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Grafting in Vegetable Crops for Combating Biotic and Abiotic Stresses and Enhancing Productivity: A Critical Review

Arpita Nag [a++], Shibashis Das [b++], Tanmoy Mondal [a++*], Soustav Datta [c], Anasuya Sil [d], Samarpita Roy [e] and Amrita Nag [f#]

[a] *Department of Horticulture, MITS Institute of Professional Studies, Rayagada, Odisha, India.*
[b] *Dhamma Dipa International Buddhist University, Sabroom, Tripura-799145, India.*
[c] *Rathindra Krishi Vigyan Kendra, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, Birbhum 731 236, West Bengal, India.*
[d] *Department of Plantation, Spices, Medicinal and Aromatic Crops, Bidhan Chandra Krishi Vishwavidyalaya, Mohanpur (741252), Nadia, West Bengal, India.*
[e] *Department of Fruit Science, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia 741 252, West Bengal, India.*
[f] *United Nations Development Programme, New Delhi-110003, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Vegetable production is increasingly constrained by soil-borne pathogens, nematodes, salinity, drought, temperature extremes, waterlogging and heavy-metal contamination, all of which threaten yield stability and produce quality. Grafting, the union of a commercial scion with a stress-tolerant or disease-resistant rootstock,

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[++] *Assistant Professor;* [#] *Project Officer;*
**Corresponding author: E-mail: tanmoymondalbckv@gmail.com;*

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offers a practical approach for strengthening vegetable crop performance without altering the market-preferred shoot genotype. This review critically synthesises the physiological, molecular and agronomic evidence on grafting in major solanaceous and cucurbitaceous vegetables. It examines graft union formation as a coordinated process involving wound signalling, callus proliferation, vascular reconnection and long-distance rootstock–scion communication. The review further evaluates how rootstocks influence ion transport, water relations, hormonal balance, antioxidant responses, nutrient acquisition and rhizosphere microbial assembly under biotic and abiotic stresses. Evidence is assessed for the use of grafting against Fusarium wilts, bacterial wilt, root-knot nematodes, salinity, drought, heat, chilling, waterlogging and cadmium stress, alongside its effects on nutrient-use efficiency, yield stability and fruit quality. The synthesis indicates that grafting is most reliable where clearly defined stress pressure exists, particularly from soil-borne diseases or adverse root-zone conditions. However, responses remain strongly dependent on crop species, production environment and rootstock–scion compatibility. The review therefore emphasises targeted rootstock selection, standardised compatibility screening and multi-stress field validation as priorities for improving the predictability of grafting in sustainable vegetable production.

Keywords: Vegetable grafting; rootstock–scion compatibility; abiotic stress tolerance; biotic stress resistance; soil-borne pathogens; salinity tolerance; drought tolerance; nutrient-use efficiency; yield stability; fruit quality; sustainable horticulture.

1. Introduction

1.1 Global Importance of Vegetable Production and Emerging Stress Challenges

Vegetable crops occupy a central place in global agri-food systems. They supply fibre, vitamins, minerals and phytochemicals that are indispensable to human nutrition, and they generate disproportionately high economic returns per unit area compared with staple cereals. Global vegetable output reached approximately 1.17 billion tonnes in 2022, a 71% increase since 2000, with tomato alone contributing roughly 186 million tonnes — making it the single most produced vegetable worldwide (Food and Agriculture Organization of the United Nations, 2024). This expansion has come mainly from intensification rather than from a proportional increase in cultivated area: greater cropping frequency, protected cultivation and high-density planting have all contributed. However, this intensification has magnified the agronomic risks associated with growing the same crop in the same soil across successive seasons. Continuous cultivation of solanaceous and cucurbitaceous vegetables has allowed soil-borne fungal and bacterial pathogens and plant-parasitic nematodes to build up, while the expansion of vegetable production into marginal, saline, drought-prone or metal-contaminated land has increased exposure to abiotic stress. Climatic variability adds yet another layer of pressure, exposing crops to heat, chilling, flooding and water deficit with a frequency that erodes both yield stability and fruit quality, even where biotic threats are otherwise well controlled. Recent reviews also indicate that grafting is increasingly being considered as a practical complement to breeding because rootstock-mediated responses may help vegetables withstand salinity, drought, flooding, temperature stress and selected soil-borne constraints without changing the marketable scion genotype (Faisal et al., 2024; Singathiya et al., 2025).

1.2 Historical Development and Rationale of Vegetable Grafting

Grafting has been practised in fruit trees for millennia, but its deliberate use in herbaceous vegetable crops is a much more recent development. It began in early twentieth-century Japan, where watermelon (*Citrullus lanatus*) scions were grafted onto pumpkin or gourd rootstocks specifically to manage Fusarium wilt in fields under continuous cropping (Lee et al., 2010). Commercial-scale adoption followed in Japan and Korea from the late 1950s and 1960s, after which the practice spread across Asia and into Mediterranean Europe, eventually moving from cucurbits into solanaceous crops such as tomato (*Solanum lycopersicum*), aubergine (*Solanum melongena*) and pepper (*Capsicum annuum*). In several East Asian production systems, more than 90% of watermelon transplants and around 75% of cucumber (*Cucumis sativus*) transplants are now grafted; the proportion of grafted tomato, aubergine and pepper is smaller but continues to climb as growers look for alternatives to soil fumigants that are now banned or heavily restricted (Lee et al., 2010). The underlying concept is straightforward, although the biology is complex: a vigorous, stress-adapted or disease-resistant root system — often drawn from a wild relative or an interspecific hybrid — can be joined to a horticulturally superior, high-yielding shoot system, so that root-zone resilience is decoupled from the traits that determine how marketable the harvested fruit will be. Once the graft union has healed and vascular continuity is restored, the rootstock continues to exert continuous, long-distance influence over the scion's water and nutrient acquisition, hormonal signalling and ion balance, and it is these ongoing effects that underpin grafting's documented capacity to mitigate both biotic and abiotic stress (Razi et al., 2024). Evidence from cucumber grafting further illustrates that the magnitude of benefit depends on the specific rootstock–scion combination: interspecific cucurbit hybrids reduced Fusarium wilt severity and improved nutrient status in one study, whereas recent greenhouse work showed that commercial and local pumpkin rootstocks produced different yield and postharvest-quality responses (Reyad et al., 2021; Bikdeloo et al., 2026). Despite this expanding literature, a clear gap remains in integrating the evidence across biotic stress, abiotic stress, productivity and fruit-quality outcomes without treating grafting as a universally beneficial intervention. A critical synthesis is therefore needed to separate broadly reproducible rootstock effects from responses that depend on crop family, stress context, rootstock–scion compatibility and production environment.

