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Grafting as a good technique to improve the productivity and quality of fruit-bearing vegetables: A review

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Abstract

Grafting is the combination of two living parts from two different plants acting as a single plant. This new plant, known as a grafted plant, is used to increase plant output by giving plants better growth, vigour, and pleading against abiotic and biotic stresses. Vegetable grafting has the potential to increase the area under vegetable cultivation in non-traditional settings and unstable agro-ecosystems, where it has the potential to boost productivity per unit of available land. Grafting is suitable effectively in solanaceous and cucurbitaceous vegetables. The aim of current review focus on the impact of grafting on yield, quality, disease resistance, and stress tolerance of fruiting vegetables. Fruiting vegetables are often grafted using the tongue, cleft, tube and splice methods. Studies on tomato, eggplant, pepper, cucumber, watermelon, and melon indicated that grafting significantly improved production, quality, and the ability to withstand soil-borne and environmental stress. Breeding initiatives to produce versatile rootstocks, the creation of effective grafting tools, and improved grafting methods will surely promote the usage of grafted seedlings globally. The status of grafting technique can also be improved by the introduction of novel rootstocks with desirable features compatible with local chosen scions. Hence, the use of grafting in fruit-bearing vegetables have a promising future. Due to its advantages and value, producers in Egypt anticipate a sharp rise in demand for high-quality grafted seedlings as a result of the establishment of private farms with the intention of selling their products on the domestic and international markets.

Keywords: Grafting, Rootstock-scion, Deficit irrigation water, Salinity, Fruit quality yield, Water use efficiency.

1. Introduction

Grafting is one of the methods used to unite a plant's aerial "Scion" and root parts for another plant "Rootstock" **[1, 2]** The compatibility between the rootstock and the scion, which can support the grafted plants against stressors by promoting the nutrients uptake, transport, and water use efficiency (WUE), is the primary factor determining the success of grafting **[3, 4]**. On grafting in vegetable crops, several reviews and original articles have been published, including those by **[4-12]**.

Recently in Egypt, only few vegetables exporting company started to apply grafting technique, as an eco-friendly alternative for methyl bromide fumigation. Even, the vegetable grafting technique mainly used to overcome soil borne diseases **[13- 21]**, it has been also reported as an effective technology to maintain high yields and fruit quality **[4, 16, 22-25]** under different environmental stresses such as irregular irrigation schedules, drought & water and soil salinity **[1, 2, 26- 37]**.

Therefore, this review is aiming to not only introducing vegetables grafting as a good adapted technique, but also spreading such technique for public application in production of fruit-bearing vegetables, i.e., melon, watermelon, tomato and cucumber, as an eco-friendly application to overcome biotic and abiotic stresses, reducing agrochemicals demand, plant water requirement, increasing the net revenue/area unit **[1, 2, 26- 35, 38]** and water use efficiency **[4, 26, 27, 31, 39- 42].**

Nowadays, vegetable grafting is used to enhance the tolerance against abiotic stresses. It also induces vigor, better yield and quality and decrease soil-borne pathogen exposure **[43].** Therefore, this review article may be a step forward to apply this effective technique in improving vegetable production in new reclaimed region for both local marketing and exporting.

1. Historical view over vegetables grafting

Vegetable grafting is an ancient procedure; the first effort was made in Japan and Korea by grafting watermelon (*Citrullus lanatus*) onto pumpkin (*Cucurbita moschata*) rootstock in Japan and Korea in the late 1920s **[44]**. Vegetable grafting became a widespread practice in many countries of the world and other crops (melon, watermelon, cucumber, tomato, aubergine and pepper) have also been subjected to this practice **[45-48]**. However, the practice of grafting vegetables for commercial purposes only began in the early 20th century in an effort to control soil-borne diseases **[49]**. Spain, Italy, and France are the countries that produce the most grafted seedlings in Europe **[50]**. In Egypt, many investigations were carried out on vegetable grafting started from the fifteenth and dramatically increased by the end of 20th century, where there are about 50 theses and many papers were published from 1950 to 2023.

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2. Objectives of vegetables grafting

Grafting is regarded as an efficient and sustainable strategy in the development of intensive vegetable growing systems by assuring the sustainability of yield and quality in vegetable crops **[11, 51]**, to manage soil-borne diseases and pests **[10, 52]** and/or to promote plant vigour under diverse ecological stress, i.e., saline water **[13]**, drought **[26, 27, 31]**, minimal nutrition stress **[12, 53]**. Moreover, grafting has made it possible to increase plant vigour, water and nutrient intake, and increasing the harvest period. This eco-friendly farming strategy decreases need on agrochemicals **[54]**.

2.1. Controlling of soil-borne diseases

Using the strong tolerance or resistance of rootstocks to specific soil-borne diseases is one of the main benefits of using grafted plants. Although though the level of tolerance varies greatly amongst rootstocks, the rootstocks demonstrated notable tolerance to soil-borne diseases such as *Fusarium spp*., *Verticillium spp*., and *Pseudomonas spp*. Developing new disease-resistant cultivars requires time and raises the possibility that the resistant cultivars will become vulnerable to novel pathogen races. Grafting is used to stop soil-borne diseases including bacterial and fusarium wilt in *Cucurbitaceous* crops (Watermelon, cucumber, melon etc.) and *Solanaceous* crops (Eggplant, tomato, pepper etc.) **[54]**. The fusarium wilt resistance was improved by grafting watermelon onto bottle gourd **[55, 56]**.

