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Vegetable grafting: a century-old technique to improve organic production

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ABSTRACT

Purpose: To increase yield and quality of fruit vegetables under high pressure of soil-borne pathogens, nematode, and unfavorable environments introducing vegetable grafting in agriculture are crucial. It also helps to reduce disease susceptibility and to increase tolerance against abiotic stresses. **Findings:** Grafting in vegetables is a centuries-old practice to improve yield through organic culture. It was introduced in USA and becoming more common in organic farming of vegetables. Vegetable grafting is popular practice in many European and North American countries, Japan, Korea, and China. Vegetable crops are exposed to many abiotic and biotic stress factors, including salinity, heat, heavy metals, excess trace elements, diseases, and pests, which have a significant effect on crop growth and productivity. Grafting is effective practices in solanaceous and cucurbitaceous vegetables to control soil-borne diseases including; *Verticillium* wilt, *Fusarium* wilt, and bacterial wilt, and nematodes without using pesticides. **Limitations:** Despite of its numerous benefits, there are several difficulties associated with grafting which include added cost, graft mismatch, physiological complaints, and reductions in flower formation, quality, and yield of fruit**. Directions for future research:** Appropriate selection of scion and rootstock, scion–rootstock communication, and the reciprocal effect of the shoot and root system should be considered to get maximum benefits from this novel technique. New research should be conducted to evaluate and test diverse germplasm as a source of the viable rootstock, development of grafting tools ideal for the stable, year-round, and cost-effective yield.

INTRODUCTION

Vegetable grafting was first developed in Europe and other countries in the early 20th century but in late 20th century the improved grafting were practices for commercial seedlings production. The grafting technique was introduced later from Europe to North America. Grafting methods for fruit vegetables is an attractive technique for greenhouse and organic farmers. To overcome issues of biotic and abiotic stresses, grafting is a unique horticultural technology of herbaceous seedlings practiced for many years in East Asia. Self-grafting by increasing root to shoot ratio to produce greater fruit size in watermelon was reported first in the 5th century in a book in China and the 17th century in Korea. The first record of inter-specific grafting in watermelon [*Citrullus lanatus* (Thunb.) Matsum & Nakai] using a squash rootstock (*Cucurbita moschata* Duch.) was develop by a watermelon farmer in Japan to increase yield and control pests and diseases. Watermelon was grafted on *Lagenaria siceraria* (Mol.) Standl for production of grafted seedlings in commercial vegetable production in Japan in the 1930s (Oda, 2002). Grafting of was started in the late 1920s in cucumber (*Cucumis sativus* L.) but no success was achieved until 1960s (Sakata et al., 2008). First grafting was practiced in eggplant (*Solanum melongena* L.), a member of Solanaceae on scarlet eggplant (*Solanum integrifolium* Poir.) in the 1950s (Oda, 1999) and it was introduced commercially in tomato (*Lycopersicon esculentum* Mill.) in the 1960s (Lee & Oda, 2003). The practice of grafting had increased by 59% in Japan and 81% in Korea in Solanaceous (eggplant, tomato) and Cucurbitaceous (cucumber, melon) crops, respectively (Lee, 1994). Grafted vegetables are getting popularity on a commercial scale in different countries of the world, and most of the greenhouse in China, Japan, Korea, Turkey, Israel, Spain, Netherland, and the USA. The demand and production of grafted vegetables plant has begun to expand to North America, and continue to increase across Asia and Europe (Kubota et al., 2008). Grafting is performed intensively and successfully in watermelon around the world (Bekhradi et al., 2011). A survey conducted on hydroponic tomato cultivation showed that the total number of 40 million grafted seedlings were used in North American greenhouse (Kubota et al., 2008). In Japan, grafted vegetable seedlings use was exceeded 90% for watermelon, and cucumber, 79% for eggplant and 58% for tomato (NARO, 2011). A survey on 16 Italian nurseries showed that 10 million grafted plants were produced in 1991, and was increased to more than 60 million plants in 2011 (Leonardi, 2016). Nowadays, vegetable grafting is used to enhance the tolerance against abiotic stresses by using desired rootstocks. It also induces vigor, precocity, better yield, quality and survival rate, and reduce infection by soil-borne pathogens (Gaion et al., 2018). Grafting cucurbits, tomato, eggplant, and pepper onto vigorous and disease-resistant rootstocks has gained much fame around the globe to ensure adequate yields to feed over increasing population of the globe (Röös et al., 2017).

Purpose of vegetable grafting

Grafting is an important alternative to fight against biotic-abiotic stresses and organic farming of vegetables. It produces a novel plant by joining two plants with dissimilar genetic background, one provides shoot (scion), and the other provides root system (rootstock). Vegetable grafting has been practiced for decades, and its commercial utilization is increasing day by day around the globe. The primary purpose of grafting in fruit vegetable is to increase the yield and quality under high density of soil-borne pathogens, nematodes, and unfavorable environments (Çürük et al., 2009). Grafting can help to reduce pesticide use, enhances yield and production efficiency, and improve economic viability in sustainable vegetable production through organic agriculture (Lee et al., 2010). To minimize yield loss, grafting may be effectively utilizing to manage soil borne fungal, bacterial, viral diseases, and nematodes. Grafting can also be used as a tool for breeding to generate novel genetic combinations (e.g., pomato). Grafted plants can provide increased yield through enhanced resistance to biotic and abiotic stresses. About 106% yield increases were observed in watermelon by grafting with particular rootstock in Australia (Yetisir & Sari, 2003).

