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REVIEW ARTICLE

Advancing cucurbit production: the role of grafting in enhancing yield and quality

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Abstract

Grafting is an extensively adopted technique in horticulture to mitigate both biotic and abiotic stresses. It also has numerous advantages, including enhanced plant growth, productivity and resilience in cucurbitaceous vegetables. Cucurbitaceous crops are prone to various pests and diseases. Under these circumstances, grafting the technique contributes to the successful cultivation of cucurbitaceous vegetables by combating soil-borne diseases, optimizing resource utilization and enhancing water and nutrient absorption efficiency. Grafting involves the unification of two separate plant tissues to form a unique plant with desirable traits inherited from both parents. Successful grafting depends on compatibility, proper healing and integration of the vascular network between the source and sink. In cucurbits, grafting is frequently used to combine robust rootstocks with superior scions, resulting in increased yields, improved fruit quality and enhanced resistance to various stresses. Continuous exploration of grafting techniques, rootstock-scion interactions and molecular mechanisms promises to refine the effectiveness and applicability of grafting in cucurbit farming, thus advancing sustainable agricultural practices. This review delves into the mechanisms, applications and outcomes of grafting among the cucurbit family.

Keywords: abiotic stress; biotic stress; cucurbitaceous; grafting; rootstock; scion

Introduction

Cucurbit crops hold significant economic importance for small-scale and large-scale landholders. These vegetables are preferred worldwide mainly due to their nutritional richness in the human diet. The Food and Agriculture Organisation (FAO) reports that cucurbits cover approximately 4290000 hectares in India, yielding an average productivity of 10.52 T/ha. In 2018, the global production of cucurbits was approximately 234143923 tons, harvested from an area of 8315995 ha (1). Grafting plays a significant role in cucurbit cultivation, especially due to climate change and raise in pathogen resistance. The process, though time-consuming and requiring skilled professionals, enhances plant vigour and disease tolerance. A controlled environment, efficient grafting equipment and proper timing of rootstock and scion sowing are crucial for successful grafting (2). Incompatibility between rootstock and scion may arise early or during transplantation, requiring careful selection based on soil and environmental conditions. High seed costs for hybrids and special rootstocks can be a challenge and removing suckers from rootstocks is necessary. Grafting can increase the spread of seedborne pathogens, such as *Acidovorax citrulli* in watermelon and *Macrophomina phaseolina* in melon, making strict nursery hygiene vital. Using pathogen-free seeds, sterilized tools and disinfected grafting areas can reduce disease risks. Nursery workers often face heat stress in greenhouses, particularly from April to October. However, the implementation of cooling systems and improved facilities can help mitigate these working conditions. Despite these challenges, grafting remains a valuable tool for enhancing cucurbit production and sustainability (3).

Root-Knot Nematode (RKN) infestation led to significant yield reductions, with cucumber at 88 %, followed by zucchini at 53 % and watermelon at 35 % (4). Diseases that spread from soil inoculam, particularly RKN and *Fusarium* wilt, pose a significant challenge in cucurbitaceous crops, potentially resulting in significant yield losses and economic impact for farmers (2). *Fusarium* wilt, caused by *Fusarium oxysporum* f. sp. *lagenariae*, is widespread and damaging various species within the Cucurbitaceae family. Effective control measures, such as utilizing resistant varieties and implementing cultural practices, are crucial for managing these diseases and safeguarding cucurbit production.

Cucurbit wilt diseases affecting the vascular system of the plants are due to infestation of different species of *Fusarium oxysporum*, which resemble each other morphologically but usually show host specificity. Due to the continuous utilization of resistant sources against wilt disease, new origin of plants that can evade the current resistance mechanisms have emerged, making it more difficult to develop long-lasting resistance. For instance, *Fusarium oxysporum* f.sp.*melonis* poses a threat to both cucumber and melon crops (5), With races designated as 0, 1, 2 and 1.2, strains of Race 1.2 have demonstrated the ability to surpass two genes that are dominant and resistance (*Fusarium oxysporum f.sp.melonis*-1 and *Fusarium oxysporum* f.sp.melonis -2). These strains are again categorized into two different types based on the expression they induce: either chlorosis or wilting (6, 7). Races 0, 1, 2 and 3 of *Fusarium oxysporum f. sp. niveum* (FON) are the ones that is responsible for indexing wilt diseases in vascular system in squash and watermelon. Cucumbers, melons and watermelons are affected by *Fusarium oxysporum f. sp. cucumerinum* (FOC), which occurs in races 0, 1, 2 and 3. *Fusarium oxysporum f. sp. lagenariae* is also reported to infect *Cucurbita maxima*, *Lagenaria siceraria* and *Cucurbita ficifolia*. *Fusarium oxysporum f. sp. luffae*, which affects melon and *Luffa aegyptiaca, Fusarium oxysporum* f. sp. *momordicae* in *Momordica charantia* and *Fusarium oxysporum f. sp. benincasae* in *Benincasa hispida* are some more formae speciales.

In recent years, due to extraordinary and erratic climate change, the adaptability of cucurbitaceous plants to the changing environment has become very complicated. Although various breeding programmes are involved in developing varieties and hybrids suitable for changing climatic conditions, it takes several years for them to develop and adapt. Hence, as an alternative grafting technology facilitates field level tolerance and adaptability. Apart from field tolerance, it also provides an effective solution against diseases that occur in the soil, particularly *Fusarium wilt* and nematode infestation, thereby protecting crop health and ensuring strong yields (2). Disease-resistant cucurbitaceous crops are used as rootstocks to enhance plant vigour, which in turn improves fruit quality and increases marketability. Additionally, grafting also enhances resilience to diverse environmental stresses such as drought and salinity, ensuring consistent yields (8). Other benefits of grafting include optimised nutrient uptake, extended growing seasons, thereby improving land utilisation and providing a suitable solution for sustainable cucurbit cultivation. Fig. 1 highlights the benefits of grafted cucumber plants over seed-propagated ones. Grafted plants yield higher crops, produce better quality and exhibit disease resistance, while also reducing pesticide use and environmental impact. Despite higher initial costs, grafting enhances productivity and sustainability in cucurbit cultivation.