It has typically been grafted onto pumpkin **(***C. pepo*), squash (*C. moschata*), bottle gourd, and interspecific hybrid squash (*C. maxima* × *C. moschata*) and exhibits strong compatibility with linked rootstocks **[43]**. Of these, squash and interspecific hybrid squash have been generally known for their better root formation and resistance against *Fusarium* wilt **[56]**. The rootstock 'Shintoza' or 'Super Shintoza', an interspecific hybrid squash, gave protection to *Fusarium* wilt in watermelon when planted in contaminated soils; the rootstocks improved size of fruits and their number compared to non-grafted plants **[57]**. The yields of cucumbers were significantly improved and vegetative growth was higher in fields infested with *P. capsici* when it is grafted on bottle gourd, and wax gourd rootstocks **[58]**. Melon has been successfully grafted onto rootstocks derived from watermelon, bottle gourd, pumpkin, squash, cucumber and wax gourd, and offered resistance to soil-borne diseases **[55, 59, 60]**. Due to improved vigor of the grafted plants, eggplant varieties grafted on 'Beaufort' F1 showed boosted yield and fruit production **[60]**. The 'Beaufort' F_1 rootstock also offered resistances to Verticillium wilt in the grafted eggplant **[62, 63].** To promote resistance to Fusarium wilt, cucumber has typically been grafted onto Fig leaf gourd (*C. ficifolia*), squash, and pumpkin **[64]**. Grafting of tomato has also been practiced commonly onto tomato genotypes and interspecific hybrids to have protection against soil-borne fungi e.g., *Fusarium* spp., *Verticillium* spp. etc. **[65]**. On utilizing of vegetable grafting to manage soil borne diseases, several reviews and original articles have been published **[13- 21]**. Table (1) lists previous publications on managing soil-borne diseases by grafting tomato, melon, watermelons, or eggplants on various rootstocks.

2.2. Vegetable grafting to promote nematode resistance

Damage by soil nematodes *(Mleloiclogyne* spp.) can be also managabled by grafting onto resistant rootstocks. Grafting of *C. metuliferus* as rootstock has been used with RKN susceptible melon cultivars in reducing root gall number and nematode infection **[70]**. The bur cucumber exhibited improved resistance to RKN when grafted as the rootstock with cucumbers **[71].** Promising advancement has also been made in generating *M. incognita*-resistant rootstocks of wild watermelon (*Citrullus lanatus*). However, RKN resistance cucurbit rootstocks are not commonly available **[72]**. RKN-resistant rootstocks grafting with susceptible tomato cultivars was successful due to the reduced RKN infestation in field soils **[73]**. Grafting eggplant into rootstocks (*S. melongena* x *S. incanum* and *S. melongena* x *S. aethiopicum*) is safe and has no negative impacts on fruit quality. These rootstocks have good compatibility, high plant vigor, enhanced yield, and moderate tolerance to root-knot nematodes **[74]**. When utilized wax gourd and squash as rootstocks, that's have demonstrated the ability to promote resistance to nematodes "*M. incognita* and *M. javanica*" **[75]**.

Table 1. Plant pathogens reported to be controlled by vegetable grafting

Scion species	**Rootstock species**	**Disease**	**Plant pathogen**	**References**
Melon	Shintozwa *(C. maxima x C. moschata D.)*	Monosporascus sudden wilt	*Monosporascus cannonballus*	**[66]**
Tomato	Cuore di Bue and Natalia hybrid	Fusarium crown and root rot	*F. oxysporum;* *F. solani*	**[67]**
Eggplant	*Beaufort*	Verticillium wilt	*Verticillium dahliae*	**[63]**
Watermelon	*C. maxima* x *C. moschata*	Fusarium wilt	*Fusarium oxysporum*	**[57]**
Tomato	Celebrity, Big Beef, and Jetsetter	Root-knot	*Meloidogyne spp.*	**[68]**
Watermelon	*C. lanatus*, *C. amarus*, *C. mucosospermus* and *L.agenaria siceraria*	Powdery mildew	*Podosphaera xanthii*	**[69]**

2.3. Alternative to methyl bromide

Resistant cultivars and grafting are considering the most effective alternatives to methyl bromide (MB) could be used. Development of resistant cultivars is difficult and may take a long time to be achieved. So, grafting plants on resistant or wild rootstock was found an effective method for alternate BM. Recently, it is thought that using grafted plants might help to lessen the need for methyl bromide soil fumigation for numerous crops. **[76, 77, 78, 79, 80].**

2.4. Overcoming various environmental stresses

Vegetable grafting has been used to promote sustainable development against a variety of environmental conditions, both high and low temperatures, drought, salinity, and flooding. Grafting is an important tool to avoid or reduce yield losses caused by these different environmental stresses on vegetable crops such as Cucurbitaceae and Solanaceae families. Grafting is ongoing method which can impact environmental stress tolerance of grafted plants via higher photosynthesis and leaf water content, higher accumulation of polyamines, abscisic acid and increase anti-oxidant enzymes in leaves, better root-shoot ratio and enhance growth and yield of plants **[1, 2, 26- 34, 2, 36, 37, 79, 81].** Various published articles on the grafting using varied rootstocks under various environmental stresses in tomato, melon, watermelon and eggplant, are listed in Table (2).

Table 2. List of some published articles on grafted vegetables under environmental stresses.