1.3 Scope and Objectives

This review critically appraises the physiological, molecular and agronomic literature on vegetable grafting published over roughly the past one-and-a-half decades, focusing on the Solanaceae (tomato, aubergine, pepper) and Cucurbitaceae (watermelon, melon, cucumber), the two families in which grafting is most widely practised and most thoroughly studied. It has four specific aims: first, to bring together current understanding of the physiological and molecular events behind graft union formation and rootstock–scion communication; second, to weigh the evidence for grafting as a strategy against major biotic constraints, including soil-borne fungal and bacterial pathogens and root-knot nematodes; third, to critically assess grafting-mediated tolerance to the principal abiotic stresses affecting vegetable production — salinity, drought, temperature extremes, waterlogging and heavy-metal toxicity; and fourth, to examine what grafting means for nutrient- and water-use efficiency, yield stability and fruit quality, set against its economic, environmental and technological context. The review also flags methodological inconsistencies, knowledge gaps and directions for future work, with the broader aim of giving horticultural scientists, breeders and policymakers a balanced, evidence-weighted resource on sustainable vegetable production under mounting biotic and abiotic pressure.

2. Methods for Literature Selection

This article uses a narrative rather than a systematic review format. This approach is justified because the subject matter spans plant physiology, molecular biology, plant pathology, agronomy and agricultural engineering, and is therefore not well suited to the narrowly defined, single-outcome questions for which systematic reviews and meta-analyses are designed. Narrative reviews remain a legitimate and useful format when the goal is to synthesise and critically contextualise a broad, multidisciplinary evidence base, provided the search and selection process is sufficiently transparent and applies explicit criteria to limit bias (Ferrari, 2015). The search underpinning this review followed such a protocol, even if it does not constitute a full systematic review.

Electronic searches were conducted across Web of Science, Scopus, Google Scholar and PubMed, and supplemented by six field-specific bibliographic resources of particular relevance to horticultural and plant-protection science: CAB Abstracts, AGRICOLA, AGRIS, BIOSIS Previews, FSTA (Food Science and Technology Abstracts), and Dimensions. Search strings combined the core terms "vegetable grafting", "rootstock" and "scion" with stress- and outcome-specific terms — "abiotic stress", "biotic stress", "salinity", "drought", "heat stress", "chilling tolerance", "waterlogging", "heavy metal", "Fusarium wilt", "bacterial wilt", "Ralstonia solanacearum", "root-knot nematode", "nutrient use efficiency", "yield" and "fruit quality" — combined with the Boolean operators and truncation conventions appropriate to each database. Coverage ran from January 2010, chosen because that year coincides with several field-defining reviews that first systematised understanding of vegetable grafting's diffusion, mechanisms and applications, through to early February 2026. Eligible records were peer-reviewed original research articles, reviews and meta-analyses published in indexed journals and written in English; book chapters, conference proceedings, theses, patents, preprints and trade or other grey literature were excluded. Studies on grafting in woody fruit trees or ornamentals were excluded unless they offered mechanistic insight of direct comparative value to herbaceous vegetable grafting, in which case they were retained as supporting, comparative evidence.

Reference lists were imported into a citation manager to remove duplicates arising from overlapping database coverage, and titles and abstracts were screened for relevance to vegetable grafting and to biotic or abiotic stress responses, yield, quality, or underlying mechanism, before full-text assessment of the remaining records. Where several studies addressed essentially the same question, preference went to more recent work, to studies with larger sample sizes or multi-site validation, and to papers and meta-analyses widely recognised within the field as influential syntheses; a handful of older but still frequently cited foundational studies were kept regardless of date because of their continuing conceptual importance. No language restriction beyond the requirement for English full text was applied at the database level, although in practice most indexed literature on this topic is published in English.

3. Principles and Techniques of Vegetable Grafting

3.1 Graft Union Formation: Physiological and Molecular Basis

Successful grafting depends on an orderly cellular healing cascade that begins within hours of the rootstock and scion surfaces being brought together. Cell death at the cut interface first triggers a wound response, during which pectinaceous compounds released from the damaged cells help the two tissues adhere; this is followed by dedifferentiation and proliferation of parenchymatous cells to form a callus bridge across the wound, the formation of symplastic connections through plasmodesmata, and finally the differentiation of new vascular tissue, with phloem reconnection generally preceding xylem reconnection (Wang et al., 2024). Detailed kinematic work in *Arabidopsis thaliana* has shown that these events are temporally distinct — tissue attachment, phloem reunion, renewed root growth and, last of all, xylem reunion follow one another in sequence — and that auxin signalling originating in the scion is essential for driving vascular reconnection across the graft interface, while cytokinin responses additionally shape the timing of phloem connection (Melnyk et al., 2015). Auxin–cytokinin crosstalk, mediated partly through transcription factors such as WUSCHEL-related homeobox proteins and NAC-domain regulators, coordinates cambial activation and the orientation of newly formed vascular strands so that they align correctly with the existing tissue on either side (Wang et al., 2024). Comparable healing dynamics, and a similar reliance on auxin–cytokinin signalling, have also been described in woody fruit-tree grafting systems, which suggests that the core molecular logic of graft union formation is conserved fairly broadly across herbaceous and perennial taxa rather than being a peculiarity of any one crop group (Habibi et al., 2022). Graft incompatibility, by contrast, is frequently linked to an excess of phenolic compounds at the union, which interferes with auxin transport and so impairs vascular differentiation and lignification — one reason why taxonomic proximity between rootstock and scion remains an important, though not absolute, prerequisite for stable graft-take (Goldschmidt, 2014). The healed union, once established, is more than a structural conduit: it also acts as a selective gateway for the exchange of macromolecules such as small RNAs, messenger RNAs and proteins, and in some systems even allows the horizontal transfer of cellular organelles between genetically distinct partners — a finding that has reframed grafting as a tool not only for horticultural improvement but for studying long-distance signalling and inter-genomic communication in plants more generally (Kragler & Bock, 2025). Once vascular continuity is restored, the rootstock's root architecture, ion-transporter expression and hormonal output begin to exert sustained, systemic influence over scion physiology, and it is this influence that underlies the stress-tolerance phenotypes discussed in the sections that follow (Nawaz et al., 2016; Nie & Wen, 2023).