Grafting is a method of plant propagation in which two live plant sections are joined to form one whole, cohesive plant (9). Grafting is widely used to enhance fruit yield and plant vigour by improving water and nutrient uptake efficiency. It strengthens root systems, boosts photosynthesis and increases disease resistance. Cucumber cv. Kalaam grafted onto *Lagenaria siceraria* showed better growth, yield and

Fig. 1. Tongue approach grafting (29). A. A rootstock and scion having similar stem diameter; B. Downward angle cut is given for the rootstock and upward angle cut is given for scion; C. Bring the rootstock and scion close together; D. Place the cut potion of rootstock and scion in contact with each other; E. Fix the graft union with a grafting clip; F. Cut the rootstock top portion and scion roots 8 to 10 days after grafting.

quality, while grafting onto pumpkin increased marketable fruit yield by 27 % under copper toxicity. Grafted bitter gourd yielded 63.2 % more than self-rooted plants. Similarly, Palee F1 cucumber grafted onto *Cucurbita moschata* had higher fruit yield and weight. Watermelon grafted onto *Lagenaria* and *C. maxima* had firmer fruits with thicker rinds, improving postharvest handling. However, melons grafted onto *C. maxima* × *C. moschata* showed premature decay. Watermelon on bottle gourd rootstock flowered earlier, while grafting onto 'Shintosa' delayed flowering, affecting harvest timing. In South Africa, Kickstart and Carnivor rootstocks improved melon fruit firmness, pH, sugar-acid ratio and vitamin C content (10). The possibility of expanding the breeding program may vanish when a susceptible scion grafted onto a resistant rootstock produces a resistant or tolerant plant. In 1920, cucurbit grafting was first attempted using Cucurbita moschata as the rootstock. Gradually, in 1950, melons were grafted onto fig leaf gourds to combat *Fusarium* wilt (*Fusarium oxysporumf.sp. melonis*). Later, in 1998, 95% of watermelon seedlings were grafted onto squash or other gourds as rootstock seedlings (11). This technology not only facilitates resistance against disease-causing pathogens, but also secures tolerance against biotic and abiotic stresses, such as heat, drought, salinity, heavy metals, pollutants and alkalinity.

In the horticulture industry, grafting technology has numerous advantages and significant importance, as it creates a remarkable surge in demand for grafted seedlings (12). This is because it has high yielding potential, which was attained due to its resilience to both biotic and abiotic stress (8). In cucurbits, this technology offers tolerance to *fusarium* wilt, drought and flooded conditions. Continuous cultivation of cucurbitaceous crops increases the incidence of pests and soil-borne pathogens, resulting in significant crop losses. To mitigate these challenges, farmers often employ chemical pest control methods, which are costly, inconsistent and can have adverse environmental impacts (13). Among cucurbitaceous vegetable crops, grafting technology is extensively done in watermelon crop (14). The initial utilisation of grafted watermelon seedlings aimed to combat *Fusarium wilt* disease in *Citrullus lanatus* L. Later, it has been observed to enhance several aspects, including disease resistance, compatibility, stress tolerance, quality and yield, in cucurbitaceous vegetable crops (15). The objective of this review is to provide a suitable option for addressing adverse climatic conditions in recent years, as they exacerbate many biotic and abiotic stresses in the cultivation of cucurbitaceous vegetable crops. To combat the above situation, grafting cucurbitaceous vegetables using resistant or wild rootstocks will provide an appropriate solution to increase the yield and quality of cucurbitaceous vegetable crops under unfavourable conditions.

History of grafting

In 1920, research on cucurbit grafting was initiated. Early research on grafting applications in vegetables was done at Kyusyu University (16, 17). In particular, research indicates that grafting watermelon onto Cucurbita moschata rootstocks, which was very popular at that time (18). Subsequently, it was demonstrated that watermelon was compatible when grafted with bottle gourd and wax gourd (*Benincasa hispida*) as rootstocks. (19) Reported that cantaloupe (*Cucumis melo L. var. cantalupensis*) was found to be compatible with varieties of pumpkin and squash, including *Cucurbita maxima Duchense ex. Lam., Cucurbita pepo L*. and *Cucurbita moschata*, as well as *Cucurbita ficifolia Bouch ́e*, cucumber and bottle gourd.

For over two decades, vegetable grafting has been widely practiced in countries such as China, Korea, Turkey, Israel, France, Italy and several other European nations. In 2019, approximately 58 million grafted plants were cultivated in North America, with watermelons accounting for 24 % (13.5 million) of the total. The adoption of grafted vegetables varies across regions, with Mexico leading at 51.5 %, followed by Canada at 35 % and the United States at 13.5 %. In watermelon production, grafted plants are extensively used in various countries viz., Korea utilises grafted plants in about 99 % of its cultivation, Japan at 94 % and China at 40 % (20).

Grafting methods

Several grafting methods have been advocated based on the needs and requirements; the grafting methods can be utilised accordingly. Plant breeding focuses on improving yield, disease resistance and postharvest quality, but it can take time and may lead to trade-offs in desirable traits. Grafting enables the independent selection of scion and rootstock traits, thereby enhancing stress tolerance and productivity in crops such as Solanaceae and Cucurbitaceae. Using wild genetic resources, grafting improves resilience to salinity, nutrient stress and drought. Scientists use reverse genetics to study root-to-shoot signalling, but the epigenetic effects of grafting remain largely unexplored. Understanding epigenetic modifications in grafted plants could aid in the development of climate-resilient crop varieties (3).Tongue approach grafting ensures a high success %age and it is the easiest methods compared to other method of grafting. This method originated from the Netherlands and spread to others parts of the world (11). For performing grafting the rootstock and the scion should be of equal size, the cotyledons of the root stock should be fully developed and scion should have cotyledon and first true leaf. First, the rootstock is cut through the hypocotyl at a 45° angle, keeping the growing point cut downward and still attached to the rootstock (3). Similarly, the scion is also cut at an angle upward; still, the growing point remains attached and finally joins the cut ends, aligned. Finally it is supported with aluminium foil and metal clips until the union is healed. However, this method involves more labour and space. It is not suitable for rootstocks with hollow hypocotyls. Examples: Melon (*Cucumis melo L.*), cucumber (*Cucumis sativus L.*), watermelon (*Citrullus lanatus*), squash and pumpkin (*Cucurbita spp*) are the major crops. (Fig. 2)

Splice grafting is practiced when the rootstock and scion are of the same size. To achieve uniform hypocotyl diameter and ensure proper attachment of the scion to the rootstock, the rootstock should be sown 7-10 days before the scion. Depending on grower preference, either intact or excised (root-removed) rootstock seedlings can be used. Splice grafting can be performed by making slant incisions on both the rootstock and scion while retaining only one cotyledon leaf on the cucurbit rootstock, a technique known as splice grafting (3). In cucurbit's plants, grafting is typically performed at the lower epicotyl and secured with simple clips. To ensure a successful graft union, grafted plants should be maintained at