Grafting increased rapidly in the cultivation of fruit vegetables in many countries to control soil-borne pathogens (*Fusarium* wilt, *Verticillium* wilt, *Ralstonia* wilt, *Phytophthora*, *Pyrenochaeta*, *Phomopsis* rot, *Monosporascus*) and root-knot nematodes (Collonier et al., 2001). It also used to enhance plant vigor, to extend the harvesting period, to increase yield and fruit quality, to prolong postharvest life, to increase nutrient uptake, to allow tolerance to be low and high temperatures, to cope with salinity and heavy-metal stress, and to increase tolerance to drought and waterlogging.

Pre-requisites for Vegetable Grafting

Selecting the right rootstock/scion

Specific root traits can be exploited by grafting from natural genetic variation to influence the marketable aerial part. Scion morphology can be influenced by grafting, and manage more biotic stresses i.e., air-borne and soil-borne pathogens, and abiotic stresses such as extreme temperatures, drought, waterlogging, and soil acidity or alkalinity by selecting a suitable rootstock (Lee et al., 2010). Suitable rootstocks can be defined as those with resistance to biotic and abiotic stresses, good compatibility, encourage a good growth of the scion, and increase production without reducing the quality. These rootstocks can be either to the same or a related genus, or F_1 of related species. Suitability of the rootstocks depends on the growing season, the cultivation method (open field or green house), the climatic condition and soil of the region, and the crop varieties. The desired scion and rootstock would be chosen at 2-true leaf stage. The diameter of stem must be identical for both scion and rootstock.

Grafting compatibility

Plants that are lacking vascular cambium, like monocots, can't generally be grafted as grafting involves the joining of vascular tissues between the scion and rootstock. The mortality rate can be minimized in the later stages of growth if growers can select compatible rootstock and scion. Vascular bundles are formed by rapid callus formation between scion and rootstock. Grafting resulted as successful when there is an entire joining of the vascular system of the scion and the rootstocks with permitting the regular transmission of nutrients and water from the rootstocks to the scion and the transmission of growth substances and photosynthetic materials from the scion to the rootstock. Generally, the more genetically closer two plants are, the more likely the graft union will form. Identical clones, intra-species, or sometimes interspecific plants have a high success rate for grafting. Due to high compatibility watermelon exhibits better grafting with related rootstocks, for example, squash and interspecific hybrids for the vigorous root system, *Fusarium* resistance, and extreme temperature (Lee et al., 2010; Ling et al., 2013; Mohamed et al., 2014; Yassin & Hussen, 2015). Watermelon, squash, interspecific hybrids, pumpkin, bottle gourd, or *C. melo* rootstocks has been successfully use for grafting melon as the same species (King et al., 2010; Lee et al., 2010). In the case of plants in the same family but different genera, grafting has a low success rate. Grafting between dissimilar families is rare.

Grafting aid

Standard tools and accessories used for grafting include grafting knives, tying and wrapping materials, grafting clips, and grafting waxes. The knives have either a folding or a fixed blade. The fixed-blade type is more potent, and it is most desirable to protect the cutting edge. Grafting knives are available for both right and left-handed people. The ordinary grafting clips are generally made out of plastic with a round spring. It has been most widely used for cucurbits and other crops in tongue grafting. Depending upon manufacturer, the clips with different sizes and shapes are cheap, easy to operate, and handle for different stem sizes, and can be used in many times. Another time-tested tying material is waxed string or twine that adheres to itself and the plant parts without tying. It should be strong enough to hold the grafted positions together. Sometimes aluminum foil is alternative means of keeping the grafted complements in place.

Screening house

Screening house is necessary to grow seedlings before grafting. Rootstock seedlings are raised in pots with a diameter of 6 cm and seedlings of scion in flatbeds. The nursery is made up of a 60-mesh nylon net to prevent the vectors of different diseases. A silver shading net is also recommended to be used for covering the screen house. To protect seedlings from UV rays, the upper half of the screening chamber is protected with a UV resistant double-layer polythene sheet. About two to three degrees of temperature can be decreased in the summer season with this type of shading.

Healing of graft

Healing is the most essential part as it decides whether the grafting will be successful or not. It’s most critical to deliver advantageous conditions to enhance callus development in grafted seedlings. A chamber with 28-29°C temperature, 95% RH, and low light intensity (3–5 Klux) with 1-2 days darkness is required for healing the union of scion and rootstock. The healing chamber should have the facility to provide darkness for 1-2 days. This controlled environment helps the development of better graft combination by decreasing transpiration. Relative humidity and high temperature can rise rates of respiration and transpiration that result in wilting of the scion. It takes 5-7days to promote callus formation at the union (Wilson et al., 2012).

Acclimatization of grafted plants

Acclimatization may be accomplished simply by covering the scion and rootstock in a black plastic bag that checks heat formed during the union. Gardeners typically use plastic film coverings to achieve acclimatization. This is mainly used to prevent leaf burning and wilting of the just healed seedlings during hardening. The light intensity can be manipulated by different degrees of shading. Usually, hardening takes 7-10 days for acclimatization. Several hardening compartments have been established and extensively used in Korea and Japan.

