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VEGETABLE GRAFTING FOR ENHANCING CROP RESILIENCE AND PRODUCTIVITY: A REVIEW

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ABSTRACT

Vegetable grafting, an age-old horticultural practice, is gaining renewed interest as a sustainable production strategy. The increasing incidence of soil-borne pathogens, climate variability, and the need for reduced chemical input have driven research and commercial applications of grafting, especially in high-value vegetable crops such as tomato, brinjal, pepper, watermelon, and cucumber. Vegetable grafting has gained prominence as a sustainable agronomic strategy to mitigate soil-borne diseases and enhance tolerance to abiotic stresses, thereby improving yield and quality in vegetable crops. It has emerged as an effective technique to overcome challenges related to biotic and abiotic stresses, improve crop yield, and ensure sustainability in intensive vegetable production systems. Moreover, the role of grafting in sustainable and organic agriculture has been increasingly recognized. With the global movement toward reduced chemical use, environmental conservation, and residue-free produce, vegetable grafting is positioned as a promising strategy that aligns well with sustainable development goals. In high-input systems such as greenhouse and hydroponic farming, grafting also contributes to enhanced productivity and resource-use efficiency. Given its increasing relevance, this review aims to provide a comprehensive overview of vegetable grafting, encompassing its historical development, physiological basis, techniques, protocols, rootstock-scion compatibility, commercial applications, and future prospects.

***Keywords* :** Vegetable grafting, rootstock, scion, disease resistance, abiotic stress.

Introduction

Vegetable production systems worldwide face increasing challenges due to the intensification of cultivation, depletion of soil health, climate variability and rising incidences of biotic and abiotic stresses. These constraints not only hamper yield and productivity but also affect the economic viability of smallholder and commercial farms alike. In this context, vegetable grafting has emerged as an effective and eco-friendly alternative to mitigate these challenges and improve crop resilience. Grafting, a technique that joins the shoot system (scion) of one plant to the root system (rootstock) of another so that they grow as a single plant, has traditionally been employed in woody perennials such as grapevine and citrus. However, its application in herbaceous vegetable crops is a relatively recent innovation that has gained global attention due to its multifaceted benefits.

The practice of grafting dates back over 2000 years in fruit crops, but its application in vegetables started in East Asia during the early 20th century. Japan and Korea pioneered vegetable grafting, particularly in watermelon and tomato. Over the decades, the practice has spread to Europe, the Middle East, and more recently to India and Africa, driven by protected cultivation and organic farming needs. The commercial use of grafting in vegetables was first reported in Japan during the early 20th century, where grafting watermelon (*Citrullus lanatus*) onto gourd rootstocks was practiced to combat *Fusarium* wilt (Lee *et al.*, 2010). The technique gradually spread to other parts of Asia and Europe, and today, countries like China, Korea, Spain, Italy, and Turkey have integrated grafting into their intensive vegetable production systems. In India, although still in its nascent stage, grafting is gaining interest, especially in protected cultivation and organic farming sectors where chemical inputs are restricted.

The main objectives of grafting in vegetables are: (i) to confer resistance or tolerance to soil-borne pathogens such as *Fusarium oxysporum*, *Verticillium dahliae*, *Ralstonia solanacearum*, and nematodes; (ii) to enhance tolerance to abiotic stresses like salinity, drought, temperature extremes, and flooding; (iii) to improve plant vigor and nutrient uptake; and (iv) to increase yield and fruit quality parameters (Louws *et al.*, 2010; Davis *et al.*, 2008). Additionally, grafting enables the use of elite commercial varieties (scions) with desirable fruit characteristics while benefitting from the hardiness and disease resistance of genetically different rootstocks.

Modern grafting practices have evolved significantly with the advent of precision tools, healing chambers, and even robotic grafting units that allow large-scale, uniform, and high-throughput grafting. Depending on the crop species, compatibility, and production environment, various techniques such as splice grafting, cleft grafting, and hole-insertion grafting are employed. The selection of compatible rootstock-scion combinations is critical for the success of grafted plants and requires a thorough understanding of physiological interactions, vascular connectivity, hormonal cross-talk, and potential incompatibility issues.

Moreover, the role of grafting in sustainable and organic agriculture has been increasingly recognized. With the global movement toward reduced chemical use, environmental conservation, and residue-free produce, vegetable grafting is positioned as a promising strategy that aligns well with sustainable development goals. In high-input systems such as greenhouse and hydroponic farming, grafting also contributes to enhanced productivity and resource-use efficiency.