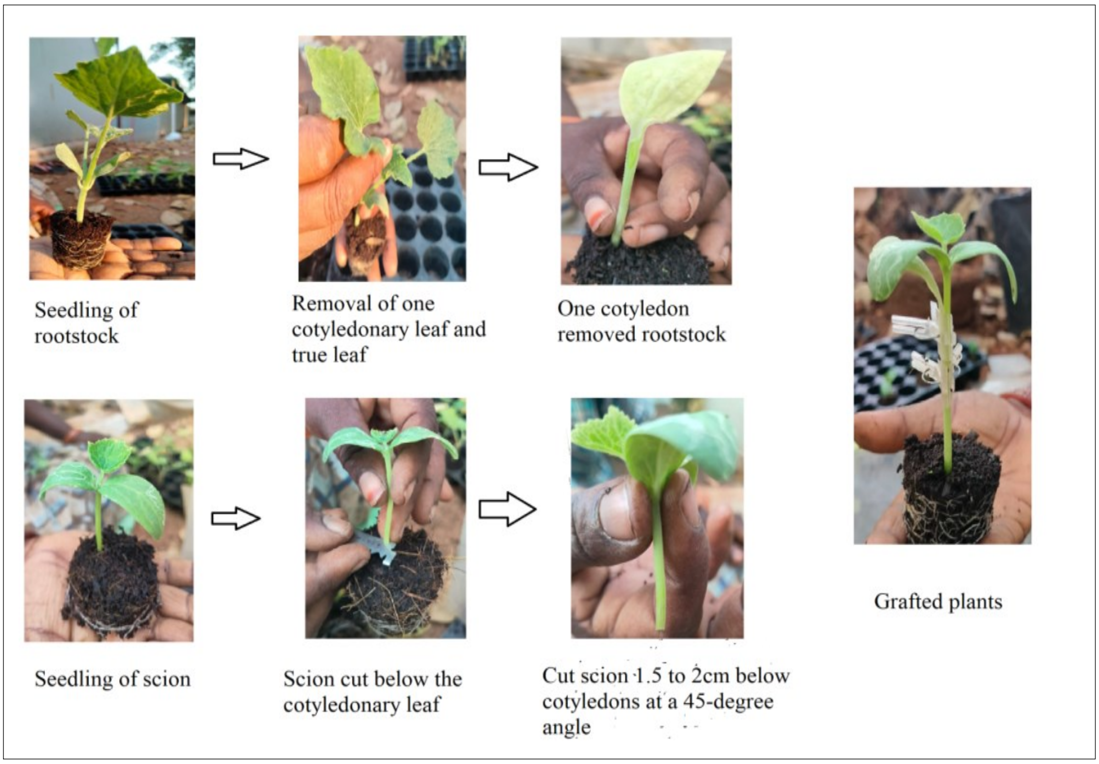

Fig. 2. Splice grafting

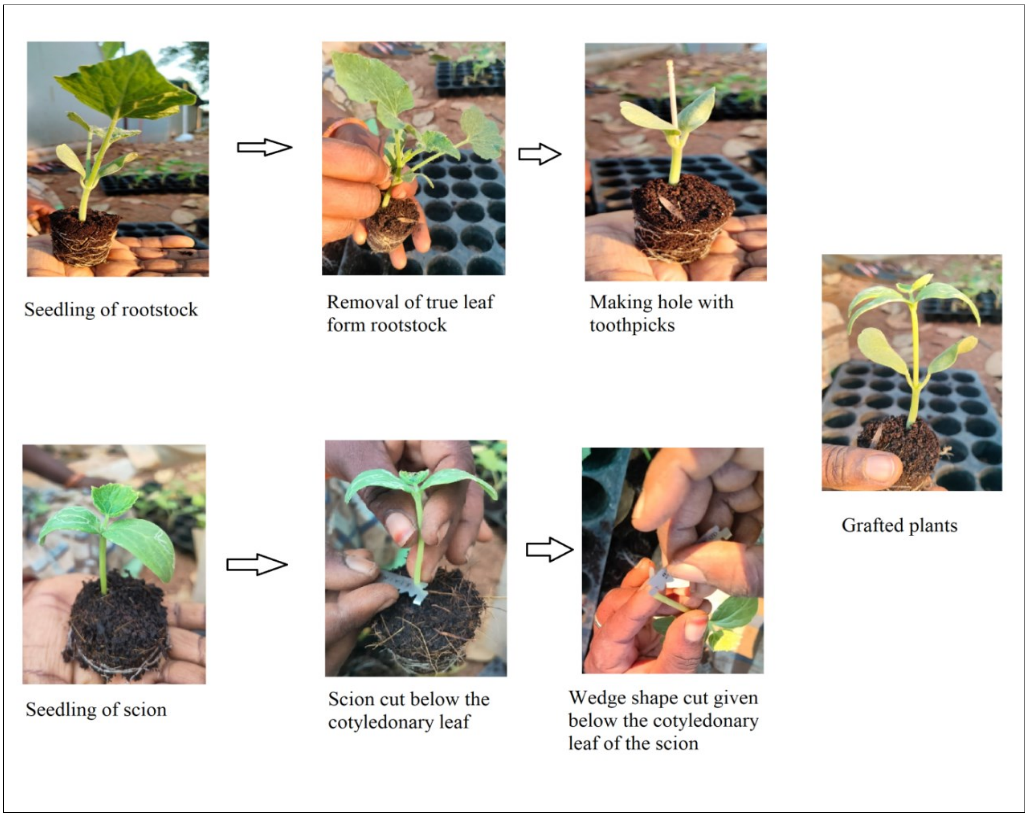

Fig. 3. Hole insertion grafting

25°C with 100 % humidity for three days (Fig. 3).

Hole insertion technique is referred to as top insertion grafting and it is predominantly practiced in China. This method is commonly practicsed for grafting watermelons (21). When using this strategy, the scion seeds should be seeded 2 - 4 days ahead of the rootstock seeds. After seeding, rootstock seedlings are to be grafted in seven to ten days. The top of the rootstock should be beheaded and drilled using a toothpick before being placed in the rootstock hole then the scion hypocotyl is sliced to create a wedge since the seedlings are usually smaller than the bottle gourd or squash rootstock. For healing, the ideal temperature range is between 21 and 36 º C. (Fig. 4)

Cleft/ approach grafting is also known as side insertion grafting. Usually, 7-10 days old rootstock can be used for grafting. The top growth of the rootstock should be removed and a slit is made in the rootstock. Similarly, in scion, a cut is made at an angle of 350-450 on both sides and it is intruded into the slit created in the rootstock. It is united by using a clip and it is kept in a humidity chamber until it heals (11).