3.2 Grafting methods and rootstock–scion selection

Commercial vegetable seedling production relies on several grafting methods, which differ chiefly in the developmental stage at which grafting is carried out and in the geometry of the cut itself. Splice (or tongue) grafting and tube grafting are most common in cucurbits and are typically performed at the cotyledon or first true-leaf stage, when rootstock and scion hypocotyl diameters are closely matched. Hole-insertion grafting — in which the rootstock apex is removed and a wedge-shaped scion inserted into a drilled cavity — is particularly favoured for watermelon, since it limits regrowth of adventitious shoots from the rootstock, while approach grafting, cleft grafting and pin grafting all find use across both cucurbit and solanaceous systems depending on stem morphology and the throughput a given operation needs (Yan et al., 2022). Choosing the right rootstock genotype is arguably the single most consequential decision in the whole process: it determines not only disease and pest resistance but also the size and direction of subsequent effects on water relations, nutrient acquisition, hormonal status and, ultimately, fruit yield and quality. Rootstocks are commonly drawn from interspecific hybrids (for example, *Cucurbita maxima* × *Cucurbita moschata* for cucurbits, or *Solanum lycopersicum* ×

Solanum habrochaites for tomato), from related wild species (*Solanum torvum* for aubergine and tomato, *Cucurbita ficifolia* for cucumber), or from elite intraspecific lines selected for vigorous, well-developed root systems (Lee et al., 2010; Nawaz et al., 2016).

3.3 Automation and Robotic Grafting Systems

Manual grafting is skilled, slow and labour-intensive, and is consequently a major cost driver in grafted-seedling production — which is why considerable investment, particularly in China, Japan and Korea, has gone into semi-automatic and fully automatic grafting robots. These machines mechanise the sequence of seedling picking, cutting, joining, clipping and row placement. Throughput has risen from a few hundred plants per hour in the earliest single-arm designs to well over a thousand plants per hour in more recent bidirectional and assembly-line configurations, and machine-vision systems are increasingly built in for automated seedling grading, diameter matching between rootstock and scion, and quality assessment after grafting (Yan et al., 2022). Even so, current grafting robots remain limited in their versatility across crop species and graft geometries, and are not yet well integrated with downstream seedling biotechnology such as humidity-controlled healing chambers — suggesting that further convergence of mechanical engineering, machine vision and plant physiology will be needed before fully automated grafting can match the reliability of skilled manual practice (Razi et al., 2024; Yan et al., 2022).

Table 1. Representative rootstock–scion combinations and principal reported benefits in major vegetable crop groups

Crop group	Scion	Representative rootstock genus/species	Principal reported benefit
Solanaceae – tomato	*Solanum lycopersicum*	*S. lycopersicum* × *S. habrochaites* interspecific hybrids; *S. pennellii*; *S. peruvianum*	Salinity, drought and heat tolerance; vigorous root system; improved water-use efficiency
Solanaceae – aubergine	*Solanum melongena*	*Solanum torvum*; resistant *S. melongena* accessions	Resistance to *Ralstonia solanacearum* (bacterial wilt); reduced cadmium translocation
Solanaceae – pepper	*Capsicum annuum*	Interspecific *Capsicum* hybrid rootstocks	Improved water-stress tolerance via photosynthetic and antioxidant maintenance
Cucurbitaceae – watermelon	*Citrullus lanatus*	*Lagenaria siceraria*; *Cucurbita moschata*; *C. maxima* × *C. moschata*	Resistance to *Fusarium oxysporum* f. sp. *niveum*; enhanced vigour
Cucurbitaceae – cucumber	*Cucumis sativus*	*Cucurbita moschata*; *Cucurbita ficifolia*	Chilling and cold tolerance; improved nitrogen-use efficiency
Cucurbitaceae – melon	*Cucumis melo*	*Cucurbita* spp.; resistant melon rootstocks	Resistance to *Fusarium oxysporum* f. sp. *melonis*; continuous-cropping tolerance

Sources: Lee et al. (2010); Nawaz et al. (2016); Liang et al. (2021); Liu et al. (2021); Padilla et al. (2021); Ling et al. (2013); Sivasankarreddy et al. (2024).

Table 1 summarises the principal rootstock genera used across the two dominant vegetable families and the stress-tolerance or productivity benefits most consistently associated with each. It shows that, although interspecific hybridisation and the use of wild relatives are common strategies in both families, the specific biotic and abiotic targets differ quite markedly between the two: bacterial wilt resistance and broad abiotic stress tolerance dominate rootstock breeding objectives in Solanaceae, whereas Fusarium wilt resistance and cold tolerance have historically driven rootstock development in Cucurbitaceae.