Scion species	**Rootstock species**	**Environmental treatments**	**The main findings of the study**	**References**
Tomato (*Solanum lycopersicum* L.) cv Reem	Tomato Heman, 1G-48-6031, 1G-48-6032 and Edkawy	Salt stress (448, 2000, 4000 and 6000 ppm)	vegetative growth, nutrient status, fruit quality and total yield	**[28]**
Melon (Ideal and Veleta)	Cobalt and Strong-Tosa	salinity levels [0.8 (control), 3.9, 7.1 and 10 dS m^{-1}]	Stem length, branches number, leaves number, leaf area, total fresh weight, total dry weight, Early yield, fruits number and total yield	**[26, 27]**
Melon, cv Baimi (*Cucumis melo*)	Jingxin 3 (*C. maxima* × *C. moschata*)	150 mM NaCl	Growth parameters; photosynthetic measurement; antioxidant system; enzymes for sugar metabolism; Na^+, K^+, Ca^{2+}, and Mg^{2+} concentrations	**[82]**
Angela (*Solanum melongena*)	'Maxifort' (*Solanum lycopersicum*)	55.5 mM Na^+ and 148 mM Cl^-	Yield and ion uptake in leaves and fruits	**[41]**
Chaoyan 298 (*S. lycopersicum*)	Yanqi (*Lycium chinense*)	7.42 g kg^{-1} (total salt include Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-,	SPAD, fruit production, shoot biomass and leaf ion	**[83]**
Melon (Ideal and Veleta)	Cobalt and Strong-Tosa	Deficit irrigation (100, 75, and 50% of ETc)	fruit number, total yield and WUE	**[31]**
Cucumber (*Cucumis sativus* L.), Gianco F_1	Ferro, Cobalt, VSS-61 F_1, Bottle gourd, and Super Shintoza	heat (43°C) and soil salinity (4.49 dS m^{-1})	vegetative growth, biochemical, mineral content traits, yield quality and total yield	**[1]**
watermelon (cv. Aswan)	*Giada, Shintoza, Strong toza, Ferro and Pumpkin*	Deficit irrigation 100%, 70% and 50% of ET	No. of leaves and branches, length of the main stem, leaf relative water content and fruit yield	**[84]**
Tomato (*S. lycopersicum* L.) cv. Strain B	*S. pimpinellifolium* and Edkawy	Salt stress (4000, and 8000 mg L^{-1} NaCl)	shoots contents of nutrients, phytohormones, peroxidase and proline	**[85]**
Cucumber (*Cucumis sativus* L.)	VSS-61 F_1, Ferro and Super Shintoza	heat (43°C)	vegetative growth, biochemical, mineral content traits, yield quality and total yield	**[2]**

2.5. Vegetable grafting strengthens the integrated pest management (IPM) programs

Grafting is not only used to manage soil diseases but it has sometimes also positive effect in foliar parts of vegetable crops. Rootstocks in the grafting technique use specific essential resistance genes or non-host resistance or multi-genic resistance mechanisms to protect pests and pathogens **[49]**. By including grafting resistance to pathogens, pests, and weeds to endure biotic pressure together with comprehensive knowledge on the pathogen or pest biology, variability, and population dynamism, the role of IPM in sustainable farming system activities might be more successful.

2.6. Improving plant growth, productivity and fruit quality

Numerous researchers claimed that there is a connection between rootstocks and scions that causes the root system to be more vigorous and to absorb more water and minerals, which increases production and improves fruit quality **[86, 87, 88]**. Moreover, others suggested that vegetables grafting boost endogenous hormone production and increase crop output when plants are grown in diseased soils **[30, 89, 90, 91, 92].** Comparing grafted plants on Cucurbita rootstocks to non-grafted plants, **[93]** found that the average weight of the melon fruit on non-grafted plants was substantially lower. They also added that, TSS varied among graft combinations without consistent trends. It was carried out an experiment on five watermelon cultivars, as non-grafted plants or grafted onto different rootstocks. They found in most cases, the yields of grafted plants were on par with or even higher than those of non-grafted plants. Grafting had a minor impact on sugar content. Fruit from grafted plants had lycopene concentration that was on par with or somewhat higher than that of fruit from non-grafted plants. Fruit from grafted plants had noticeably more firmness than fruit from non-grafted plants. It was stated that grafting watermelon, onto rootstocks increased fruit size, led to higher yields compared to control, and the fruits from the grafted plants had a thicker rind and a somewhat lower TSS content. Nonetheless, it is believed that these variations in fruit traits do not represent major quality flaws, hence watermelon grafting is regarded as favourable [**94**]. On pepper it was found that grafted pepper plants on various rootstocks were having the higher marketable yields **[95]**. The effect of cucurbit rootstocks (Giada, Shintoza, Strong-tosa and Ferro) on quality of watermelon *cv*. Aswan was investigated. Results showed that rootstock Ferro recorded the highest quality for fruits **[39].**

The impact of 3 different rootstocks ("Atlante", "Creonte", and "Terrano") on a commercial sweet pepper variety's physiological and agronomic responses was studied. It was noticed that rootstocks enhanced total and economic production in comparison to non-grafted plants **[96]**. Several published articles on grafted vegetables including different rootstocks and their effects on plant growth and productivity are listed in Table (3).

2.7. Improving the production economic efficiency

Grafting vegetable seedlings is not only in order to make more money, but the main goal is to employ it to overcome some unfavourable conditions. Where, it mentioned that, although grafted tomato seedlings are more expensive than nongrafted one but using of grafted tomato plants can be the only bath away for harvesting a good crop otherwise no yield at all. They advise to use grafted tomato plants only if there is a possibility of flooding, root-knot nematode, or soil-borne like bacterial wilt or fusarium wilt **[96]**. Also, grafting tomato plants on vigor rootstocks contributed in profitable tomato production **[97].** The possible economic benefit of growing grafted eggplant was mentioned by **[48].** The application of grafting is a valuable and environmentally acceptable alternative to the application of methyl bromide for it boosted disease protection and yield. The production of grafted tomato seedlings may appeal to business-minded farmers, entrepreneurs, or cooperatives, according to **[98, 99]** analysis. Where they can focus on growing grafted seedlings that they can sell to anyone who want to grow tomatoes outside of the growing season.

Table 3. List of some published articles on grafted vegetables to enhance growth, productivity and fruit quality.