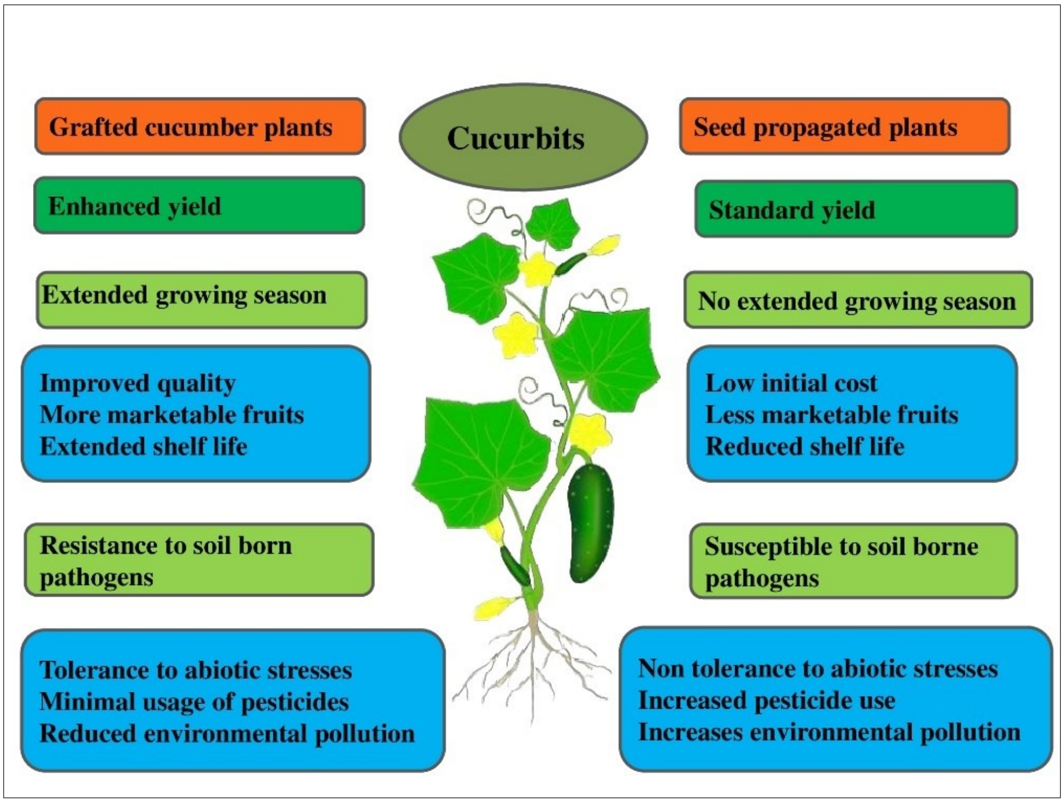

Fig. 4. Merits and demerits of cucurbit grafting

Instead of using grafting clips to hold the grafted position in place, this method uses specially made pins. This method is similar to splice grafting.

Utilising automation in conjunction with human support or complete robotic control has the potential to reduce costs associated with growing grafted seedlings (22, 23). The quality of crops and environmental sustainability both greatly benefit from automated machinery. These advantages are significantly enhanced by its low need for pesticides and its ability to perform operations such as pruning, picking, selecting and grafting two plants together (24).

Grafting methods and rootstocks used for cucurbit crops. For cucumber, multiple rootstocks such as *Cucurbita ficifolia*, *C. maxima* × *C. moschata, Cucumis sativus* and *Sicyos angulatus* are used with the Tongue Approach method, while *Cucurbita moschata* uses Tongue and Hole insertion and *Cucurbita maxima* employs the Tongue method. For watermelon, rootstocks like *Benincasa hispida* and *Cucurbita moschata* are grafted using methods like Cleft and Hole insertion, Hole insertion and Cleft and Splice Grafting, among others. Melon is typically grafted with *Cucumis melo* using both Tongue and Cleft methods. In bitter gourd, Cucurbita *moschata* and *Lagenaria siceraria* are used with methods like Hole insertion and Tongue. Bottle gourd can be grafted with either *Cucurbita moschata* or *Luffa sp*. using Hole insertion and Tongue methods. These various grafting techniques and rootstocks are employed to improve disease resistance, growth and yield in cucurbit crops (Supplementary Table 1).

Different cucurbit grafting techniques, such as hole insertion, splice and tongue approach grafting, impact plant performance under various environmental conditions. Hole insertion grafting ensures strong rootstock-scion unions, improving nutrient uptake and resistance to soil-borne diseases, making it ideal for saline soils, drought-prone fields and those infested with nematodes. Splice grafting, a simpler method, enables quick healing in controlled environments, such as polyhouses, but requires precise alignment. Tongue approach grafting keeps both rootstock and scion connected until full healing, helping plants withstand extreme temperatures and low humidity. Grafted cucurbits generally show better drought tolerance, disease resistance and improved water and nutrient use, making grafting a valuable technique for enhancing crop resilience and yield under changing climatic conditions.

Cucurbitaceous crops

Watermelon

Grafting has gained widespread adoption in watermelon (*Citrullus lanatus*) production globally; primarily it was utilized in combating stresses (Biotic and Abiotic). The benefits of grafted plants extend to enhancing plant resistance against soil-borne diseases, which have been widely accepted, as chemical fumigation faces restrictions or outright prohibition in various regions worldwide. Watermelon (*Citrullus lanatus*) holds significance as a vital vegetable crop cultivated globally. Grafting watermelons has become an increasingly prominent practice within the watermelon production sector. In watermelon, the main sugars are sucrose, fructose and glucose. Grafting may affect the metabolic pathways involved in the fruit's sugar accumulation. Studies reveal a correlation between reduced invertase activity, enhanced sucrose synthase activity, decreased sucrose phosphate synthase activity and reduced sugar transmembrane transport capacity in grafted watermelon with low sugar content. The two most common commercial techniques for grafting watermelons are the one-cotyledon and hole-insertion methods. However, in terms of grafting speed, both approaches show poor efficiency. Furthermore, they frequently cause post-grafting rootstock regrowth, which is a major obstacle to the widespread adoption of grafted watermelon plants, as it results in the preservation of bud meristem tissue at the rootstock cotyledon base. Producers of watermelons use rootstocks derived from pumpkin and bottle gourd to enhance the fruit's flavour and pulp texture. It should be mentioned that although the rootstocks are compatible, their resistance to soil-borne diseases is weaker (25-28).

The hole insertion technique is extensively employed for watermelon grafting in China due to its notable success rate and the relatively low level of management required during the healing phase (29). During grafting, it is recommended that rootstock seedlings should posses one true leaf, while the scion seedlings must have cotyledons, possibly with the emergence of the first true leaf. It should be asserted that the diameter of the scion stem should be smaller than the rootstock stem inorder to facilitate easy insertion into the hole created between the two cotyledons of the rootstock (30). Historically, splice-grafted watermelon has exhibited a low success rate, attributed to the restricted levels of carbohydrates in the rootstock following the removal of both cotyledons (13, 31). Removing both cotyledons prolongs the time needed for callus formation, consequently diminishing the success of watermelon grafting. This suggests a potential connection between the carbohydrate content of the rootstock and the survival of grafted watermelon seedlings (32).

The inconsistent results seem to stem from the absence of genuine resistance in melon rootstocks to *M. cannonballus*. Combining grafting with other control methods to decrease pathogen populations seems to be a crucial factor in mitigating the severity of monosporascus vine decline. Additionally, watermelon has shown improved tolerance to this disease when grafted onto resistant rootstocks. *Verticillium dahliae* Kleb. is a widespread soilborne pathogen that impacts cucurbit crops in various areas. Research on grafting as a method to manage verticillium wilt has been conducted for crops such as watermelon. *Phytophthora capsici* causes Phytophthora blight in watermelon and cucumber, leading to plant wilting and decay. *Podosphaera xanthii* is responsible for Powdery mildew in cucumber and watermelon, creating white, powdery growth on leaves. *Meloidogyne spp*., or root-knot nematodes, damage roots in watermelon, leading to poor nutrient and water uptake (Table 1).