4. Grafting for Management of Biotic Stresses

4.1 Soil-borne Fungal Pathogens

Fusarium wilt, caused by host-specific formae speciales of *Fusarium oxysporum*, is the classical target of vegetable grafting and the historical basis for the technique. In watermelon, grafting onto bottle gourd

(*Lagenaria siceraria*) or interspecific *Cucurbita* rootstocks confers near-complete protection against *Fusarium oxysporum* f. sp. *niveum*: proteomic analysis of bottle-gourd-grafted seedlings challenged with the pathogen recorded a disease incidence of just 3.4%, against 89% in self-grafted controls, accompanied by induction of pathogenesis-related proteins and a reorganisation of carbohydrate and energy metabolism that together underlie the heightened resistance of the grafted root system (Zhang et al., 2021). Resistance is not simply a passive consequence of rootstock genotype. Root exudates collected from bottle-gourd-grafted watermelon roots measurably inhibited *Fusarium oxysporum* f. sp. *niveum* growth in vitro, which implicates exudate chemistry as a contributing mechanism behind graft-induced disease suppression rather than resistance being purely structural (Ling et al., 2013). Similar principles apply in melon, where grafting onto resistant *Cucurbita* or interspecific rootstocks substantially reduces *Fusarium oxysporum* f. sp. *melonis* incidence even under long-term continuous cropping, a system in which inoculum pressure accumulates progressively across successive seasons.

4.2 Bacterial Wilt

Bacterial wilt, caused by the *Ralstonia solanacearum* species complex, ranks among the most economically damaging soil-borne diseases of solanaceous vegetables in the tropics and subtropics, and grafting onto resistant rootstocks is one of the few management options with consistent field-level efficacy. *Solanum torvum* and resistant cultivated-aubergine accessions are the most widely deployed rootstock sources. In field trials, aubergine scions grafted onto the resistant rootstock 'CARI-1' achieved yield increases of 69.23% and 33.46% over two non-grafted scion genotypes grown in bacterial-wilt-affected acidic soils, alongside a marked reduction in disease severity (Barik et al., 2023). A comprehensive review of bacterial wilt in aubergine concluded that grafting onto *S. torvum* and related resistant genotypes remains among the most dependable disease-management strategies currently available, while also cautioning that durable, longer-term resistance will depend on combining marker-assisted breeding with a deeper mechanistic understanding of the pathogen's diverse strains and effector repertoire (Sivasankarreddy et al., 2024). At the molecular level, transcriptomic and metabolomic profiling of aubergine challenged with *R. solanacearum* has pointed to jasmonic acid signalling as a key component of host defence, which gives some mechanistic basis for selecting rootstocks on hormonal responsiveness rather than on resistance phenotype alone (Xiao et al., 2023). An editorial synthesis of rootstock development for pest and disease resistance across both Solanaceae and Cucurbitaceae makes the broader point that bacterial wilt, together with Fusarium wilt and root-knot nematodes, continues to dominate commercial rootstock breeding objectives worldwide (Thies & Panthee, 2023).

4.3 Plant-parasitic Nematodes

Root-knot nematodes of the genus *Meloidogyne*, particularly *Meloidogyne incognita*, cause substantial yield losses in solanaceous and cucurbitaceous vegetables, and have historically been controlled through soil fumigation — an approach now increasingly restricted on environmental and regulatory grounds. Grafting susceptible, high-yielding scions onto nematode-resistant rootstocks, commonly carrying the *Mi* resistance gene complex in tomato or sourced from resistant aubergine, *Solanum sisymbriifolium* or wild cucurbit relatives, has proven a workable and environmentally safer alternative, cutting nematode population build-up, root galling and the associated yield decline under both protected and open-field conditions (Thies, 2021). It is noteworthy that rootstocks bred for resistance to one soil-borne constraint often confer resistance to several constraints simultaneously: rootstocks selected primarily for bacterial wilt resistance, for example, have also shown effective suppression of *M. incognita* populations, which speaks to the multifunctional value of well-characterised resistant germplasm rather than a need for narrowly targeted rootstocks for every threat (Thies, 2021).

4.4 Rhizosphere Microbiome Modulation and Indirect Biocontrol

There is growing evidence that grafting affects plant health not only through the rootstock's own genetic resistance but also through its capacity to reshape the root-associated microbial community. Comparative 16S rRNA profiling of grafted tomato systems found that rootstock genotype significantly altered bacterial diversity and community composition in both the endosphere and rhizosphere relative to non-grafted and self-grafted controls, with the vigorous interspecific rootstock 'Maxifort' supporting markedly higher bacterial diversity than a standard hybrid rootstock. This raises the possibility that rootstock selection could be used to recruit beneficial, disease-suppressive microbial consortia (Poudel et al., 2019). This rhizosphere-mediated side of graft-induced resistance is still comparatively underexplored next to direct genetic resistance, but it appears to be a promising frontier for designing synthetic or rootstock-selected microbiomes that complement, rather than substitute for, intrinsic disease resistance.

Table 2 indicates that grafting's most dramatic and reproducible benefits are against soil-borne biotic constraints, especially Fusarium wilts, where near-complete disease suppression is the norm rather than the exception. Efficacy against bacterial wilt, while still substantial, tends to be more variable from one pathogen strain or rootstock genotype to the next — which is expected, given how much more genetically and pathotypically diverse the *Ralstonia solanacearum* species complex is compared with the largely clonal, formae-speciales-structured *Fusarium oxysporum*.

