3. Grafting Equipment

Successful grafting requires the use of specific tools, such as grafting clips, tubes, pins, and blades. These implements help firmly connect the rootstock and scion, ensuring stability and supporting the healing and union process.

4. Grafting Screening Chamber

Before grafting, seedlings should be cultivated in a controlled setting, typically a screening house. This structure is usually constructed with a 60-mesh nylon net to prevent the entry of pests and diseases. Additionally, the screening house should feature a double door, with the upper section covered in UV-resistant polyethylene. This arrangement shields the seedlings from harmful UV radiation, providing an optimal environment for healthy growth.

5. Graft Integration

The healing phase is a critical step in vegetable grafting, requiring the creation of optimal conditions to stimulate callus development in grafted seedlings. Within a healing chamber, the temperature should be kept around 28–29°C with relative humidity maintained at about 95% for 5–7 days, including 1–2 days in complete darkness under partial shade (Bhoite *et al*., 2022). Such conditions promote callus growth at the graft interface, resulting in a stronger and more secure graft union. The central aim during this stage is to establish a controlled healing environment by managing temperature, humidity, and light intensity.

6. Hardening of Grafted Plants

Once callus formation is complete and the wounded surfaces have healed, it becomes essential to acclimate the grafted seedlings to external conditions. This can be done by placing them in a greenhouse, under a misting system, or covering them with transparent plastic to reduce leaf scorch and wilting, thereby supporting their successful establishment (Vince-Prue *et al*., 2014). Careful attention to these critical prerequisites allows the intricate process of vegetable grafting to be carried out effectively. Adhering to them greatly determines the success of the operation, resulting in the development of improved plant varieties. Such varieties express multiple desirable traits, offering greater advantages to growers. Additionally, successful grafting contributes to higher plant productivity, showing that these prerequisites not only ensure grafting success but also enhance yield potential.

7. Different Grafting Approaches

Different grafting methods are employed based on the choice of scion and rootstock, the purpose of grafting, growers' expertise, and the conditions provided after grafting. The success and survival of grafted plants are influenced by several factors, including scion–rootstock compatibility, the age and quality of seedlings, the precision of the graft union, and subsequent management practices (Fallik *et al*., 2014). In the early stages, cleft grafting was commonly practiced for melon, but its use decreased markedly with the introduction of the tongue approach grafting method, which offered greater success and more uniform seedling growth (Malik *et al*., 2021). This method became particularly popular across Asia. In contrast, Spain predominantly uses the one-cotyledon method, where more than 90% of watermelon plants are grafted using this technique (Malik *et al.,* 2021).

Conclusion and future trust

Vegetable grafting has emerged as a highly effective technique for overcoming production challenges such as soil-borne diseases, abiotic stresses, and low productivity. Its success largely depends on the compatibility of rootstock and scion, precise grafting methods, and careful post-grafting management. The practice not only improves yield and crop quality but also reduces the reliance on chemical inputs, aligning with sustainable and eco-friendly agriculture.

Looking ahead, the future of grafting in India and globally lies in the development of region-specific, disease-resistant, and stress-tolerant rootstocks, supported by advanced breeding programs. Mechanization and robotic grafting will help reduce the labor-intensive nature of the process and expand its adoption among farmers. Greater integration of grafting into organic and protected cultivation systems will further enhance its role in sustainable crop production. With increasing demand for healthy, residue-free vegetables, grafting technology is expected to play a pivotal role in ensuring food security, higher productivity, and improved profitability for growers.

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