Methods of vegetable grafting

Cleft grafting

In several countries, cleft grafting had been used in cucurbits for a while, but the use is usually confined to solanaceous crops like tomato, brinjals these days. The seeds for the rootstock are sown 5-7 days earlier than the scion. The seedlings are selected for rootstock at 4-5 leaf stage with a 1- to 4-inch diameter and are cut at right angles of 2 to 3-inch-deep, having 2-3 leaves remaining on the stem. The scion must comprise 2 to 3 buds and have a diameter of one-quarter inch. The scion having two angled cuts on either side of its bottom end, fits inside the vertical cut on the rootstock. Grafting wax or clip is used over the rootstock's top to seal the cuts and stabilizes the graft. The cleft grafting is easy and simple technique and appropriate for rootstocks with wide hypocotyls.

Tongue approach/Approach grafting

This method is most widely used by farmers and small nurseries but is usually favored by less experienced farmers and those who do not have a greenhouse with a good microclimate control system. Though this method requires more space and labor than other methods, it can be attained even by beginners due to the high seedling survival rate. It is commonly used on members of the cucurbitaceous vegetables but not suitable for rootstocks with hollow hypocotyls (Table 1). The rootstock and scion need to be grown at least three days interval to gain the same size of a diameter that should be optimally less than 1 inch. The shoot apex of the rootstock is removed so that the shoot growth can be stopped. The hypocotyl of the scion and rootstock are cut so that each piece is cut at a matching 45-degree angle. A second, vertical cut creates notches or tabs, so that scion fits against the rootstock by interlocking together. The hypocotyl of the scion is left to heal for 3-4 days that results in the scion off of its roots and then partially cut below the graft. Finally, wrapping the graft with grafting tape holds the pieces in place while they grow together.

Table 1. Grafting methods and rootstocks used in vegetable crops†

Scion Plant	Rootstock	Method
Eggplant	*Solanum torvum*	Tongue and Cleft
	Solanum sissymbrifolium	Cleft method
	Solanum khasianum	Tongue and Cleft
	Solanum integrifolium	Tongue and Cleft
Tomato	*Lycopersicon pimpinellifolium*	Cleft
	Lycopersicon hirsutum	Cleft
	Lycopersicon esculentum	Cleft
	Solanum nigrum	Tongue and Cleft
Cucumber	*Cucurbita ficifolia*	Tongue Approach
	C. maxima × *C. moschata*	Tongue Approach
	Cucumissativus	Tongue Approach
	Sicyos angulatus	Tongue Approach
	Cucurbita moschata	Hole insertion and Tongue
	Cucurbita maxima	Tongue
Water melon	*Benincasa hispida*	Hole insertion and Cleft
	Cucurbita moschata	Hole insertion and Cleft
	Cucumis melo	Cleft
	C. moschata × *C. maxima*	Hole insertion
	Lagenari asiceraria	Splice Grafting
	Sicyos angulatus	Tongue Approach
Melon	*Cucumis melo*	Tongue and Cleft
Bitter gourd	*Cucurbita moschata*	Hole insertion and Tongue
	Lagenari asiceraria	Hole insertion
Bottle gourd	*Cucurbita moschata*, Luffa sp.	Hole insertion and Tongue

† (Modified from Ashok & Sanket, 2017; Lee, 1994).

Hole insertion/Top insertion grafting

This is the most popular method in cucurbits scion and rootstock that have hollow hypocotyls. To achieve a similar diameter of both scion and rootstock, scion should be sown 3-8 days after the sowing of the rootstock. This gap varied according to the different types of rootstocks used (Lee et al., 2010). The true leaf, including the growing point should be removed, and a hole is made using a bamboo or plastic gimlet at a slant angle to the longitudinal direction on the rootstock. The hypocotyl portion of the scion is prepared by slant cutting to have a narrow end for easy insertion. 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), hole insertion hypocotyl grafting is favoured by many farmers in many areas (Lee et al., 2010). As it results in a strong union and vascular connection compared with the tongue grafting approach, this is very common in China.

One cotyledon/Slant/Splice grafting

Splice grafting is very familiar among experienced growers and commercial nurseries. It can be done by hand, machine, or robot and can be applied to most vegetables. Rootstock should be sown 7–10 days before scion sowing to ensure uniform diameter of hypocotyls and hold the scion on rootstock correctly. According to the growers and farmers' preference, intact or excised i.e., root-removed rootstock seedlings may be used. Grafting can be done by making slant cuts on both rootstock and scion by retaining only one cotyledon leaf on the cucurbit rootstock (Table 1) so that it is also called one cotyledon splice grafting (OC-SG). For solanaceous crops, grafting is usually made at lower epicotyl and fixed with ordinary clips. For successful graft union, grafted plants should be maintained in the dark at 25°C and 100% humidity for three days.