Table 2. Reported efficacy of grafting against major biotic stresses in vegetable crops

Biotic stress	Crop	Rootstock strategy	Reported outcome
Fusarium oxysporum f. sp. *niveum*	Watermelon	Bottle gourd (*Lagenaria siceraria*)	Disease incidence reduced from 89% (self-grafted) to 3.4% (grafted)
Ralstonia solanacearum (bacterial wilt)	Aubergine	Resistant *S. melongena* ('CARI-1')	Yield increase of 33–69% over non-grafted scions; reduced wilt severity
Fusarium oxysporum f. sp. *melonis*	Melon	*Cucurbita* spp. and resistant melon lines	Substantial reduction in wilt incidence under continuous cropping
Root-knot nematode (*Meloidogyne incognita*)	Tomato, aubergine	*Mi*-gene rootstocks; resistant aubergine; *S. sisymbriifolium*	Reduced root galling and nematode population build-up
Rhizosphere pathogen pressure (indirect)	Tomato	Vigorous interspecific hybrid ('Maxifort')	Increased rhizosphere/endosphere bacterial diversity

Sources: Zhang et al. (2021); Ling et al. (2013); Barik et al. (2023); Sivasankarreddy et al. (2024); Xiao et al. (2023); Thies (2021); Thies & Panthee (2023); Poudel et al. (2019).

5. Grafting for Mitigation of Abiotic Stresses

5.1 Salinity Stress

Salinity in soil and irrigation water constrains vegetable production across roughly a fifth of the world's irrigated land, and grafting has been studied extensively as a way of conferring salt tolerance without the long timelines that conventional breeding requires. In one well-established demonstration, grafting the commercial tomato cultivar 'Jaguar' onto rootstocks differing in their capacity to exclude saline ions raised fruit yield under 50 mM NaCl by around 80% relative to self-grafted controls — an effect attributed mainly to the rootstock limiting sodium and chloride transport from root to shoot, rather than to any direct effect of the grafting procedure itself on yield potential (Estañ et al., 2005). More recent transcriptomic work on grafted tomato seedlings exposed to 175 mM NaCl confirmed that salt-tolerant rootstocks reprogram scion leaf metabolism and gene expression across several pathways, including those governing sodium transport, amino-acid accumulation and hormone signal transduction, so that the scion becomes more salt-tolerant than it would have been on its own roots (Wu et al., 2023). Comparable rootstock-mediated ion-partitioning effects have been documented in aubergine-grafted tomato, where resistant eggplant rootstocks moderated sodium accumulation in tomato scions and substantially improved fruit yield under irrigation with moderately to highly saline water (Sanwal et al., 2022), and in tomato grafted onto interspecific rootstocks that preferentially shunt sodium into older, senescing leaves while sparing the younger, photosynthetically active canopy — maintaining favourable potassium-to-sodium and calcium-to-sodium ratios in physiologically important tissues (Di Gioia et al., 2013).

5.2 Drought and Water-deficit Stress

Water scarcity is among the most pervasive constraints on vegetable productivity, and grafting onto deep-rooted or hydraulically efficient rootstocks has repeatedly been shown to improve drought tolerance and water-use efficiency relative to non-grafted plants. High-throughput phenomic screening of tomato rootstocks derived from crosses with the wild relative *Solanum pennellii* identified the interspecific line 'RF4A' as conferring notably conservative water use: grafted plants maintained higher plant water status through tighter stomatal control and sustained greater biomass accumulation under progressive soil drying than plants grafted onto standard cultivated rootstocks (Khapte et al., 2022). A dedicated review of vegetable grafting as a drought-mitigation strategy concluded that improved water-use efficiency in grafted plants typically comes from some combination of better root architecture, finer stomatal control and hormonally mediated adjustments to shoot biomass allocation — although the same review cautioned that drought-avoidance responses driven by constitutively reduced leaf area can, in some rootstock–scion combinations, trade off against yield potential when water is not limiting (Kumar et al., 2017). At the molecular level, proteomic and gene-regulatory-network analysis of drought-stressed grafted tomato has shown that rootstock-conferred drought tolerance involves coordinated shifts in proteins governing osmotic adjustment, antioxidant defence and stress signalling, which supports the view that drought tolerance transmitted through grafting reflects genuine systemic reprogramming of scion physiology rather than being a passive consequence of altered root morphology (Mahapatra et al., 2025). In pepper, short-term water-stress experiments comparing tolerant and sensitive rootstocks found that tolerance is closely tied to rootstock-specific adjustments in hormonal balance, including shifts in abscisic acid and cytokinin status, that appear to precede — and arguably orchestrate — the downstream physiological responses seen in the scion (Padilla et al., 2023).

5.3 Temperature Extremes: Heat and Chilling Stress

Heat stress disrupts pollen viability, fruit set and photosynthetic capacity in vegetable crops, and grafting onto thermotolerant rootstocks — including wild tomato relatives such as *Solanum pennellii* and *Solanum peruvianum* — has been explored as a way of buffering these effects. A comparative evaluation of tomato grafted onto the commercial interspecific rootstock 'Maxifort' versus the two wild relatives under controlled heat-stress conditions found that the wild-relative rootstocks actually produced lower shoot biomass than Maxifort, despite broadly comparable photosynthetic rates and chlorophyll fluorescence; all three grafted treatments, however, showed distinct, rootstock-specific shifts in antioxidant enzyme activity and abscisic acid accumulation, which suggests that the thermotolerance conferred by grafting depends on rootstock identity rather than simply mirroring how heat-tolerant the donor species is when grown intact (Lee et al., 2023). Subsequent reciprocal-grafting work, testing whether prior knowledge of genotype-level heat tolerance could predict the performance of the corresponding rootstock–scion combinations, confirmed that grafting can transfer measurable heat-stress tolerance between Mediterranean tomato landraces — while also showing that transcriptomic and phenotypic responses to heat stress do not always track the heat-tolerance ranking of the donor genotype when grown whole, which underlines just how hard it is to predict graft-transmitted thermotolerance from scion or rootstock phenotype alone (Biermann et al., 2025). At low temperatures, chilling stress is a major constraint on cucurbit production in temperate and subtropical greenhouse systems, where cucumber is conventionally grafted onto pumpkin (*Cucurbita moschata*) or figleaf gourd (*Cucurbita ficifolia*) rootstocks to push the growing season into cooler months. Detailed transcriptomic and physiological work on pumpkin rootstock varieties under chilling stress identified differential regulation of α-linolenic acid biosynthesis and downstream unsaturated fatty-acid metabolism as a key biochemical correlate of chilling tolerance — more tolerant rootstock genotypes maintained greater membrane lipid unsaturation and lower relative electrolyte leakage, properties that are then transmitted to the grafted cucumber scion and help preserve membrane integrity and photosynthetic function at low temperature (Liu et al., 2021).