Cucurbits, particularly watermelon, are more susceptible to the conditions required for healing after grafting compared to grafted solanaceous plants like tomatoes. When temperatures are maintained between 22 and 28°C and 90% relative humidity, there is little to no exposure to light for several days after grafting, which provides the highest survival rate. Grafted seedlings of watermelon may not survive as long if any of these requirements are not satisfied. The substantial expense associated with grafted seedlings is primarily attributed to the labor-intensive processes involved in propagation using traditional grafting techniques, as well as the extended production period and additional expenses related to rootstock seed procurement. When compared to non-grafted plants, the price of grafted watermelon transplants may reach five times its level (33), with labour accounting for between 48% and 60% of the overall costs in manual grafting procedures (34). Consequently, effective labour-saving grafting techniques are considered essential for the large-scale production of grafted watermelon seedlings. The implementation of automation and mechanization technologies is expected to address the requirements for large-scale production more effectively.

The main goal of watermelon grafting is to provide resistance against soil borne diseases, such as *Verticillium spp*., *Fusarium oxysporum f. sp. niveum* and RKNs (13, 23). Watermelons that were grafted onto a hybrid of *Curcubita maxima* Duch. and *Curcubita moschata* Duch., known as a 'Shin-tosa'-type interspecific hybrid squash, exhibited increased tolerance to low temperatures and higher yields in comparison to melons that were not grafted or self-grafted (35, 36). Watermelon grafting on bottle gourd rootstock greatly increases the plant's resistance to flooding, especially in loamy or very loamy soils (37).The compatibility of the scion and rootstock, the age and quality of the seedlings, the quality of the graft joint, post-grafting care techniques and the rootstock's resistance to soil-borne diseases are some of the factors that affect the survival rate of grafted plants (38). On watermelon, *meloidogyne incognita* and FON do not show any interaction effects. Therefore, the illness brought on by one of these viruses would not worsen in the presence of the other. On ungrafted watermelon, yield losses ascribed to FON (55 %) were similar to those on grafted watermelon (49 %) caused by *M. incognita*. However, treatments that were infected with both pathogens showed comparable yield losses (39).

Different rootstocks used for watermelon offer various advantages in coping with biotic and abiotic stresses. Bottle Gourd (*Lagenaria siceraria*) tolerates chilling and resists *Fusarium* wilt, while Wax Gourd demonstrates drought tolerance. Squash (*Cucurbita moschata*) is resistant to *Fusarium* and low temperatures and Pumpkins (*Cucurbita*

Table 1. Effect of grafting in controlling plant pathogens

Plant pathogen	Crop	Disease	References
Fusarium oxysporum	Watermelon, melon, cucumber	Fusarium wilt	(42)
F. oxysporum; F. solani	Watermelon	Fusarium crown and root rot	(80)
Verticillium dahliae	Watermelon, melon, cucumber	Verticillium wilt	(81)
Monosporascus cannonballus	Watermelon, melon	Monosporascus sudden wilt	(82)
Phytophthora capsici	Watermelon, Cucumber	Phytophthora blight	(83)
Corynespora cassiicola	Cucumber	Target leaf spot	(84)
Phomopsis sclerotioides	Cucumber, melon	Black root rot	(85)
Didymella bryoniae	Melon	Gummy stem blight	(86)
Podosphaera xanthii	Cucumber, watermelon	Powdery mildew	(87)
Meloidogyne spp.	Cucumber, melon,watermelon	Root-knot	(88)
Melon necrotic spot virus	Watermelon	Melon necrotic spots	(89)

pepo) establish a vigorous root system while also resisting *Fusarium* and low temperatures. Watermelon (*Citrullus lanatus*) itself has tolerance to Fusarium and Citron melon provides resistance to root-knot nematodes. African horned cucumber (*Cucumis metuliferus*) imparts Fusarium resistance and nematode tolerance, while the interspecific hybrid squash (*Cucurbita maxima* x *C. moschata*) is known for its resistance to Fusarium wilt, vigorous root system and high-temperature tolerance. Lastly, Ash gourd (*Benincasa hispida*) enhances disease resistance. These rootstocks help improve the resilience and overall growth of watermelon crops in challenging environmental conditions (Table 2).

The grafting of the watermelon variety 'Fantasy' with the pumpkin rootstock 'Strong Tosa' led to a significant increase in biomass production and leaf area under salt stress conditions in comparison to native plants (40). When watermelon plants were grafted onto pumpkin rootstocks, they exuded more citric and malic acids by 89 % and 91 %, respectively than when they were grafted onto Lagenaria siceraria rootstocks or non-grafted plants. Under conditions of alkalinity stress, this trend was most noticeable.

Grafting under deficit irrigation conditions results in a 60% increase in marketable yield and a 7-10% increase in water use efficiency (41). This enhancement was observed in mini-watermelon (*Citrullus lanatus* 'Ingrid') scions grafted onto the commercial rootstock 'PS 1313' (a hybrid of *Citrullus maxima* × *Citrullus moschata*). The rootstocks, which are hybrids of *Citrullus maxima* × *Citrullus moschata*, when grafted with watermelon, withstood in soils infested with *Fusarium*. Additionally, these rootstocks resulted in increased fruit size and yield compared to non-grafted plants (42, 43). Watermelon grafted onto certain rootstocks demonstrated the ability to alleviate the adverse impact of inadequate potassium availability in the root zone. This may be due to the effectiveness of grafted plants in absorbing potassium and transporting it to the above-ground biomass (44).

Melons (*Cucumis melo* L.)

Melon (*Cucumis melo* L.) is one of the most widely grown and economically significant vegetable crops in the Mediterranean region. One of the top ten fruit crops in the world, muskmelon is a melon cultivar that is highly regarded for its flavor, rich vitamin profile and delicious sweetness. The hallmark characteristic of muskmelons lies in their sweetness, which is closely associated with their soluble sugars content. Melon is highly vulnerable to RKN, resulting in significant yield reductions. Although there was no change in Pf values between non-grafted and grafted plants, grafting melon onto *Cucurbita moschata* rootstock reduced root galling in comparison to non-grafted plants. (45).