Tube grafting

Tube grafting is similar to slant grafting except that in this method, rootstock and scion joined are held with an elastic tube instead of clips (Kubota et al., 2008). Prepare rootstock with 45 angles under cotyledons and the scion with matching cut in the same angle at about 5-10 mm below the cotyledons. One tube should be placed about halfway down on top of the cut end of rootstock hypocotyl. Insert the scion into the grafting tube, so that the cut surface set perfectly with that of the rootstock. The tube may be used several times, depending on the materials. About seven days is required for healing. It is more common in tomato, brinjal (Table 1).

Pin grafting

It is the same as the splice or slant grafting. To hold the grafted position, specially designed pins are used instead of grafting clips. 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 (Lee et al., 2010).

Grafting root stock

Though the early purpose of grafting was to avoid or reduce soil-borne disease, the reasons and types of grafting have increased dramatically. Watermelons, other melons *(Cucumis* spp.), cucumbers, tomatoes, and eggplants are commonly grafted to the various rootstock, especially for cultivation in greenhouses or plastic houses (Morra, 2004). Numerous rootstock also has been developed for the various cucurbitaceous and solanaceous crop. For example, watermelons are commonly grafted to the gourd or interspecific hybrids. Cucumbers are most frequently grafted to fig leaf gourd or interspecific hybrids (Sakata et al., 2008). However, now many rootstocks having distinctive characteristics are available. Growers select the rootstock depending on their growing season, cultivation methods (field or greenhouses), soil environments, and the type of crops and cultivars (Table 2).

Grafting improve abiotic stresses

Vegetable crops are also exposed to many factors of abiotic stress, including salt, heat, soil alkalinity, heavy metals, and excess trace elements, which have a significant effect on crop growth and productivity (Colla et al., 2013). In adverse environmental changes, it is worthy to be graft vegetables on to rootstocks for mitigating the impacts of external stress on the shoot and a way to avoid or reduce production losses (Schwarz et al., 2010). Grafting is a mutual integrative method that can be impaired by both scion and rootstock for the resistance of grafted plants to adverse environments (Colla et al., 2010). Grafted plants raised under unfavorable soil chemical circumstances also displayed higher growth and production, higher photosynthesis, improved environmental and nutritional quality, and the lower concentration of Na and/or Cl, heavy metals, and a significant number of trace essential elements in shoots than un-grafted or self-grafted plants (Siamak & Paolo, 2019).

Grafting improve biotic stresses

For economic success in vegetable cultivation, healthy and well-established seedlings are required. These healthy seedlings boost the yield of vegetables but reduce the cost of production by preventing plant death and spreading diseases to new areas (Ventura et al., 2019). However, owing to the lack of enough cultivable land, vegetables such as cucurbit and solanaceous crops are often grown on disease contaminated soil and environmental conditions due to their high demand and market price (Schwarz et al., 2010). Vegetable seedlings are affected by diseases and exhibit arrested growth and significant damage in yield and fruit quality. The most effective approach to the prevention of vegetable diseases of resistant cultivars (Ventura et al., 2019). For many vegetables, resistance sources have not yet been detected, although in some cases the resistance is reduced or lost with the introductions of new pathogen or strain or races. In that scenario, one way to minimize the production losses incurred by soil-borne diseases in vegetables would be to graft them onto rootstocks that can limit or prevent the negative impact of external biotic stress on the plant (Colla et al., 2013). Grafting approaches have been shown to protect vegetable crops against wide-ranging soil-borne diseases in various environments and conditions by employing resistant rootstocks (Rivard and Louws, 2011). In many countries, grafting has been effectively utilized in the fight against *Verticillium* wilt, *Fusarium* wilt, corky root rot and bacterial wilt diseases.

In the production of many solanaceous and cucurbitaceous vegetables, grafting technique has developed into a unique component for the up-gradation of pest control and crop productivity strategies. The available supply of disease-resistant rootstocks and the generation of greatly effective grafting technology have contributed to a growth in the usage of grafted seedlings globally (Table 3, Jabnoun-Khiareddine et al., 2019). Studies also offered an improved knowledge of grafting-conferred protections from innate resistance to mediate systemic resistance within rootstocks (Guan et al., 2012).

Table 2. Selected scion and rootstock combinations for vegetable grafting†

Scion	Rootstock
Watermelon (*Citrullus vulgaris* syn. *C. lanatus*)	Bottle gourd (*Lagenaria siceraria*) White gourd (*Benincasa hispida*) *Cucurbita* spp.
Melon (*Cucumis melo*)	White gourd (*Benincasa hispida* Cogn.) *Cucumis* spp.; *Curcurbita* spp. *C. moschata x C. maima*
Cucumber (*Cucumis sativus* L.)	Pumpkin (*Cucurbita* spp.) *Cucurbita ficifolia* Cucurbita interspecific hybrids, bottle gourd, wax gourd, fig leaf gourd (*C. ficifolia* Bouché), and luffa *C. moschataxC. maima*
Aubergine (*Solanum melongena* L.)	*Solanum integrifolium;* *Solanum torvum; Solanum melongena*
Tomato (*Lycopersicon esculentum*)	Tomato hybrids Interspecific tomato hybrids (*S. lycopersicon* × *S. habrochaites* Eggplant
Eggplant (*Solanum melongena* L.)	*S. integrifolium* Tomato hybrids *Solanum torvum* *S. torvum x S. sysimbriifolium*
Sweet pepper *(Capsicum annuum* L.)	*Capsicum annuum,* AR-96023 (*Capsicum annuum*) AF-2638 & AF-2640

† (Passam, 2003; Morra, 2004; Oka et al., 2004; Santos & Goto, 2004; Sakata et al., 2008).