5.4 Waterlogging Stress

Excess soil moisture causes root hypoxia and anoxia, conditions that are particularly damaging to solanaceous vegetables given their comparatively shallow, oxygen-demanding root systems. Grafting tomato onto aubergine rootstocks, which have an inherently greater tolerance of low-oxygen rhizosphere conditions, has been shown in field and controlled-environment trials to extend plant survival under flooding from around four days to as long as six days, with smaller reductions in chlorophyll fluorescence yield and photosynthetic rate than seen in non-grafted controls (Bahadur et al., 2024). The pattern suggests that rootstock-conferred flooding tolerance works principally by keeping the root system functioning and photosynthesis running, rather than by changing the intrinsic flood sensitivity of the aerial scion tissue itself.

5.5 Heavy-Metal and Trace-Element Stress

Agricultural soils contaminated with cadmium and other heavy metals pose a dual threat — to crop productivity and to food safety — and grafting has attracted interest as a potential agronomic tool for limiting metal translocation into edible plant parts. A recent synthesis of the mechanisms governing cadmium accumulation in grafted vegetables concluded that rootstock genotype substantially shapes cadmium uptake and root-to-shoot translocation, acting through changes in root morphology, the expression of metal-transporter genes, and the composition of the rhizosphere microbial community. Several rootstock–scion combinations achieved marked reductions in shoot and fruit cadmium concentration relative to non-grafted controls, although the degree of protection is highly genotype-dependent and not yet predictable simply from rootstock phylogeny (Zhang et al., 2025). This variability matters in practice: heavy-metal mitigation cannot currently be treated as a generic benefit inherent to grafting, but instead calls for deliberate screening of candidate rootstocks for metal-exclusion or metal-retention traits specific to the contaminant and crop in question.

Table 3. Physiological and biochemical mechanisms underlying grafting-mediated abiotic stress tolerance in vegetable crops

Abiotic stress	Representative crop/rootstock system	Principal underlying mechanism
Salinity	Tomato grafted onto ion-excluding rootstocks	Restricted root-to-shoot Na^+/Cl^- transport; preferential Na^+ sequestration in older leaves
Drought	Tomato grafted onto *S. pennellii*-derived rootstocks	Conservative water use via stomatal regulation; proteomic reprogramming of osmotic and antioxidant pathways
Heat	Tomato grafted onto Maxifort, *S. pennellii*, *S. peruvianum*	Rootstock-specific modulation of antioxidant enzymes and abscisic acid accumulation
Chilling/cold	Cucumber grafted onto pumpkin rootstocks	Enhanced α-linolenic acid biosynthesis and membrane lipid unsaturation; reduced electrolyte leakage
Waterlogging	Tomato grafted onto aubergine rootstocks	Sustained root function and photosynthesis under hypoxic conditions
Heavy metals (cadmium)	Tomato/aubergine grafted onto resistant rootstocks	Altered root morphology, metal-transporter expression and rhizosphere microbiome

Sources: Estañ et al. (2005); Wu et al. (2023); Sanwal et al. (2022); Di Gioia et al. (2013); Khapte et al. (2022); Kumar et al. (2017); Mahapatra et al. (2025); Padilla et al. (2023); Lee et al. (2023); Biermann et al. (2025); Liu et al. (2021); Zhang et al. (2025).

A notable pattern emerges from Table 3: although the specific molecular pathway differs from one stressor to the next, grafting-mediated tolerance consistently depends on three broad physiological levers — control of long-distance ion or water transport, modulation of hormonal and antioxidant signalling, and, for heavy metals and certain disease constraints, changes in root-zone biochemistry and microbial activity. That convergence suggests rootstock breeding programmes may be more effective if they target these shared mechanisms collectively, rather than treating each stress as an entirely separate problem to be solved independently.

6. Effects of Grafting on Nutrient and Water Use Efficiency

Beyond conferring tolerance to specific stresses, grafting often improves how efficiently vegetable crops take up and use water and mineral nutrients, an effect mainly attributable to the more extensive, architecturally distinct root systems that vigorous rootstocks bring with them. Rootstocks generally have greater absorptive surface area and denser fine-root systems than the scion cultivars they support, which translates into better capture of both mobile and immobile nutrients when nutrients are in short supply (Nawaz et al., 2016). In cucumber, grafting commercial scions onto pumpkin rootstocks selected for nitrogen-use efficiency substantially eased the growth-limiting effects of low nitrate supply: grafted plants had larger root systems, greater nitrate accumulation and higher activity of nitrogen-metabolising enzymes than self-grafted controls under the same nutrient regime, which shows the benefit comes specifically from rootstock genotype rather than from the act of grafting itself (Liang et al., 2021). At the molecular level, ion transport across the graft union is governed by a fairly intricate signalling network in which sugars, phytohormones and microRNAs act as long-distance messengers, influencing the expression and activity of root ion transporters — a plausible explanation for why different rootstock genotypes, even within the same species, can give a genetically identical scion markedly different nutrient-uptake phenotypes (Nawaz et al., 2016). These nutrient-efficiency benefits overlap closely with the water-relations effects discussed in Section 5.2, since better root architecture simultaneously underpins enhanced nutrient capture and more conservative water use; this hints that breeding for vigorous, well-branched rootstock root systems could be a relatively efficient way to improve resource-use efficiency across several input categories at once. That said, the size of nutrient-use-efficiency gains reported in the literature varies considerably with rootstock genotype, nutrient regime and growing system, and an excessively vigorous rootstock can sometimes promote disproportionate vegetative growth at the expense of reproductive allocation — an agronomic trade-off growers need to weigh against the efficiency gains seen under nutrient-limited conditions.