Scion species	Rootstock species	Aim of study	The main findings of the study	References
Tomato (Big Red)	He-man and Primavera	Growth and yield	Plants grafted onto 'Heman' and 'Primavera' enhanced the yield in the greenhouse and the open-field. Grafting had no effect on fruit quality traits.	**[100]**
Tomato (Beril, Swanson and Yeni Talya)	Arnold' and 'Beaufort'	Yield and quality	Grafting tomato on Beaufort rootstock recorded highest values of fruit shape index, No. of fruits, fruit yield, pH, TSS, total sugar and lycopene and vitamin C.	**[101]**
TA209 and Zhongshu5	Goji berry	Growth, yield and fruit quality	Total soluble solids (TSS), titratable acidity (TA), ratio of TSS/TA, and vitamin C are some fruit quality indices that were improved by the grafting method (Vc).	**[102]**
Watermelon (cv. Peacock wm60)	6001 F_1, Super Shintoza F_1, Ferro F_1, bottle gourd)	Growth, yield and fruit quality	Grafting on commercial rootstocks improved fruit yield and quality (fruit weight, and TSS content) compared to grafting on local rootstock.	**[103]**
Watermelon (Zaojia 8424)	Pumpkin (*C. maxima*×*C. moschata)* cv. Qingyan Zhenmu	Growth	Plant growth, chlorophyll and carotenoid content, photosynthetic assimilation, and stomatal conductance were all increased by using pumpkin rootstock.	**[104]**
Aswan F_1, Misr1 F_1 and Star F_1	Cobalt F_1, Ferro F_1 and New Star F_1	Growth and fruit quality	Misr 1 F_1/ onto Cobalt, followed by Aswan F_1/ Cobalt F_1 recorded the highest values of fruit quality and yield.	**[105]**
Tomato (Cervo, Karina, and Timoty)	Eggplant, Gelatik, EG203 line, and Takokak	Yield and quality	Yield, shelf-life capacity, total dissolved solids, red colour intensity (a+), lycopene content, fruit hardness and water content %. Vitamin C.	**[106]**

Considering grafted plants' benefits, which include higher yield and, consequently, higher profit, to be the most practical idea for farmers **[99, 100]**. Grafting increased water-use efficiency, also demonstrated that some rootstocks can promote the vigour of the scion by avoiding soil pathogens, tolerating, low soil temperatures and/or salinity **[107]**. The graft combination *Ideal /Strong-Tosa* and *Veleta / Cobalt* achieved the highest benefit and income at 3.9, 7 or 10 dS/m of salinity compared with non-grafted plants. This is due to enhancing the yield of these combinations compared with non-grafted plants **[27, 31]**. Also, the grafting combinations for melon crop *Ideal/Strong-Tosa* and *Veleta/Cobalt* achieved the highest benefit and income at 75% and 100% ETc of irrigation water. Where these graft combinations recorded the highest yield compared to non-grafted plants *Veleta* and *Ideal*) **[31]**.

2.8. Investigation of signals, water and nutrients translocation

The first organ to face soil stress is the root. Early signals provided by rootstocks under soil stress play a critical role in activating scion stress tolerance **[108]**. Hormones and other substances make up the majority of the signals that are sent by root grafts. The most thoroughly investigated root-borne signals for enhancing stress tolerance are ABA and ROS. It has been shown that ABA sensitivity enhances grafted plant water status **[90, 109, 110]** under abiotic stress. Under Ca $(NO_3)_2$ stress, the pumpkin (*Cucurbita maxima* × *Cucurbita moschata*), which used as rootstock for cucumber scion, performed better than non-grafted plants, presumably because ABA signaling in roots **[111]**.

Meanwhile**,** water potential and chlorophyll content of tomato leaves 8 weeks after grafting onto tomato, eggplant and torvum rootstocks were differed significantly whereas the latter increased inversely to the plant water potential. Hence, water stress of grafted plants differed, depending on rootstock species **[112]**. They also added that, time for the transfer of xylem fluid and index of hydraulic resistance (IHR) of tomato shoots 8 weeks after grafting onto tomato, eggplant and torvum rootstocks were not significantly different at scion and rootstock among scion/ rootstock combination. Meanwhile there was an increase of IHR value obtained with tomato grafted onto eggplant. Root hydraulic conductance differed among rootstock, but it is questionable if it extends to the graft union. Their results show that limited transfer of xylem sap at graft union. They also added that, physiological disorder due to differential mineral absorption by rootstocks might be another cause of delayed graft-incompatibility **[112]**. Some published articles on the mechanism by which root signals improve the environmental tolerance of grafted vegetables are listed in Table (4).

3. Vegetables grafting methods

The primary grafting methods are tongue approach, single cotyledon, hole insertion, splice grafting, cleft grafting and automatic approach **[12]**.

3.1. Tongue approach/Approach grafting

Tongue approach is a method that permits the scion continues on its own root until the graft heals. This technique is applied by small nurseries which have less experienced and not have a greenhouse with a good microclimate control system. This technique, which results in a greater survival (success) rate for Cucurbitaceae crops, but it, is not appropriate for rootstocks with hollow hypocotyls.

Table 4. List of some published articles on the mechanism by which root signals improve the environmental tolerance of grafted vegetables.

Scion species	Rootstock species	Stress treatments	Tested traits	References
Lycopersicon esculentum Mill.	Potato *(Solanum tuberosum L)*	No stress	Gibberellin, auxin, ABA.	**[113]**
watermelon (cv. Aswan)	*Giada, Shintoza, Strong toza, Ferro and Pumpkin,*	deficit irrigation	proline content and antioxidant enzymes: superoxide dismutase (SOD) and catalase (CAT)	**[84]**
Jinchun No. 2 (*Cucumis sativus*)	*Cucurbita moschata*	Saline stress (75 mM NaCl)	Photosynthetic rate, ABA, and ABA biosynthesis-related genes	**[90]**
Gacela' (*Capsicum annuum*)	Creonte, Atlante, and Terrano (commercial rootstocks)	35 mM NaCl	Plant growth and fruit yield, gas exchange, and hormones (IAA, ZA, GA, SA, JA, ABA, ACC)	**[114]**
Adige' (*Capsicum annuum*)	NIBER®' (*Capsicum annuum* x *Capsicum annuum)*	Saline stress (75 mM NaCl)	Na+ and K+ concentrations; gas exchange; ABA, NR, and proline content; H_2O_2	**[110]**

Some nurseries also choose this method for grafting tomato, particularly when the healing and acclimatization circumstances in greenhouses are not optimal for tube grafting. This method makes use of larger seedlings for tomato "14 to 21 days", cucumber "10 to 13 days", and pumpkin "7 to 10 days". Next, the stems of the scion and rootstock are both cut so that they tongue into one another (Figure, 1), and then fixed with the larger clips.