Advantages of vegetable grafting

Vegetable grafting to induce resistance to fungal pathogens and oomycetes

Vegetable grafting has been effectively practiced to prevent soil-borne *Fusarium* and *Verticillium* wilt diseases in vegetable crops (Table 3, Louws et al., 2010). Most of the cultivated rootstocks of cucurbits are not hosts to diverse formae speciales of *F. oxysporum*. Hence, in the cultivation of cucurbits, grafting was successfully employed to manage fusarium wilt disease (Louws et al., 2010). Watermelon (*Citrullus lanatus*) had been grafted onto bottle gourd (*Lagenaria siceraria*) to avoid *Fusarium* wilt in Japan in the 1920s for the first time. Then, the grafting approach has been spread to many other countries around the globe. Approximately 90% of the cultivated vegetable fields in Japan and Korea use grafted watermelon (Lee et al., 2010). It has typically been grafted onto pumpkin (*Cucurbita pepo*), squash (*Cucurbita moschata*), bottle gourd, and interspecific hybrid squash (*C. maxima* × *C. moschata*) and exhibits strong compatibility with linked rootstocks (Gaion, et al., 2018). Of these, squash and interspecific hybrid squash have been generally known for their better root formation and resistance against *Fusarium* wilt (Keinath & Hassell, 2014). The rootstock ‘Shintoza’ or ‘Super Shintoza’, an interspecific hybrid squash, gave resistance to *Fusarium* wilt in watermelon when planted in contaminated soils; the rootstocks improved size of fruits and yield compared to non-grafted plants (Álvarez-Hernández et al., 2015).

Table 3. Plant pathogens reported to be controlled by vegetable grafting

Plant pathogen	Crops	Disease	References
Fusarium oxysporum	Tomato, pepper, watermelon, melon, cucumber	Fusarium wilt	Álvarez-Hernández et al., 2015
F. oxysporum; F. solani	Tomato, pepper, watermelon	Fusarium crown and root rot	Vitale et al., 2014
Verticillium dahliae	Tomato, eggplant, watermelon, melon, cucumber	Verticillium wilt	Miles et al., 2014
Monosporascus cannonballus	Watermelon, melon	Monosporascus sudden wilt	Park et al., 2013
Phytophthora capsici	Tomato, pepper, watermelon, Cucumber	Phytophthora blight	Jang et al., 2012
Pyrenochaeta lycopersici	Tomato, eggplant, pepper	Corky root	Al-Chaabi et al., 2009
Corynespora cassiicola	Cucumber	Target leaf spot	Hasama et al., 1993
Phomopsis sclerotioides	Cucumber, melon	Black root rot	Shishido, 2014
Didymella bryoniae	Melon	Gummy stem blight	Keinath, 2013
Sclerotium rolfsii	Tomato	Southern blight	Rivard et al., 2010
Colletotrichum coccodes	Tomato, eggplant,soybean	Brown root rot	Bachman & Nickell, 1999; Garibaldi et al.. 2008
Rhizoctonia solani	Tomato	Rhizoctonia damping off	Gilardi et al., 2010
Podosphaera xanthii	Cucumber, watermelon	Powdery mildew	Kousik et al., 2018
Pseudoperonospora cubensis	Cucumber	Downy mildew	Wehner et al., 1997
Ralstonia solanacearum	Tomato, pepper, eggplant	Bacterial wilt	Rivard et al., 2012
Meloidogyne spp.	Cucumber, melon,watermelon, tomato, eggplant, pepper	Root-knot	Thies et al., 2010; Kokalis-Burelle et al., 2011; Owusu et al., 2016
Melon necrotic spot virus	Watermelon	Melon necrotic spot	Huitrón-Ramírez et al., 2009
Tomato yellow leaf curl virus	Tomato	Tomato yellow leaf curl	Mahmoud, 2014
Tomato spotted wilt virus	Tomato	Tomato spotted wilt	Spanò et al., 2015
Pepino mosaic virus	Tomato	Pepino mosaic	Schwarz et al., 2010

Verticillium dahliae causes verticillium wilt and affects the vascular system of Solanaceae and Cucurbitaceae plants (Paplomatas et al., 2000). Plants grafted onto agricultural rootstocks and scion infected with *V. dahliae* demonstrated that both scions and rootstocks helped to develop disease resistance in melons (*Cucumis melo*), watermelons, cucumbers (*Cucumis sativus*), and tomatoes (*Solanum lycopersicum*) (Traka-Mavrona et al., 2000). The rootstock 'Super Shintoza' have shown resistance to *Verticillium* wilt, decreasing occurrence of *Verticillium* spp. microsclerotia (Gaion et al., 2018).