Grafted melon seedlings are primarily used to provide resistance against soilborne diseases, including RKNs and *Monosporascus cannonballus*, *Fusarium oxysporum f. sp. melonis* (FOM) and *Stagonosporopsis spp* (46-49). Interspecific hybrid squashes are frequently utilized as rootstocks for melon plants. They are produced by crossing *Cucurbita*

Table 2. Special characteristic features of different cucurbit rootstocks in mitigating biotic and abiotic stresses (71)

Crop	Rootstock	Remarks
Cucumber	Fig leaf Gourd	Shows *Fusarium* wilt resistance and low temperature resistance
	Burr cucumber (*Sicyos angulatus*)	Resistant to southern root-knot nematode
	Interspecific hybrid squash (*Cucurbita maxima* × *C. moschata*)	Impart resistance to *Fusarium* Wilt and low temperature resistance
	African horned cucumber (*Cucumis metuliferus*)	Provides *fusarium* resistance and shows tolerance to nematode
	Cucurbita moschata	Impart stress tolerance
	TRC 11550 (Intraspecific Hybrid)	Resistant to Nematode
	Ardito/TRC 1401	The root stocks growth is uniform, very strong with vigorous root system.
	TRC 15NTB4	Resistance to soil-borne diseases and abiotic stress factors.
Watermelon	Bottle Gourd (*Lagenaria siceraria*)	Tolerate chilling and resistance to *Fusarium* wilt.
	Wax Gourd	Show drought tolerance
	Squash (*Cucurbita moschata*)	Resistant to *fusarium* and low temperature
	Pumpkins (*Cucurbita pepo*)	Establish vigorous root system, resistant to *fusarium* and low temperature
	Watermelon (*Citrullus lanatus*)	Tolerance to *Fusarium*
	Citron melon	Root knot Nematode
	African horned cucumber (*Cucumis metuliferus*)	Impart resistance to *fusarium* and tolerance to nematode
	Interspecific hybrid squash (*Cucurbita maxima* × *C. moschata*)	Resistant to *fusarium* wilt and vigorous root system, high temperature tolerance
	Ash gourd (*Benincasa hispida*)	Transforms disease resistance
Melon	Squash	Provide tolerance to *fusarium* and low temperature
	(*Cucurbita maxima* × *C. moschata*)	Resistance to *fusarium*, impart tolerance to low, high soil temperature and high soil moisture
	Cucurbita pepo	Establish tolerance to low, high soil temperature and high soil moisture
	Melon (*Cucumis melo*)	Improved fruit quality resistance to *fusarium*
	African horned cucumber (*Cucumis metuliferus*)	Tolerance to high and low soil moisture stress
	Sponge Gourd (*Luffa cylindrica*)	Tolerance to heat stress and flooding stress
Bitter gourd	Mithipakal (*Momordica Charuntia* var. *amoicatai*)	Resistant to pest and diseases
	Fig leaf gourd (*Cucurbita ficifolia*)	Highly tolerant to low temperature, salinity and moderately resistant to *Fusarium* wilt
	Pumpkin (*Cacurbita moschata*)	Tolerant to vine squash borer, root knot nematode and *Fusarium* wilt Tolerance to low temperature
	Zucchini squash (*Cucurbita pepo*)	Resistant to *Fusarium* wilt tolerance to high and low temperature

maxima Duchesne with *Cucurbita moschata Duchesne* (26). *Cucumis melo* rootstocks and a variety of other species, including squash, interspecific hybrids, pumpkin and bottle gourds, have all been successfully grafted with melons (23, 26). In fields contaminated with FOM, farmers select rootstocks that offer increased growth and productivity, as resistant melon cultivars are not readily available. This decision was made in part because rootstocks tolerant of all FOM races have been identified (50).

Various rootstocks used for melon offer significant advantages in managing both biotic and abiotic stresses. Squash provides tolerance to *Fusarium* and low temperatures, while the (*Cucurbita maxima* x *C. moschata*) hybrid offers resistance to *Fusarium* and tolerance to both low and high soil temperatures and high soil moisture. *Cucurbita pepo* also helps establish tolerance to varying soil temperatures and moisture levels. Melon (*Cucumis melo*) enhances fruit quality and provides resistance to Fusarium. African horned cucumber (*Cucumis metuliferus*) offers tolerance to both high and low soil moisture stress and Sponge Gourd (*Luffa cylindrica*) is particularly resistant to heat stress and flooding. These rootstocks improve melon growth and resilience in the face of challenging environmental conditions (Table 2).

Grafting the cultivar Dikti onto the interspecific hybrid rootstock 'RS 841' resulted in increased nitrate uptake, increased biomass output and better photosynthetic efficiency (51). 'RD 841' rootstock enhanced sodium exclusion and potassium uptake (52). The researchers linked the enhanced ability to withstand salt stress to better regulation of stomatal functions, which may be the consequence of grafting-induced modifications in hormone transmission between the root and shoot. However, attempts to control the fall of the soil-borne pathogen-caused monosporascus vines *Monosporascus cannonballus*, rootstocks were grafted, but they did not prove effectiveness against the pathogen. Even with the pathogen present, these grafted rootstocks showed enough vigor to support crop growth. When the Melon cultivar 'Paloma' was grafted onto the *Cucumis metuliferus* BGV11135 rootstock, both spring and summer plantings showed less root galling and more yield than non-grafted plants (53). *Cucumis metuliferus* has effectively reduced RKN proliferation and disease severity while simultaneously encouraging greater melon plant growth, it has been recommended as a viable rootstock for melon (54).

Phomopsis sclerotioides causes Black root rot in melons, damaging the roots and impairing growth. *Didymella bryoniae* leads to Gummy stem blight in melon, producing sticky lesions on the stems. *Podosphaera xanthii* is the cause of Powdery mildew in both cucumber and watermelon, resulting in a white, powdery coating on the leaves. Lastly, Melon necrotic spot virus induces Melon necrotic spots in watermelon, causing lesions on the fruit. These pathogens and associated diseases have a considerable negative effect on crop yield and quality (Table 1).

Hybrid interspecific squash has been observed that six rootstocks can withstand low temperatures and salinity (13, 55). However, they detrimental effects on the fruit quality of certain melon cultivars as they are not resistance to RKNs (13, 56, 57). *Cucumis metulifer* E. Mey. ex Naud. (African horned cucumber) has been explored for use in melon grafting due to its ability to withstand under RKNs and *fusarium* wilt (Table 2) (45, 58, 59). When developing rootstocks, it is necessary to take into consideration two main types of diseases: wilts, which are mainly caused by FOM and diseases that affect the roots and stems, which include infections brought on by *Macrophomina phaseolina*, Stagonosporopsis various species and *M. cannabinosus* (26). The pumpkin cultivar TZ-148 exhibits a robust capacity for accumulating sodium ions within its roots, although it has a constraint to move them to the scion. Grafted melon plants have lower salt concentrations than self-grafted and non-grafted melon plants in both exudates from the cut stem and shoot (60).

A squash hybrid led to enhanced tolerance to low temperatures and high yields when compared to nongrafted and self-grafted melons (35, 36). Enhancing the growth performance of melon in saline conditions could be accomplished by grafting onto the Cucurbita ('P360') hybrid rootstock (61). The melons grafted onto rootstocks composed of three squash hybrids exhibited increased tolerance to salinity and yielded higher marketable produce compared to plants non-grafted (62). Grafting melon onto the commercial rootstock 'TZ-148' (a hybrid of *Cucurbita maxima* and *Cucurbita moschata*) helped in alleviating the negative effects of excessive external boron concentrations, it resulted in increased tissue boron concentrations and a decrease in development and fruit output.