Physiological and Molecular Basis of Grafting

Successful grafting depends on the formation of a functional vascular connection between the rootstock and scion. This process involves wound healing, callus formation, cambial alignment, and vascular differentiation. Hormonal signaling, particularly auxins and cytokinins, play a critical role. Advances in molecular biology have revealed genes associated with graft compatibility and stress response. The successful union between the scion and rootstock in vegetable grafting is a complex biological process that involves a series of physiological, anatomical, and molecular events. These processes are fundamental to graft compatibility and the long-term viability of the grafted plant. Understanding the underlying mechanisms not only helps improve grafting efficiency but also contributes to the development of better rootstock-scion combinations and selection protocols.

Anatomical and Cellular Events in Graft Union Formation

The graft union formation progresses through distinct physiological stages:

(i) Wound Healing and Callus Formation:

Immediately after grafting, both the scion and rootstock experience mechanical injury at the cut site, which triggers wound responses. Cells near the cut surfaces dedifferentiate and form parenchymatous callus tissue. This callus acts as a bridge between the scion and rootstock (Pina and Errea, 2005).

(ii) Adhesion of Graft Partners:

Adhesion begins with the exudation of cell wall materials such as pectins and glycoproteins that glue the cut surfaces together. Callus cells from both partners proliferate and intermingle at the interface (Goldschmidt, 2014).

(iii) Cambial Connection and Differentiation:

As the callus matures, cambial cells from both partners re-establish contact and differentiate into vascular tissues. The formation of continuous xylem and phloem is critical for the resumption of nutrient, water, and signal translocation across the graft junction (Melnyk *et al.*, 2015).

(iv) Vascular Reconnection:

Within 7–14 days post-grafting, depending on the crop and environmental conditions, new vascular tissues are fully formed. This reconnection is crucial for the full physiological integration of the two partners and restoration of systemic communication (Moore, 1982).

Role of Plant Hormones

Hormonal signaling is essential for graft union development and compatibility. Auxins (particularly indole-3-acetic acid, IAA) are vital for initiating cell division and vascular differentiation. They accumulate at the graft site and induce genes involved in vascular tissue regeneration (Yin *et al.*, 2012). Cytokinins promote cell division in the callus and support shoot and root development. An appropriate auxin-to-cytokinin ratio is critical for successful grafting. Gibberellins and brassinosteroids enhance cell elongation and vascular tissue development, though their exact role in graft healing is less defined. Ethylene and abscisic acid are typically stress-response hormones and their excessive production may signal incompatibility or delay graft union formation (Cookson *et al.*, 2013).

Molecular Mechanisms and Gene Expression

Recent advances in transcriptomics and proteomics have uncovered gene regulatory networks activated during graft union formation. Genes involved in cell wall modification, such as expansins, pectin methylesterases, and cellulases, are upregulated to facilitate adhesion and remodeling (Notaguchi *et al.*, 2020). Genes related to vascular development such as VND (Vascular-related NAC-domain) transcription factors and HD-ZIP III are induced to promote xylem and phloem formation. Stress-response genes, including those coding for heat shock proteins, antioxidant enzymes (SOD, CAT), and pathogenesis-related proteins, are expressed to counter graft-induced oxidative stress. Inter-tissue communication also involves mobile RNAs, transcription factors, and small RNAs that move across the graft interface and regulate gene expression systemically. For example, miR165/166 gradients influence vascular patterning and development in grafted tissues.

Graft Compatibility and Incompatibility

Graft compatibility is governed by the genetic, anatomical, and physiological affinity between the scion and rootstock. Compatible combinations lead to successful vascular reconnection and balanced hormonal interactions, while incompatible grafts often display symptoms such as swelling at the union, delayed healing, necrosis, or poor vascular continuity. Inter-specific grafts (e.g., tomato onto eggplant rootstock) may succeed due to shared genomic and vascular characteristics. Incompatibility may arise from mismatched hormone signaling, immune responses, or failure to form vascular bridges. Molecular markers and genomic tools are increasingly being explored to screen for compatibility before large-scale grafting (Goldschmidt, 2014).

Methods of grafting in vegetable crops

Grafting in vegetable crops employs a variety of methods, each selected based on the physiological characteristics of the crop, the purpose of grafting, and the available infrastructure. The most commonly adopted techniques include splice (or slant-cut) grafting, cleft grafting, approach grafting, tube (or Japanese top) grafting, tongue approach grafting, and side grafting.