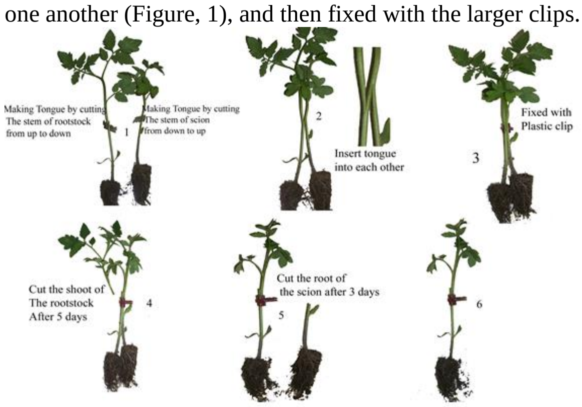

Figure (1). Diagram of the technique used for tongue approach grafting of tomato plants [118].

3.2. A modulated tongue grafting method

The grafting stage was started with at the first true leaf stage of both scion and rootstock. The true leaf of rootstock was carefully removed and making hole in rootstock between cotyledons (cleft method). Tongue of scion was made by cutting the stem of scion from down to up (tongue approach method) as described in (Fig., 2) then, the tongue of scion was inserted into the hole of rootstock, and the graft is secured with a larger clip.

Figure (2). Diagram of the technique used for modified tongue approach grafting of cantaloupe plants [26, 27].

3.3. Cleft grafting method

Five to seven days prior to the scion's seeds, the rootstock's seeds are sowed. When the plants have four to five leaves, cut the stems of the rootstock and the shoot at an angle, leaving two to three leaves on each stem (see Figure 3 below). The stem of the (scion) is then inserted with a tapered end into a cleft that has been made in the end of the rootstock. A plastic clip is then used to secure the graft. The cleft grafting technique is straight forward and suitable for rootstocks with big hypocotyls. Cleft grafting had been used in solanaceous crops like tomato, pepper and eggplant.

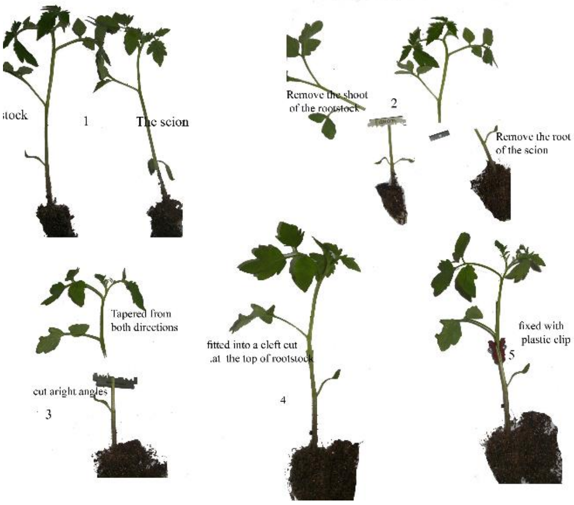

Figure (3). Diagram of the technique used for cleft grafting of tomato plants [118].

3.4. Hole insertion /Top insertion grafting method

This is the most common technique for cucurbits with hollow hypocotyls in the rootstock. The scion should be planted 3-8 days after the rootstock in order to get them to have similar diameters. Make a hole on the rootstock after removing the true leaf. By slant cutting, the hypocotyl section of the scion is made to have a thin end for simple insertion (Figure, 4). About 1500 or more grafts can be produced by a single person per day, which is very economical for small farmers. About 95% relative humidity and 21-36°C optimum temperature from healing to transplanting can assure a high rate of success. Due to the smaller seedling size of watermelons than its rootstock (usually Squash or Bottle gourd), this method is favored in many areas **[55]**. This is often used in China because it produces a stronger union and vascular connection than tongue grafting does.

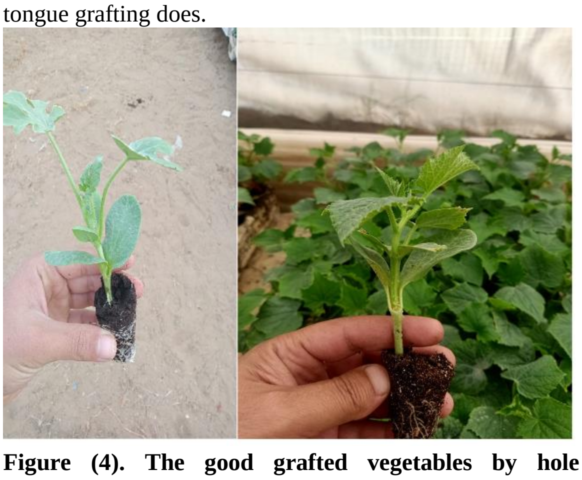

Figure (4). The good grafted vegetables by hole insertion/top insertion of grafting methods (All photos were taken by Authors).