Grafting melon plants of the 'Arava' variety onto commercial pumpkin rootstocks of Cucurbita 'TZ-148' resulted in a reduction of boron accumulation in the leaves of plants grafted, compared to plants with non-grafted melon when subjected to watering with two different water quality (63). They hypothesized that the root system of 'TZ-148' absorbed boron to a lesser extent than that of the 'Arava' plants. The study investigated the impacts of five distinct boron concentrations spanning from 0.1 mg L-1 to 10.4 mg L-1 on the vegetative growth, yield and boron uptake of both 'Arava' melon non-grafted and grafted 'Arava' melon onto pumpkin 'TZ-148' rootstock. It was observed that boron concentrations in the plants increased proportionally with the boron levels in the water used for irrigation with the highest concentrations (ranging from 150 to 2224 mg kg-1) detected in matured leaves, intermediate concentrations (ranging from 47 to 282 mg kg-1) in the roots and the lowest concentrations (ranging from 10 to 100 mg kg-1) in the fruit (64). Under field conditions, grafting the melon variety 'Arava' onto the commercial rootstock Cucurbita 'TZ-148' affected the quantities of heavy metals in the vegetative shoots and fruit (65).

Cucumber (*Cucumis sativus* L.)

Cucumber (*Cucumis sativus* L.) is a popular vegetable crop grown widely in plastic greenhouses throughout the Mediterranean region. They favor cucumber because it grows quickly and has a high economic value during off-season harvests. Soil-borne diseases, such as *Fusarium* and Verticillium wilt, are common in greenhouse culture due to the irregular and intensive nature of greenhouse production, which negatively impacts cucumber yields. The major purpose of cucumber grafting is to provide resistance to cold temperatures and *Fusarium* wilt while increasing growth and yield.

Cucumber grafting is employed by using splice, hole insertion and tongue approach methods, though there are many methods, the hole insertion technique is utilized in Oriental Hybrid Summer Delight cucumber (*Cucumis sativus*) cultivar and Japanese hybrid squash (Tetsukabuto) rootstock (*Cucurbita maxima* × *Cucurbita moschata*) (29). Additionally, other cucumber varieties such as Southern Delight Hybrid (*Cucumis sativus*) can also be grafted using Tetsukabuto as the rootstock. Following this scenario, various strategies have been employed to address the issue, including the utilization of resistant cultivars, grafting resistant cultivars onto resistant rootstocks, adoption of soilless growing systems and crop rotation. Among the various strategies utilized, grafting with *Cucurbita maxima* × *Cucurbita moschata* (interspecific hybrid RS 841 F1) contributed towards the enhancement of marketable yield in cucumber. The squash hybrids 'Strong Tosa' and 'RS841' significantly improved vegetative growth and yield when compared to ungrafted cucumber plants. Both ungrafted plants and grafted plants showed similar % of root galling and nematode proliferation (66). No symptoms of damping-off infection were noticed in cucumber plants when grafted onto 'Titan' and 'Hercules' the squash hybrids (67).

Traditionally, cucumber was grafted onto interspecific hybrid Squash, Fig leaf Gourd (*Cucurbita ficifolia Bouché*), Pumpkin and Squash rootstocks (23, 47, 68). Grafting cucumber cv. Jinchun No. 2 onto *C. moschata* ('Chaojiquanwang') rootstock resulted in a stronger ability to exclude salt and retain sodium in its roots than cucumber (Table 2). This trait reduces sodium transit to the scion and improves the cucumber's salinity tolerance (44). Higher vitamin C content in cucumber was noticed when fruits were harvested from grafted plants onto Fig leaf gourd rootstock. *Cucumis sativus* when grafted onto *Cucurbita moschata* rootstock showed resilience against both *fusarium* wilt (Table 2) and phytophthora blight (57).

Luffa rootstock offers both drought tolerance and heat stress tolerance through the stimulation of abscisic acid biosynthesis (69, 52). Luffa's root system is more sensitive to variations in root-zone moisture levels, allowing for a faster response to water scarcity by accumulating ABA in roots, xylem sap and leaves than self-grafted cucumber plants. When cucumber plants of the Jinyan No. 4 cultivar were grafted onto luffa rootstock, they showed higher water use efficiency and a lower transpiration rate. Recent breakthroughs have been achieved by using grafting to enhance salt tolerance in cucumber. Specifically, grafting cucumber cultivar Jinchun No. 2 onto 'Chaojiquanwang' rootstock (*Cucurbita moschata*) caused a decrease in salt level in the scion (70). *Corynespora cassiicola* results in Target leaf spots in cucumbers, causing circular lesions on the leaves. *Phomopsis sclerotioides* leads to Black root rot in both cucumbers damaging roots and hindering growth. *Meloidogyne spp*., or root-knot nematodes, damage roots in cucumbers leading to poor nutrient and water uptake (Table 1).

Pumpkin, Bottlegourd, Squash hybrids (*Cucurbita maxima* × *Cucurbita moschata*) and Fig leaf gourd were resistant to FOC and compatible with cucumbers (71). *Cucurbita ficifolia*, *Cucurbita moschata* and squash hybrids were promising sources of resistance to *Fusarium oxysporum f. sp. radices -cucumerinum* (FORC) (Table 1), making them suitable for grafting cucumber (72). Cucumber plants grafted onto *Cucurbita maxima*, *Benincasa hispida*, *Lagenaria siceraria* or the squash hybrid 'Ercole No.6001' exhibited minimum root galling and number of RKN compared to ungrafted plants (Table 1), regardless of the growing season (autumn or spring) in which they were cultivated (73). Root galling grew gradually over time after planting, with squash hybrids showing the greatest difference, with 25 to 50 % and more than 75 % of the roots galling at 43 and 70 days, respectively. Reduced root galling at midseason most likely contributed to the improvement in cucumber output when grafted onto squash hybrids (66).

Different cucurbit rootstocks provide various benefits in mitigating both biotic and abiotic stresses. For cucumber, Fig leaf Gourd offers resistance to *Fusarium* wilt and low temperatures, while Burr cucumber (*Sicyos angulatus*) is resistant to southern root-knot nematode. The Interspecific hybrid squash (*Cucurbita maxima* × *C. moschata*) imparts resistance to *Fusarium* wilt and enhances low temperature tolerance and the African horned cucumber (*Cucumis metuliferus*) offers *Fusarium* resistance and nematode tolerance. *Cucurbita moschata* improves stress tolerance and TRC 11550 (an intraspecific hybrid) is resistant to nematodes. Ardito/TRC 1401 is known for its uniform growth, strong structure and vigorous root system, while TRC 15NTB4 is resistant to soil-borne diseases and can tolerate various abiotic stress factors. These rootstocks help enhance the resilience and growth of cucurbit crops under challenging environmental conditions (Table 2).