Vegetable grafting involves various techniques tailored to crop species, anatomical characteristics of seedlings, and cultivation systems. The most commonly employed methods include splice (slant-cut) grafting, cleft grafting, approach grafting, tube grafting, tongue approach grafting, and side grafting, each with specific suitability and technical requirements. Among these, splice grafting is extensively used in solanaceous crops like tomato and eggplant. It involves cutting both scion and rootstock seedlings at complementary angles (typically 45°) and joining them with grafting clips under high humidity conditions to facilitate vascular fusion (Lee *et al.*, 2010). The cut surfaces must be perfectly aligned to ensure cambial contact for successful vascular union. This method is suitable for small-diameter seedlings (2–3 mm) and requires a healing chamber with high humidity (90–95%) and moderate temperature (22–28°C) for 5–7 days. Cleft grafting, frequently applied in cucurbits such as watermelon and cucumber which are often grafted onto squash or bottle gourd rootstocks. In this type of grafting a wedge-shaped scion is inserted into a vertical slit on the rootstock, enabling a strong mechanical and vascular union (Louws *et al.*, 2010). Cleft grafting offers good success rates but requires precise cutting and skilled handling. Approach Grafting is used when it is difficult to graft young seedlings or when a higher success rate is needed. Both the scion and rootstock retain their root systems during the initial healing phase. A slanted cut is made on each stem, and the wounded surfaces are tied together until the graft union is established. Once healing occurs, the root system of the scion and the shoot of the rootstock are removed. This method is labor-intensive but ensures high success, particularly in field conditions. It is particularly beneficial in cases where compatibility is uncertain or delicate seedlings are involved (Rivero *et al.*, 2003). Tube grafting, also known as Japanese top grafting, is widely used in commercial nurseries due to its efficiency and suitability for automation. It involves cutting young seedlings at uniform angles and securing them with silicone tubes, followed by healing in controlled environments (Schwarz *et al.*, 2010). Tongue approach grafting, though less common, allows for greater surface contact and mechanical strength through interlocking cuts on the scion and rootstock. Side grafting, wherein the scion is inserted into a side cut on the rootstock, offers another alternative, particularly for thicker or woody seedlings. Regardless of the method, successful grafting depends heavily on precise alignment of the vascular cambium, optimal environmental conditions (20–28°C, >90% RH), and proper post-grafting care, including healing chambers or humidity tents (Bletsos, 2005). Each technique has trade-offs between labor intensity, success rate, and adaptability, and thus selection should be crop-specific and resource-oriented. Continuous refinement in grafting protocols and healing technology is crucial for scaling up its adoption in commercial vegetable production systems. Each grafting method has its own advantages and limitations, and the choice depends on crop species, seedling age, environmental conditions, and the goal of grafting such as resistance to soil-borne diseases, abiotic stress tolerance, or yield enhancement. Successful grafting also requires post-grafting care, including maintaining appropriate humidity, temperature, and light conditions in healing chambers to promote callus formation and vascular connectivity.

Benefits of grafting in vegetable crops

Grafting has emerged as a promising horticultural tool in vegetable production, offering multiple agronomic and physiological benefits that enhance crop resilience, productivity, and sustainability. One of the most significant advantages of grafting is its ability to confer resistance to soil-borne pathogens such as *Fusarium oxysporum*, *Verticillium dahliae*, *Ralstonia solanacearum*, and root-knot nematodes (*Meloidogyne* spp.), which are notoriously difficult to manage with conventional methods (Louws *et al*., 2010). By utilizing resistant rootstocks, growers can minimize the use of chemical pesticides, thereby promoting environmentally sustainable farming systems (Lee *et al*., 2010). Moreover, grafting contributes to enhanced tolerance to abiotic stresses, including salinity, drought, flooding, and temperature extremes (Estañ *et al*., 2005; Schwarz *et al*., 2010). For instance, grafted tomato plants on salt-tolerant rootstocks exhibit improved growth and fruit yield under saline irrigation conditions (Santa-Cruz *et al*., 2002). Additionally, grafting often results in more vigorous root systems, leading to better water and nutrient uptake, increased biomass accumulation, and higher yields (Djidonou *et al*., 2013). Grafted plants also demonstrate extended crop longevity and prolonged harvesting periods, particularly under protected cultivation, where plant health and productivity are key to profitability (Rouphael *et al*., 2018). The technology further allows for the strategic combination of scion and rootstock genotypes, enabling the integration of high fruit quality with stress tolerance traits. Thus, grafting serves as an effective and eco-friendly approach to address the challenges posed by biotic and abiotic stresses in intensive vegetable production systems.