7. Effects of Grafting on Yield, Fruit Quality and Nutritional Attributes

The agronomic case for grafting ultimately rests on its net effect on marketable yield and fruit quality, and the evidence suggests these effects are substantial on average but highly uneven across individual rootstock–scion combinations. The most comprehensive synthesis to date — a meta-analysis covering 159 publications, 202 distinct rootstocks, 126 locations and 1,023 experimental treatments of grafted tomato — found that grafting failed to produce a statistically significant yield improvement in roughly 65% of the combinations examined, yet across the full dataset the average yield increase attributable to grafting was about 37%, with the largest gains seen where resistant rootstocks allowed yields to be maintained in pathogen-infested fields that would otherwise have required soil fumigation (Grieneisen et al., 2018). This finding has an important bearing on how the wider grafting literature should be interpreted: positive yield outcomes reported in individual studies, often conducted under controlled or disease-challenged conditions specifically designed to showcase rootstock benefits, should not be assumed to generalise to all production contexts. Growers should expect reliable yield gains from grafting mainly where soil-borne disease pressure, salinity or some other identifiable stress factor is actually present, rather than under otherwise benign growing conditions, where the rootstock's main advantages have less opportunity to be expressed. Yield stability across variable environments is a related but distinct benefit: multi-environment trials of grafted tomato across diverse Texan growing conditions showed that selected rootstock–scion combinations not only raised mean yield but also reduced year-to-year and site-to-site variability in yield components — a property of real value to growers facing increasingly unpredictable seasons (Djidonou et al., 2020).

Table 4. Summary of reported effects of grafting on yield and fruit quality in vegetable crops

Outcome category	Reported pattern	Representative evidence
Mean yield effect	Average increase of ~37% across combinations, but no significant effect in ~65% of individual rootstock–scion pairings	Grieneisen et al. (2018)
Yield stability across environments	Reduced year-to-year and site-to-site variability with selected rootstocks	Djidonou et al. (2020)
Fruit weight	Up to ~55% increase in compatible combinations (most clearly in watermelon); reductions indicate incompatibility	Kyriacou et al. (2017)
Sweetness/acidity (cucurbits)	Frequently reduced with certain interspecific *Cucurbita* rootstocks	Kyriacou et al. (2017)
Nutrient/ion content	Variable; influenced by rootstock-mediated ion partitioning and uptake efficiency	Sanwal et al. (2022); Liang et al. (2021)

Sources: Grieneisen et al. (2018); Djidonou et al. (2020); Kyriacou et al. (2017); Sanwal et al. (2022); Liang et al. (2021).

Effects on fruit quality are more variable, and in some respects are not always aligned with the yield benefits of grafting. A detailed review of grafting's implications for vegetable fruit quality concluded that a decrease in fruit weight, where it occurs, typically signals rootstock–scion incompatibility, whereas in fully compatible combinations — most clearly documented in watermelon — fruit weight can increase by up to roughly 55%. The same review noted, however, that a loss of sweetness and acidity is a recurring problem in cucurbits grafted onto certain interspecific *Cucurbita* hybrid rootstocks, pointing to a genuine biological trade-off between disease resistance and eating quality that rootstock breeding has not yet fully resolved (Kyriacou et al., 2017). This implies that fruit-quality outcomes cannot simply be assumed to track yield outcomes; rootstock evaluation programmes therefore need to build in dedicated sensory and compositional assessment alongside agronomic performance metrics, if grafting is to deliver consumer-acceptable produce alongside greater productivity and resilience.

Table 4 provides a useful corrective against treating yield enhancement as an automatic, guaranteed by-product of grafting. More accurately, grafting's real agronomic value lies chiefly in protecting and stabilising yield potential under stress, with outright yield enhancement under stress-free conditions being a far less consistent, and far less predictable, outcome.

8. Comparative Perspectives Across Major Vegetable Crop Groups

The Solanaceae and Cucurbitaceae, the two families in which grafting is most extensively practised, have different rootstock-breeding histories and technical demands, and this comparison warrants explicit consideration. Cucurbit grafting developed first and remains technically more demanding for certain crops, particularly watermelon, where the close hypocotyl-diameter matching and physiological compatibility required between *Citrullus lanatus* scions and *Cucurbita* or *Lagenaria* rootstocks call for considerable operator skill and have, historically, driven much of the push toward robotic grafting (Yan et al., 2022). Cucurbit rootstock objectives have centred mainly on resistance to Fusarium wilts and, more recently, on improving cold tolerance for extended-season greenhouse cucumber production, with preserving fruit quality — particularly sweetness and rind characteristics — remaining a persistent secondary challenge (Kyriacou et al., 2017; Liu et al., 2021). Solanaceous grafting, by contrast, has broadened its objectives to cover not just bacterial wilt and nematode resistance but a wide spread of abiotic stresses, including salinity, drought, heat and heavy-metal toxicity. This reflects both the relatively recent intensification of tomato, aubergine and pepper cultivation in marginal and climatically difficult environments, and the comparative ease with which closely related wild *Solanum* species can be used as rootstock donors of new stress-tolerance traits (Razi et al., 2024; Mahapatra et al., 2025). A further point of contrast concerns compatibility constraints: aubergine and tomato, both within the *Solanum* genus complex, are close enough taxonomically to permit reciprocal and interspecific grafting with comparatively few compatibility failures, whereas cucurbit rootstocks drawn from genera as distinct as *Cucurbita*, *Lagenaria* and *Luffa* sometimes show reduced compatibility or altered fruit quality precisely because of that greater taxonomic distance (Kyriacou et al., 2017). These contrasts suggest that lessons learned in one family should not be transferred uncritically to the other, and that rootstock-breeding strategy needs to be tailored to the compatibility constraints, disease spectrum and market quality expectations specific to each crop group.