Monosporascus sudden wilt, is a significant soil-borne disease of watermelon and melon, produced by *Monosporascus cannonballus* in hot and semiarid countries (Edelstein et al., 1999). Grafting of vulnerable melon varieties onto *C. maxima* and interspecific hybrids of squash rootstocks strengthened melon tolerance to *M. cannonballus* (Cohen et al., 2005). Nevertheless, the enhanced tolerance, along with the improved yield of grafted vegetables was found not be consistent. The variable results could be due to dissimilarities in combinations of rootstock and scion and surrounding environments. *Phytophthora capsici* causes Phytophthora blight and is considered as one of the most damaging diseases in cucurbit production. 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, *C. moschata*, and wax gourd (*Benincasa hispida*) rootstocks (Nnemati & Banihashemi, 2015). Watermelons scions grafted onto rootstocks of the *Lagenaria siceraria* also showed tolerance to *P. capsici* (Kousik & Thies, 2010). Grafted tomatoes and eggplants (*S. melongena*) had a reduced incidence of corky root disease, better yields, and large-sized fruits when grafted onto rootstocks of 'Beaufort' (*S. lycopersicum*× S. *habrochaites*) (Hasna et al., 2009).

Melon has been successfully grafted onto rootstocks derived from watermelon, bottle gourd, pumpkin, squash; interspecific hybrids; *C. melo*, cucumber and wax gourd, and offered resistance to soil-borne diseases produced by *Monosporascus cannonballus*, *F. oxysporum*, and *Stagonosporopsis* spp. (King et al., 2010, Lee et al., 2010, Zhou et al., 2014). Wilts, produced primarily by Fom, and root and stem rot, produced by *M. cannonballus*, *Macrophomina phaseolina*, and *Stagonosporopsis* spp are the key antagonists to generate rootstock (King et al., 2010). Multiple different races of Fom have been made challenging to develop melon cultivars with complete Fom resistant (Dhall, 2015). Farmers can use rootstocks that may contribute increased growth and development in Fom-infested regions, as rootstocks that are tolerant of all races have been detected (Oumouloud et al., 2010). The cucurbits are almost tolerant to *Fusarium* wilt disease and which may utilize as rootstocks for melon. For instance, interspecific hybrid rootstocks (SYTZ and NZ1) have been proven to be tolerant to diverse races of Fom, and rootstock usage has improved yield compared to non-grafted melon cv. Liyu (Zhou et al., 2014).

Cucumber has usually been grafted onto Fig leaf Gourd (*C. ficifolia*), squash, interspecific hybrid squash, and pumpkin provide tolerance to *Fusarium* wilt (Dhall, 2015). 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. (Polizzi et al., 2015).

In general, eggplants have been grafted to wild species such as *S. integrifolium* or hybrid tomato rootstocks. The prior is then used for resistance to soil borne disease *Fusarium* wilt, while rootstocks of hybrid tomatoes are more common among farmers who employ them for grafting tomato (King et al., 2010). There are several informations on loss of resistance or damaging impacts of grafting on traditional rootstocks (Kawaguchi et al., 2008), which led to the need for alternative rootstocks, such as interspecific hybrids, and more closely linked to wild species (King et al., 2010). Wild species rootstock, including *S. torvum* or *S. sisymbriifolium* for eggplant grafting, has demonstrated potential since it showed strong resistance to *Fusarium* or *Verticillium* wilt. The eggplant cv. Tsakoniki grafted onto the rootstocks of *S. torvum* or *S. sisymbriifolium* cultivated in infested or non-infested soil had improved harvest and resistance to *Verticillium* wilt (Bletsos et al., 2003). Due to increased vigor of the grafted plants, eggplant varieties grafted on 'Beaufort' F_1 showed boosted yield and fruit production (Kacjan Maršić et al., 2014). In the grafted eggplant cv. Epic, 'Beaufort' F_1 rootstock also provides resistance to the *Verticillium* wilt (Johnson et al., 2014; Miles et al., 2015). Fungal infections such as black root rot on cucumber and melon, target leaf on cucumber, gummy stem blight on melon, a southern blight on tomato, brown root rot on tomato and eggplant, and *Rhizoctonia* damping-off on tomatoes have been controlled by grafting (Louws et al., 2010). Grafting was also documented to increase crop resistance to foliar diseases such as downey and powdery mildew on cucurbits, while employed with definite rootstocks (Louws et al., 2010).

Vegetable grafting to induce resistance to bacteria

Bacterial wilt produced by *Ralstonia solanacearum*, is a destructive disease of tomato. Resistance in tomatoes against this wilt disease is a quantitative phenomenon and is stringently linked to the size of the fruits (Louws et al., 2010). There are few commercially stable wilt-resistant cultivars of tomatoes (King et al., 2010). Susceptible tomato cultivars (e.g. BHN 602 *tomato* line) were grown successfully onto resistant rootstocks to prevent bacterial wilt in tomato (Table 3, Rivard et al. 2012). Instead of protecting xylem tissues from bacterial infections, the resistance in grafted plants enhanced could be due to minimal colonization in the lower stem (Nakaho et al., 2000). The eggplant was grafted on a rootstock of wild scarlet eggplant (*S. integrifolium*) to combat soil-borne bacterial wilt disease (King et al., 2010). Wild relatives e.g., *S. torvum* or *S. sisymbriifolium*, has exhibited a higher degree resistance to bacterial wilt (Gousset et al., 2005).