3.5. One cotyledon/Slant/Splice grafting

Splice grafting is a process that professional nurseries and seasoned growers are well familiar with. It can be applied to most vegetables and can be carried out manually, mechanically, or by a robot. To achieve equal hypocotyl diameter and properly keep the scion on the rootstock, rootstock should be seeded 7-10 days prior to scion sowing. One cotyledon splice grafting, also known as slant grafting, is a type of grafting that involves making slant cuts on the scion and rootstock while maintaining only one cotyledon leaf on the cucurbit rootstock (Figure, 5). Grafted plants need to be kept for three days in the dark at 25°C and 100% humidity for graft union to be successful. Photo in Figure (6) is testifying success of one cotyledon method for watermelon crop.

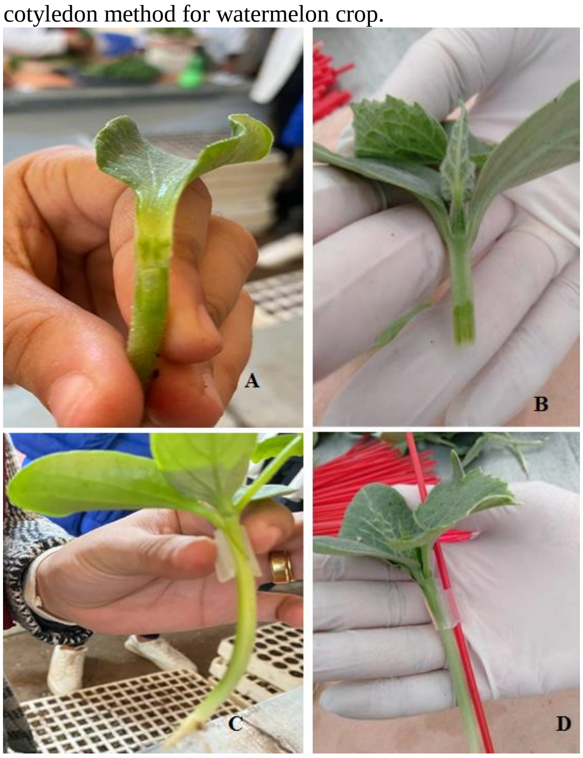

Figure (5). Diagram of the technique used for one cotyledon/slant/splice grafting (1).

Figure (6). The good grafted vegetable by one cotyledon/slant/splice grafting methods (Photo was taken by Authors).

3.6. Tube grafting method

Tube grafting is common among Japanese seedling growers because of plants can be accommodated in healing chambers or acclimation rooms. Small plants require tubes with a smaller interior diameter and must be grafted at an early growth stage. The rootstock is first slanted chopped. The scion is cut in a similar manner. Onto the cut end of the rootstock are positioned elastic tubes with a side slit. The cut surfaces of the scions and rootstock are then joined by inserting the scions' cut ends into the tube. Tomatoes are more typical of it (Figure, 7).

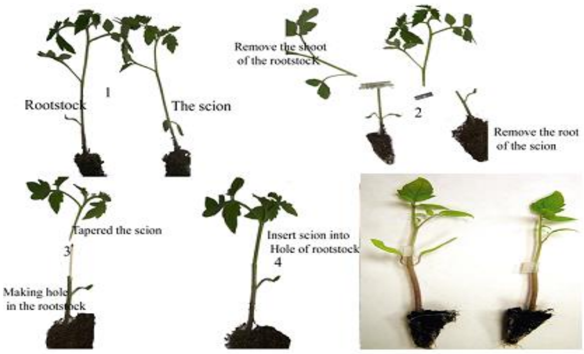

Figure (7). Diagram of the technique used for tube grafting of tomato plants [115

3.7. Pin grafting method

It is the same as the splice or slant grafting. To hold the grafted position, grafting clips are replaced with specifically crafted pins (Figure, 8). The shape of the ceramic pin is hexagonal cross-section with nearly about 15 mm long and 0.5 mm width. Natural ceramic is used to make this pin to be left on the plant without any problem. As the price of the ceramic pin is relatively high, bamboo pins with rectangular cross-sectional shape could successfully replace it at a much lower price. It could be used in watermelon and other solanaceous crops **[55]**.

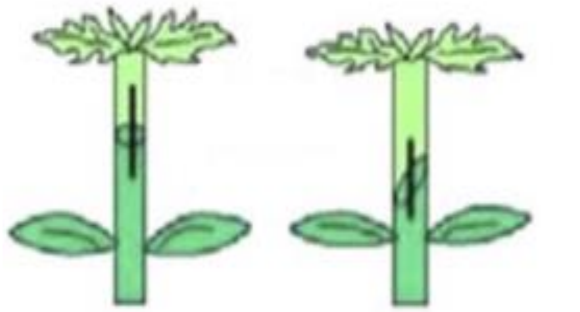

Figure (8). Photo cleared the pin method of grafting methods [55].

4. Post-graft healing environment

To prevent the grafted plants from wilting, grafting should be done in an area that is shaded and protected from the wind. For grafted plants to survive, the healing and acclimation processes are crucial. The tunnel is covered with silver/white cheesecloth (outside) and translucent film to give shade and preserve interior humidity (inside) (Figure, 9). Healing chambers are made of plastic tunnels. Using healing rooms, grafting success rates of 95% can be achieved on a commercial scale **[116]**. When the grafted plants are healing, keep them out of direct sunlight. It is advised to keep light levels during acclimation between 3 and 5 klx. Before grafting, the plants should not be watered to prevent spindly growth, expose the scion and rootstock to sunlight for two to three days, and check that the stems of the scions and rootstock are of a similar diameter. When grafting, it's crucial to maximize the area of the cut surfaces that are spliced together and to press the spliced cut surfaces together in order to improve the likelihood that the vascular bundles of the scion and rootstock will come into contact. You shouldn't let the sliced surfaces dry out. Maintaining the grafted plants at a healing temperature of around 30°C and a relative humidity of more than 95% for three days after grafting increases the survival rate. The relative humidity is then gradually decreased as the light intensity is raised (Figure, 10). It's crucial to maintain a steady air temperature in the tunnel during the healing and acclimatization processes in order to sustain high humidity. If wilting is seen, water can be sprayed onto the leaves of grafted plants to assist them live. According to the daily weather, the shading materials and films should be modified, providing additional shade on sunny days. Finally, it's crucial to keep the graft union above the soil line when you put the grafted plants in the growing field.