9. Economic, Environmental and Practical Considerations

Adopting grafted seedlings carries economic implications that growers need to weigh against the agronomic benefits. Grafted transplants are substantially more expensive to produce than conventionally raised seedlings, reflecting the extra labour, specialised facilities and healing-chamber infrastructure required, and the question for any grower is whether the expected gains in disease avoidance, yield stability or input-use efficiency justify that price premium under their own specific conditions (Thies, 2021). Where soil-borne disease pressure is severe, or where regulatory restrictions on fumigants have removed previously available chemical options, the economic case for grafting is usually strong: the alternative of crop loss or abandoning an infested field carries far greater cost than the price of grafted transplants. In benign growing environments free of significant biotic or abiotic constraint, however, the case is considerably weaker, which fits with the meta-analytic finding that most rootstock–scion combinations fail to deliver a statistically significant yield gain in the absence of specific stress pressure (Grieneisen et al., 2018). Environmentally, grafting offers a sustainable alternative to soil fumigation and broad-spectrum nematicide application, both of which carry well-documented risks to soil microbial communities, non-target organisms and — in the case of methyl bromide and related fumigants — to stratospheric ozone; its capacity to restrict heavy-metal translocation into edible tissue also offers a useful, food-safety-oriented benefit in contaminated production areas (Zhang et al., 2025). Practical barriers to adoption remain, though, including the need for specialised grafting and healing infrastructure, reliable and well-characterised rootstock seed sources, and the technical skill to match rootstock and scion vigour appropriately. The continuing development of grafting robots offers a partial solution to the labour-cost side of these barriers, although current machines are still imperfectly adapted to the full range of species and graft geometries used commercially (Yan et al., 2022).

10. Knowledge Gaps and Future Research Directions

Several substantive knowledge gaps limit the confidence with which findings on vegetable grafting can be generalised, and they deserve priority in future research. First, the great majority of mechanistic studies on abiotic stress tolerance have looked at single stressors in isolation, under controlled environmental conditions, whereas field production routinely exposes grafted plants to combinations of stresses — concurrent drought and heat or salinity layered on top of soil-borne pathogen pressure — whose interactive effects on graft performance are still poorly understood. Second, the molecular basis of graft-transmitted stress tolerance, while increasingly well described for particular rootstock–scion pairings, has not yet been synthesised into predictive frameworks capable of forecasting how an untested combination will perform from rootstock or scion genotype alone, which means extensive and resource-intensive empirical screening is still needed for every new pairing (Lee et al., 2023; Biermann et al., 2025). Third, although grafting's influence on rhizosphere and endosphere microbial communities is evident, it has only been characterised in a relatively small number of systems, and deliberately engineering rootstock-associated microbiomes to complement intrinsic genetic resistance remains a largely untapped avenue (Poudel et al., 2019). Fourth, the genetic and physiological basis of fruit-quality deterioration in otherwise agronomically successful graft combinations — particularly the loss of sweetness and acidity seen in certain cucurbit systems — is still not fully resolved, which limits breeders' ability to select simultaneously for disease resistance and fruit that consumers are willing to purchase (Kyriacou et al., 2017). Finally, continued refinement of robotic grafting technology, paired with machine-vision-based compatibility and quality assessment, together with advances in rootstock genomics that enable marker-assisted selection for multi-trait resistance and tolerance, are likely to be central to making grafting accessible to a wider range of producers, crops and growing environments (Yan et al., 2022; Razi et al., 2024).

11. Conclusions

The evidence gathered in this review shows that vegetable grafting is a scientifically well-grounded and agronomically valuable strategy for managing both biotic and abiotic constraints on vegetable production. The evidence is particularly strong and consistent for its efficacy against soil-borne fungal and bacterial pathogens, and for its capacity to confer measurable, mechanistically grounded tolerance to salinity, drought, temperature extremes, waterlogging and certain heavy-metal stresses. These benefits arise from a well-characterised physiological cascade: graft union formation re-establishes vascular continuity between rootstock and scion, after which the rootstock exerts sustained, long-distance influence over water and nutrient transport, hormonal balance, antioxidant capacity and, in some systems, rhizosphere microbial composition. At the same time, the literature is consistent in cautioning against treating grafting as a universally beneficial intervention. Yield and fruit-quality outcomes vary substantially across rootstock–scion combinations, most pairings fail to deliver significant yield gains in the absence of specific stress pressure, and certain rootstock choices — particularly within Cucurbitaceae — can compromise fruit sweetness and acidity even as they confer disease resistance. The technology's future contribution to sustainable vegetable production will therefore depend less on simply increasing the use of grafted seedlings and more on matching specific rootstock traits, in an evidence-based way, to the particular biotic and abiotic constraints and quality expectations of individual production environments — supported by continuing advances in rootstock genomics, automation and rhizosphere science.

12. Limitations

This review has several limitations that should be considered. As a narrative rather than a systematic review, the literature selection process, although conducted with explicit and transparent criteria, was not exhaustive, and necessarily involved a degree of judgement in prioritising influential and recent studies — which may have prioritised well-cited or readily accessible work over equally valid but less prominent studies. Restricting eligible literature to English-language, peer-reviewed journal publications may also have excluded relevant findings published in other languages or in regional grey literature, particularly from countries where vegetable grafting is extensively practised commercially but less often documented in internationally indexed journals. The evidence base itself is unevenly distributed across crops, stresses and regions, with tomato and watermelon considerably overrepresented relative to other vegetable species, and controlled-environment studies overrepresented relative to multi-season, multi-site field validation — both of which limit how far some of the mechanistic conclusions here can be generalised to commercial production. Finally, because rootstock–scion performance is so genotype- and environment-specific, the patterns synthesised in this review are best interpreted as indicative of general physiological tendencies rather than as universally applicable recommendations; practitioners are advised to validate specific rootstock–scion combinations under their own local conditions before committing to large-scale adoption.

Declaration of AI Use

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Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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