Vegetable grafting to induce résistance to nematode

A typical symptom of root-knot nematode (RKN, *Meloidogyne spp*.) infection in susceptible plant is root galling, resulting in low uptake of nutrients and water (Table 1). In *Cucumis metuliferus*, *Cucumis ficifolius*, and bur cucumber (*Sicyos angulatus*) resistance, to *M. incognita* was detected (Gu et al., 2006). Grafting of *C. metuliferus* as rootstock has been used with RKN susceptible melon cultivars in reducing root gall number and nematode infection (Sigüenza et al., 2005). Additionally, *C. metuliferus* has shown strong graft compatibility with many melon cultivars (Nisini et al., 2002). The bur cucumber exhibited improved resistance to RKN when grafted as the rootstock with cucumbers (Zhang et al., 2006). 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 (Thies et al., 2010).

The Mi gene was incorporated onto rootstock cultivars and cultivated tomatoes, which enabling successful management of RKN in tomatoes (Louws et al., 2010). RKN-resistant rootstocks grafting with susceptible tomato cultivars was successful due to the reduced RKN infestation in field soils (Rivard et al., 2010). However, temperature sensitivity of the Mi gene resistance to RKN may not be consistently stable (Cortada et al., 2009). The pepper genotypes (*Capsicum annuum)* having N gene have been useful as rootstocks to control RKNs in pepper, which controls resistance to RKNs (*M. incognita*, *M. arenaria*, and *M. javanica*) (Oka et al., 2004).

The grafted melon seedlings offer resistance to root-knot nematodes (Zhou et al., 2014). Wax gourd and squash has shown induce resistance to nematodes (*Meloidogyne incognita* and *M. javanica*) and used as rootstocks, (Galatti et al., 2013). Wild species, such as *S. torvum* and *S. sisymbriifolium*, have shown high level of resistance to RKN and provide potential as a rootstock for eggplant.

Interspecific hybrid rootstocks *S. melongena* × *S. incanum* and *S. melongena* × *S. aethiopicum*, which have good compatibility, high plant vigor, increased yield, and moderate tolerance to root-knot nematodes can be grafted onto the eggplant without adverse effects on fruit quality (Gisbert et al., 2011). Successful grafting may be a possible future tool for controlling disease, mainly caused by root-knot nematode in sweet pepper on rootstocks of *Capsicum annuum* (Oka et al., 2004). The cv. Celica, grafted onto accession 'AR-96023' (*C. annuum*) grown in infested soils achieved significantly better than non-grafted plants, which is resistant to RKNs (*M. incognita* and *M. javanica*) (Oka et al., 2004).

Vegetable grafting to induce resistance to the virus

Investigation on tolerant to viral diseases by vegetable grafting has produced inconsistent results due to a lack of comprehensive works in this field (Table 3). Wang et al. (2002) demonstrated enhanced performance of grafted plants of antivirus feature in the seedless watermelon. In Israel, the use of resistant rootstocks in cucurbits showed a significant advantage over soil fumigation with methyl bromide that does not prevent viral disease to control a soil-borne virus, melon necrotic spot virus in cucurbits (Cohen et al., 2007). In the meantime, it has also been reported that grafting can manage tomato yellow leaf curl virus, tomato spotted wilt virus, and the pepino mosaic virus (Louws et al., 2010). Several reports, however, indicated that grafted plants were much more prone to diseases produced by viruses, possibly due to graft incongruity that negatively affected the scion (Davis et al., 2008).

Vegetable grafting strengthens the integrated pest management (IPM) programs

Grafting is an efficient method in integrated management of soil-borne pest and pathogens, even 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 (Louws et al., 2010). The role of IPM in sustainable farming system activities could be more effective by incorporating grafting resistance to pathogens, pests and weeds to withstand biotic pressure along with detailed information on the pathogen or pest biology, variability, and population dynamism.

Root grafts play a significant role in the survival of the outbreak of crippling diseases

Phylogenetic closeness ensures effective grafting and long-term viability of grafted vegetable seedlings (Goldschmidt et al., 2014). Grafting of vegetables on resistant rootstocks is a vital tool in managing soil-borne diseases. The epigenetic modulation of DNA-methylation patterns interprets for these grafting-transformation phenomena (Goldschmidt et al., 2014). Root graft is a common natural concept; both intra-specific and intra-specific root grafts have been documented for disease resistance. Root grafts play an evolutionary function to avoid devastating diseases attack.

Grafting causes the switching of the microbial population of the Rhizosphere

Microorganisms of the rhizosphere may play a vital role in controlling soil-borne pathogens through several processes, for example, nutrient antagonism, antipathy, and parasitism (Raaijmakers et al., 2009). Analyzing rhizosphere microbial complexity linked to genotype and species of plant is also another avenue to recognize the occurrence and extent of soil-borne disease (Liu et al., 2019). A study of cucumber grafted onto *C. moschata* demonstrated that grafting enhanced the bacterial and actinomycetes population while lowering the overall counts of fungi in the rhizosphere (Guan et al., 2012). Research has also shown that actinomycete communities in the rhizosphere were significantly high in resistant rootstocks and grafted plants of peppers. The occurrence of verticillium wilt was significantly decreased when an eggplant scion prone to wilt was grafted onto the rootstock of *Solanum torvum*, together with increased ratios of bacteria and actinomycetes to fungi in the grafted plant rhizosphere (Yin et al., 2009). Actinomycetes are a community of soil-borne microorganisms of considerable ability to defend plants from pathogens (Bhatti et al., 2017). While the degree to which actinomycetes contribute to the control of plant disease remains ambiguous, relatively high communities of actinomycetes identified in the rhizosphere of grafted plants could potentially play a significant role in suppression of disease when specific resistant rootstocks are grafted with vulnerable scions (Guan et al. 2012).