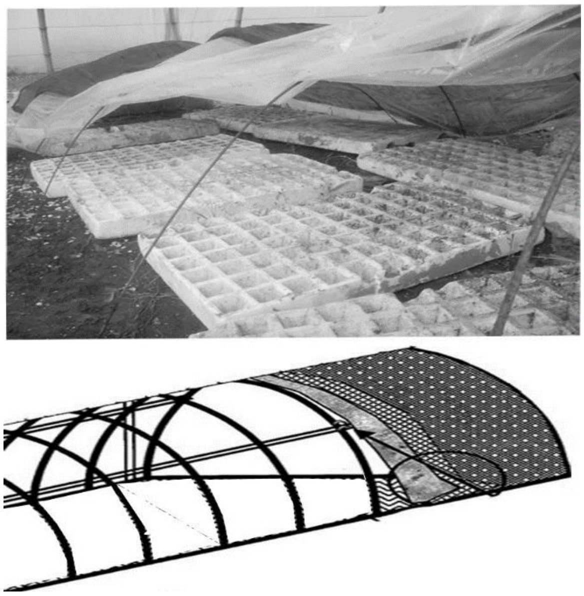

Figure (9). Drawing of grafting chamber [26, 27]

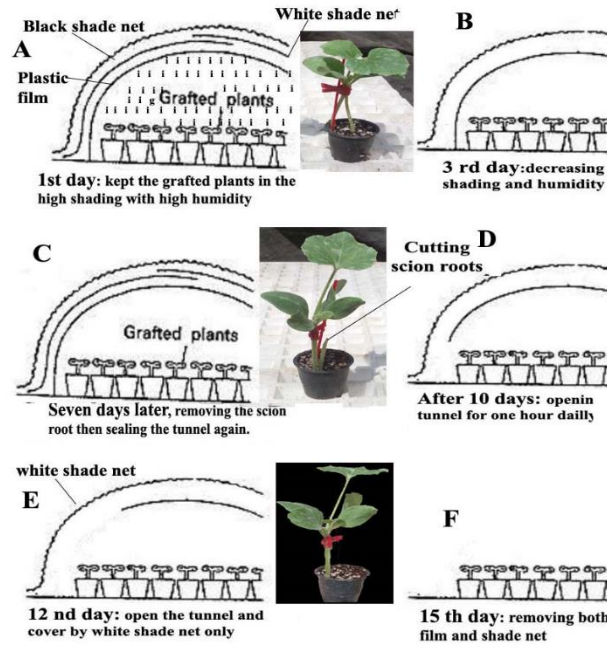

Figure (10). Drawing of acclimatization and hardening processes [26, 27].

5. Obstacles to vegetable grafting

The following are a number of issues with the manufacture and administration of grafted transplants:

- This method requires specially trained individuals and is labor-intensive.
- Timing management is necessary for the sowing of rootstock and scion seeds.
- Need a regulated setting for graft healing.
- Under field conditions, rootstock-scion incompatibility might be seen early on or following transplantation.
- Grafting can raise the danger of disease transmission, particularly when it comes to seed-borne infections in nurseries.
- Heat stress is common problem for grafting workers, especially in the months of April through June, and September **[117].**

6. Plant breeding and vegetable grafting

Plant breeding overwhelmingly targeted enhancing crop production and disease resistance, providing resilience to mechanical injury, and increasing the yield and improving quality traits. Developing a variety with a high yield may take a longer time and may also need to sacrifice a quality that was also desirable after productivity. For example, volatile aroma components seemed to be intervened by ethylene-dependent biosynthetic pathways, is also linked to shelf-life performance **[118]**. Therefore, shelf-life breeding could provoke adverse pleiotropic effects on desirable sensory traits. Undesirable effects may complicate breeding efforts during selection of desirable traits. Grafting may offer suitable technique for selecting scion and rootstock traits independently that provided the compatibility of the graft combination. The yield can also be increased by choosing vigorous marketable rootstocks and their use under safe agriculture **[119]**. Moreover, the use of wild genetic resources for developing root traits tolerance to stress independently to scion characteristics has facilitated the use of grafting for the cultivation of different fruit vegetables belonging to the *Solanaceae* and *Cucurbitaceae* families under marginal conditions of salinity, nutrient stress, water stress, organic pollutants, and alkalinity **[120]**. When also using the luffa (*Luffa cylindrica* Roem. cv. *Xiangfei*) as rootstock for cucumber (*Cucumis sativus* L. cv. Jinyan), the graft resulted in higher shoot growth and instantaneous water use efficiency **[121]**. Furthermore, delayed leaf wilting was observed under water deficit conditions. Thus, developing new variety of vegetables with desirable traits can be more comfortable by grafting compatible rootstock and scion. Trait stacking can be done by an independent breeding program for rootstock and scion. Scientists have used reverse genetics to understand root to shoot signaling by grafting genetically distinct rootstock and scion.