Grafting has become an increasingly important tool in modern vegetable production due to its ability to enhance plant vigor, improve yield, and reduce susceptibility to a range of biotic and abiotic stresses. One of the most significant benefits is its effectiveness in managing soil-borne diseases such as *Fusarium wilt*, *Verticillium wilt*, bacterial wilt (*Ralstonia solanacearum*), and root-knot nematodes (*Meloidogyne* spp.), particularly in solanaceous and cucurbit crops (Louws *et al*., 2010; Bletsos, 2005; Rivard and Louws, 2008). Grafting onto resistant rootstocks reduces dependency on chemical fumigants and pesticides, promoting sustainable and eco-friendly production systems (Kubota *et al*., 2008; Colla *et al*., 2010). Another advantage lies in improved tolerance to abiotic stresses such as salinity, drought, temperature extremes, and heavy metals (Santa-Cruz *et al*., 2002; Estañ *et al*., 2005; Schwarz *et al*., 2010). Grafted plants typically have more robust root systems, which enhance water and nutrient uptake, leading to better growth, higher yields, and improved fruit quality under both open-field and protected cultivation (Djidonou *et al*., 2013; Lee *et al*., 2010; Rouphael *et al*., 2018).

Furthermore, grafting helps extend crop lifespan and harvest duration, particularly in long-season greenhouse production (Schwarz *et al*., 2010; Gisbert *et al*., 2011). Grafting also facilitates the combination of desirable traits, such as the disease resistance and stress tolerance of the rootstock with the superior fruit quality of the scion (King *et al*., 2010; Goldschmidt, 2014). In cucurbits, for example, grafting has been shown to improve yield, fruit firmness, shelf life, and post-harvest quality. Additionally, in organic and high-value production systems, grafting is a viable tool for chemical-free crop management, enhancing both economic returns and environmental safety (Rivard *et al*., 2010). Thus, vegetable grafting represents a powerful strategy to increase production efficiency, reduce crop losses, and support sustainable intensification of horticulture.

Table : Examples of grafted vegetables and rootstock functions

Crop	Common Scion Variety	Rootstock Species	Purpose of Grafting	Reference
Tomato	Pusa Rohini	*Solanum torvum*	Bacterial wilt resistance	King *et al*., 2010
Eggplant	BR-112	*Solanum integrifolium*	Nematode resistance	Lee *et al*., 2010
Watermelon	Arka Manik	*Lagenaria siceraria*	Fusarium wilt resistance, vigor	Davis *et al*., 2008
Cucumber	Kian	*Cucurbita moschata* × *C. maxima*	Salt and temperature stress tolerance	Colla *et al*., 2010
Bitter gourd	Pusa Do Mausmi	*Momordica cochinchinensis*	Vigor and disease resistance	Sen *et al*., 2018

Limitations and future aspects of vegetable grafting

Despite its numerous advantages, vegetable grafting also faces several limitations that can hinder its widespread adoption, particularly in resource-limited farming systems. One major constraint is the high cost of grafted seedlings, which results from the labor-intensive nature of grafting and the need for controlled healing environments. Additionally, skilled labor and technical expertise are required to ensure successful graft unions, especially for delicate crops like tomato and watermelon. Another challenge is rootstock-scion incompatibility, which can lead to poor graft take, reduced vigor, or physiological disorders such as delayed flowering or reduced fruit quality. Moreover, there is a limited availability of region-specific and stress-tolerant rootstocks, particularly for abiotic stress conditions like salinity and drought. In some cases, grafting may also lead to altered plant architecture or increased susceptibility to foliar pests and diseases due to changes in plant physiology.

Looking ahead, the future of vegetable grafting lies in the development of robust, multi-resistant, and climate-resilient rootstocks through conventional breeding and biotechnological interventions. Research on molecular and hormonal signaling pathways governing graft compatibility and stress responses will enhance precision in rootstock-scion selection. Automation of grafting techniques, such as robotic grafting and improved healing chambers, will reduce labor dependency and production costs. Furthermore, integration of grafting with precision agriculture tools and organic farming systems offers great potential for sustainable vegetable production. Expansion of grafting into underutilized vegetable crops and promotion through training, subsidies, and public-private partnerships will be essential to bridge the gap between research advancements and field-level adoption, especially in developing countries.

Conclusion

Vegetable grafting represents a sustainable horticultural advancement, combining traditional techniques with modern innovation. It offers a solution to key agricultural challenges, especially in the context of climate change, reduced chemical inputs, and food security. With continued research and infrastructural support, grafting will play a pivotal role in next-generation vegetable production systems.

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