Microbial populations in the rhizosphere are widely spread and affected by a variety of reasons, including plant organisms, soil-types, environmental factors, and management activities. Even though microbial alterations in the rhizospheres of grafted plants were noticed in several research and persist an exciting research area, very little understood how these changes contribute to the rootstock's inherent resistance and what procedures cause significant such shifts (Poudel et al., 2019). Several grafting experiments tried to compare grafted plants with self-rooted scion plants as a positive control without the inclusion of non-grafted rootstock plants. For better comprehend the impact of grafting on the microbial diversity of the rhizosphere, ungrafted rootstock plants, as well as ungrafted and self-grafted scion, should also be assessed as control (Poudel et al., 2019). Beside, durable grafting researches with various rootstocks resistant to disease, soil environments, and management techniques are necessary in order to describe the impact of grafting on soil microbial communities as connected to soil-borne disease management.

Plant breeding and vegetable improvement

Plant breeding overwhelmingly targeted improving harvest and disease resistance, providing resilience to mechanical injury, and increasing total postharvest performance, 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 (Pech et al., 2008). Therefore, shelf-life breeding could provoke adverse pleiotropic effects on desirable sensory traits (Causse et al., 2002). Undesirable effects may complicates 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 (Colla et al., 2011). Moreover, the use of wild genetic resources for developing root physiological 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 (Schwarz et al., 2010; Borgognone et al., 2013). For example, in recent studies it is described that when luffa (*Luffa cylindrica* Roem. cv. *Xiangfei*) rootstock grafted with its own scion or with cucumber (*Cucumis sativus* L. cv. *Jinyan*), the graft resulted in higher shoot growth and instantaneous water use efficiency (Liu et al., 2016). 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.

Recent innovations of vegetable grafting

Grafting has beneficial contributions to crop production. In large commercial nurseries, grafting demands high labor to produce thousands of grafting seedlings in a short time. 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 1200 seedlings per day (150 seedlings per hour), but the number of seedlings depends on grafting method. The mechanized grafting can meet high demand to satisfy need as well as reducing production costs. Some more efficient advanced technology such grafting robots has been developed recently for commercial grafting (Comba et al., 2016; Kubota et al., 2017). Grafting machines are also available in the market that can graft Solanaceous plants with high rate of success. 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 (Kobayashi, 2005). 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% (Lee et al., 2010). Recently in India, robotic grafting is practiced in polyhouse bell pepper, which is fully automated (Sarswat & Kumar, 2019). 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. Arefin et al. (2019) reported the best performance for growth and yield when the tomato scion (BARI tomato 11) grafted on potato rootstock (Cardinal and Asterix).

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 (Goldschmidt, 2014; Fan et al., 2015). 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.

Future prospects of vegetable grafting

Production of vegetables, especially tomato, sometimes reduced dramatically due to the infestation of some soil-borne diseases which impact rural livelihoods. Bacterial wilt (*Ralstonia solanacearum*) one of the biggest problems that affects tomato plant in the tropics and cause 100% yield loss. It has also happened in the case of the production of eggplant, several cucurbits. Grafting of susceptible cultivar on wild rootstock is a proven technology to reduce the risk of yield loss by soil-borne diseases and nematodes. To evaluate and find out the compatible rootstocks, a systematic location specific research is required. Grafting can also overcome sexual incompatibility between two different species as it is an easy and rapid vegetative propagation technique. Another important use of this technique is to overcome yield losses due to abiotic stresses (salinity, drought, waterlogging, etc.). The essential requirement for the continued success of grafting is the identification of compatible disease resistant rootstocks with tolerance to biotic and abiotic stresses. Healthy grafted seedlings at a reasonable price are also the critical point for broader use. Nursery production and management of grafted plants are labor-intensive. It can create job opportunities for unemployed people. Many processes involve ranging from the preparation of bed soil to planting for the production of grafted nursery plants. Low cost methods of grafting should be adopted by farmers for sustainable production of grafted seedlings. Grafting skill and healing environment need to be improved for its commercial application. More awareness about the techniques and benefits of grafted vegetables among the farmers are need to be created. Grafting fruit vegetables can give useful contributions to agricultural production. Vegetable grafting has turned into more and a more popular technique in organic agriculture due to the various potentialities that it offers.

CONCLUSION

By 2050, agricultural productivity needs to be increased by 60% to manage food for the estimated world population of 10-11 billion. It can be accomplished by sustainable use of natural resources. But vegetable production is increasingly affected by abiotic (salinity, drought, heat, waterlogging, heavy metal concentration) and biotic (soil-borne diseases and nematodes) stresses. Future research should contribute towards improve grafting technologies and nursery management practices to ensure high-quality grafted transplants for growers of organic farms. Like many other applications in advancing sustainable crop production, grafting can be used as a tool in both breeding and research.

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