7. Recent innovations of vegetable grafting

Grafting has beneficial contributions to crop production. In large commercial nurseries, grafting demands high labor to quickly generate thousands of grafting seedlings. Although cultural practices and control of the environment in the greenhouse can be carried out automatically, the actual grafting has been done manually. A skilled person can graft 150 seedlings per hour, but the number of seedlings depends on grafting method. Recently, some more effective sophisticated technology for commercial grafting has been created, including grafting robots **[122, 123]**. In manual grafting technique, a person can graft 1000 grafts in a day, where a simple grafting machine can graft 350-600 seedlings/hour with two operators. There are various semi and fully automated grafting robots are available in the market and the first commercial model of a grafting robot became available for cucurbits in 1993 **[124]**. The robots are run by computer programs that can sort and select uniform graft seedlings. A fully automated grafting robot can perform 750 grafts/hour with a success rate of 90-93% **[55]**. Recently in India, robotic grafting is practiced in polyhouse bell pepper, which is fully automated **[125]**. Another recently advanced technique named *in vitro* micro grafting provides rapid propagation of virus-free plants. Micro explants (< 1/1000th mm^3) from meristematic tissues are used in this method. In herbaceous plants, micro grafting is mostly used to value the physiology of grafting and estimate the biochemical basis of the cell to cell contacts. But this method is costly. Nowadays, methodology of double grafting is also developed for vegetables. The best performance for growth and yield when the tomato scion (BARI tomato 11) grafted on potato rootstock (Cardinal and Asterix) was reported **[126].**

8. Problems allied to vegetable grafting

Grafting in fruit vegetables is carried out in many countries where in organic farming the land use is very intensive. But an array of problems is associated with grafting and in grafted seedlings production. The most important issues are the methods required for grafting and labor. The grafted plant costs more because of high cost of rootstock and labor needed for grafting seedlings, and intensive care in raising the grafted seedlings. All species of vegetables are not competent to be grafted because of the influence of genetic background, stage of growth, and physiological condition of the plant **[127, 128]**. Graft incompatibility, failure of union of scion and rootstock, graft to continue growth, premature death creates problems due to blocking of transport of nutrient elements from rootstock to scion, and photosynthates from scion to rootstock. After graft handling, quick healing of seedlings is also an important problem for two weeks. Scion-rootstock interaction affects the flowering period, plant growth, and fruit quality. So, rootstock must be selected carefully as they have no or minimum additional, undesirable effects on the scion.

9. Vegetable grafting's present state

East Asia is the famous region or vegetable grafting because of its increased production of grafted cucurbits. About 40, 99 and 94% of watermelons grown in China, Korea and Japan, respectively, are grafted plants. Also, about 60-65% of tomatoes, eggplants, and 10-14% of peppers are generated using grafted plants **[129]**. Vegetable grafting is currently becoming more popular worldwide, especially in Eastern Europe. More than 1500 industrial nurseries in China produce grafted plants. The worldwide trade in grafted vegetable transplants is expanding quickly because Canada exports grafted transplants to Mexico **[129]**. Egypt has more than 20 nurseries to produce grafted vegetable seedlings (Figure, 11), such as the Grafting House, Sekem, Nabta, etc. in different governorates.

Figure (11). The final product of an Egyptian nursery (https://www.facebook.com/photo/?fbid=583474310459559&set=pb.100063909853494.-2207520000.)

10. Future prospects of vegetable grafting

1. Define the information about the rootstocks and the scion, as there is minus information for the used rootstocks and scion as well as their compatible and testing grafted seedlings in various environmental settings.
2. Using autonomous technology (finance), it is necessary to provide credit in order to generate grafted seedlings on a large scale in vegetable crops.
3. Using this technique, it is possible to produce grafted seedlings that are tailored to the local environment while also eradicating epidemics of pests and diseases that affect the soil inhabitants. This will lower production costs, create a serious demand for the product, and ensure that the crop is sold in the local markets in a serious state that does not harm the environment or human health.
4. This technique have good positive effects for the rootstocks used in grafting, so that it directly improves the quality of the fruits and the growth of the graft by acting on the mesocarp and exocarp cells. Fruit ripening and skin colouring are furthermore positively and satisfactorily impacted.
5. With the use of this technique, it can increase a farmer's income by increasing crop output and decreasing the expense associated with purchasing large quantities of fertilizers and products to manage pests and diseases.
6. Grafted seedlings are produced to disseminate this technology, which is environmentally benign and encourages the growth of organic foods.
7. In order to improve grafting efficiency and lower labour costs, scientists and researchers must concentrate on developing vaccine robots, particularly in developed nations.
8. Researchers in this sector ought to create a database, software, and mobile apps pertaining to the grafted vegetable crops and the resources consumed.
9. Creating a genetic bank for the rootstocks used in grafting and aiming to increase their number annually.
10. It was organized scientific technical workshops for farmers and vegetable crop producers to train them in grafting technique and how to improve their output fields.
11. This technique provides for the provision of foreign exchange to the nation and the exportation of grafted seedlings to nearby nations, but only when done so under the supervision of experts in the production and manufacture of vegetable crops, in order to prevent the cracking and forging of the grafted seedlings.
12. Enacting legislation to safeguard grafted seedling producers from traders and brokers who might enter the industry, create unfit seedlings, and manipulate market pricing through the sale of grafted seedlings.
13. To develop this tech and learn about its issues, research centers in universities and technical institutes must carry out in-depth scientific studies, relying on a database of the rootstock, species, and areas that are cultivated, whether under an adapted agricultural environment or in open fields.

11. Conclusions

Considering the assorted applications of vegetable grafting worldwide, this technique has the potency to resolve the problems of vegetable cultivation such as abiotic (salinity, drought, heat, waterlogging, heavy metal concentration) and biotic (soil-borne diseases and nematodes) stresses, it can increase a farmer's income by increasing crop output and decreasing the expense associated with purchasing large quantities of fertilizers and products to manage pests and diseases. But it takes a lot of labour to manage and produce nurseries. Scientists have to concentrate on creating and popularizing facilities, tools of grafting to improve its effectiveness and lower labour costs to overcome stress problem. Thought for researchers and nursery managers will benefit from the development of databases, software, mobile applications, and crop models connected to grafted vegetables to help them choose the best scion and rootstock cultivars. With the growth of the grafted vegetable sector in Egypt, this alternative can be used to generate foreign currency.

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