When cucumber grafted onto rootstocks of fig leaf gourd (*Cucurbita ficifolia*) which is cold tolerant and luffa (*Luffa cylindrica* L.) which is heat-tolerant (Table 2) exhibited increased expression of certain stress-responsive genes under sub-optimal (18/13°C) and supra-optimal (36/31°C) day/night temperature (74). Cucumber scions grafted onto luffa rootstocks showed improved heat resilience due to increased levels of apoplastic hydrogen peroxide (H2O2) and ABA increased expression of RBOH (Respiratory burst oxidase homologue) transcripts and a reduction in oxidative stress and heat-shock protein 70 (HSP 70) (75). Cucumber exhibits high susceptibility to elevated temperatures. Grafting cucumber onto luffa (*Luffa cylindrica*) rootstocks has been shown to enhance tolerance to root-zone temperatures reaching 40°C and air (74-76). Nonetheless, rootstock variety, SQ60 F1, showed adaptability for heat tolerance in cucumbers.

A saline nutritional solution containing 91 mM NaCl was applied to six distinct combinations of cucumber plants: self-grafted cucumber, self-grafted pumpkin, non-grafted cucumber, non-grafted pumpkin, cucumber grafted into pumpkin and pumpkin grafted onto cucumber (44). The pumpkin rootstock exhibited a superior capability for excluding Na+ ions, leading to reduced Na+ translocation to the aboveground parts of the plant and thereby enhancing the cucumber's tolerance to salt stress. Grafting onto the 'Shintoza' rootstock could potentially alleviate copper (43) toxicity in cucumber plants when subjected to elevated Cu levels in the root portion. This effect may be achieved by limiting the uptake and transport of Cu to the upper parts of the plant (41).

Bitter gourd (*Momordica charantia* L.)

Bitter gourd is one of the important cucurbitaceous crops in India. Its fruit is rich in vitamins, iron, minerals, phosphorus and dietary fibre, making it well-known for its high nutritional value. The grafting of the bitter gourd scion 'Palee F1' onto 'pumpkin (*Cucurbita moschata*)' rootstock resulted in favorable outcomes related to vegetative growth, early development, yield and fruit production, with the quality of the fruits being equivalent to that of the ungrafted plants. These findings suggest that this grafting approach holds promise for enhancing bitter gourd cultivation across various parameters, including crop growth, days to harvest, yield parameters and fruit characters (77). Additionally, when the bitter gourd scion was grafted onto sponge gourd (*Luffa cylindrica*) rootstocks, it exhibited even more favorable outcomes, including early flowering, larger fruit size and increased yield in the grafted plants. This demonstrates the potential of grafting as a valuable tool in bitter gourd breeding and plant production, offering farmers cost-effective solutions by reducing seed expenses and overall cultivation costs. Furthermore, utilizing cleft grafting techniques with luffa species as rootstock has proven effective in preventing *Fusarium* wilt caused by *Fusarium oxysporum* f.sp. *momordicae*. Grafting onto pumpkin rootstock also led to an increase in the dry matter accumulation and yield parameters in bitter gourd. Additionally, improvement in Ca2+ and K+ content were also noticed in both the fruits and leaves which highlights the significance in human nutrition (78).

Rootstocks used for bitter gourd, such as Mithipakal (*Momordica charantia* var. amoicatai), which is resistant to pests and diseases, Fig leaf gourd (*Cucurbita ficifolia*), known for its tolerance to low temperatures and salinity, Pumpkin (*Cucurbita moschata*), which withstands vine squash borer, root-knot nematode and *Fusarium* wilt and Zucchini squash (*Cucurbita pepo*), offering resistance to *Fusarium* wilt and tolerance to both high and low temperatures, all contribute significantly to enhancing the resilience and growth of bitter gourd by mitigating biotic and abiotic stresses (Table 2).

Future prospects of cucurbit grafting

The future prospects of cucurbit grafting show promising advancements in tackling various obstacles and improving its effectiveness in contemporary agriculture. Progress in rootstock research will concentrate on identifying and characterizing alternative rootstocks with enhanced disease resistance, compatibility with open-field cultivars and adaptability to varying climatic conditions. This will empower farmers to select the most suitable rootstock for their specific needs, thereby maximising the benefits of grafting. Automation technology will play a pivotal role in expanding grafting operations for large-scale commercial production. Ongoing innovation in semi or fully automated grafting robots will simplify the grafting process, decrease labour expenses and enhance efficiency, thus making grafting more accessible and cost-efficient for farmers worldwide. Moreover, efforts to refine production practices and reduce production costs will enhance the economic feasibility of grafted cucurbit crops. This encompasses strategies to reduce labor inputs, shorten production timelines and optimize resource utilization. Furthermore, the incorporation of controlled environment technologies will enable precise control of growing conditions, leading to enhanced grafting success rates and overall crop performance. In conclusion, the future of cucurbit grafting presents significant potential for transforming crop production by alleviating disease pressure, boosting yields and ensuring food security amid evolving agricultural conditions.

Graft incompatibility, which occurs when the scion and rootstock fail to form a strong vascular connection, can result in poor plant growth, reduced yield, or complete graft failure. Economic feasibility remains a concern, as grafted seedlings are more expensive due to labor-intensive processes and the need for specialized facilities, making adoption difficult for small-scale farmers. Additionally, grafting requires skilled labor, as precise cutting, alignment and healing conditions are essential for a high success rate. Addressing these challenges through research on compatible rootstock-scion combinations, cost-effective automation and farmer training programs will be crucial for making grafting a widely accessible and practical solution for sustainable vegetable production.

Conclusion

In contemporary vegetable cultivation, grafting in cucurbits, such as watermelon, melon, cucumber and bitter gourd, has become essential for enhancing disease resistance, stress tolerance, yield and fruit quality. Watermelon, highly susceptible to soil-borne diseases such as wilt, is commonly grafted onto bottle gourd, pumpkin and interspecific hybrid rootstocks for improved disease resistance and fruit quality. Melon grafting is widely used in areas affected by *Fusarium* wilt, with hybrid squashes and other rootstocks improving disease resistance and yield. In cucumbers, grafting onto luffa, fig leaf gourd and pumpkin enhances resilience to stress, nutrient uptake and overall plant health. Similarly, grafting bitter gourd onto pumpkin and luffa yields larger fruits, earlier flowering and higher yields. Despite challenges like high costs and labor-intensive techniques, grafting offers a sustainable solution for resilient, high-yielding crops. With advancements in science and technology, its adoption is expected to grow, improving vegetable production worldwide.

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Authors' contributions

MK concept- critically supported in framing the layout and content of the article. MS writing-original draft preparation. KV the sequence alignment and editing. CT gave inputs on the disease resistance. KD formulated all the tables and edited the article. GS supported with literature pertaining to rootstock breeding. CI super-vised the work and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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