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# Vegetable grafting: A sustainable and eco-friendly strategy for soil-borne pest and disease management

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## Abstract

Vegetable production around the world is more and more hampered by the unfavourable soil and environmental conditions as well as biotic ones as soil-borne pests and diseases. Among all management tactics, vegetable grafting is considered as eco-friendly for sustainable vegetable production as a result of the resistant rootstock reduces the dependency upon agrochemicals needed treating the soil-borne diseases and has opened a new vista in organic farming of vegetables. The production and cultivation of grafted solanaceous and cucurbitaceous plants are ever-increasing across Asia, Europe, and North America because of its ability to provide tolerance to biotic stress and abiotic stresses. These grafted seedlings provide resistance against biotic/abiotic stresses and also increase the yield of the cultivars. At present grafting is regarded as a rapid alternative tool to the relatively slow breeding methodology and helpful in sustainable farming that takes low input for future agriculture system. This tactic has rapidly expanded due to intensification of production practices, reliance on susceptible cultivars to satisfy specific market demands, a global movement and local invasion of novel pathogens, accrued use of organic practices, the fast adoption of high tunnel production systems, use of appropriate technologies for resource-limited farmers and the ban on methyl bromide via Montreal Protocol (Sakata *et al.* 2007). Further, inventions in mechanised and robotic grafting have given a positive stimulus to this novel eco-friendly approach. Mechanisation can significantly reduce the cost of grafted seedling production in the future. Because of the high post graft mortality of seedlings, this technology is still in infancy in India. For its commercial application in India, sharpening of grafting skills and healing environment need to be standardised.

**Keywords:** grafting, eco-friendly, defence mechanism, soil-borne diseases

## Introduction

Vegetables are considered as a very important component within the diversification of horticulture to supply food and nutritional security for the growing population (Tirupathamma *et al.* 2019) [60] and there are several factors limiting vegetable production *i.e.* biotic (pest and disease incidence) and abiotic factors (environmental and soil stresses) in India. Development of new varieties or hybrids and standardization of crop management practices have helped to surmount these constraints. Among these, grafting, with selected resistant rootstocks, for the aim of controlling diseases and pests is an ancient practice widely employed in cultivating a variety of fruits and nuts. A number of the well-known examples include controlling citrus tristeza, fire blight and collar rot on apples, and nematodes on peaches and walnuts (Mudge *et al.* 2009) [43]. However, vegetable grafting is gaining momentum in recent years among vegetable growers worldwide (Ashok Kumar and Kumar Sanket 2017) [1].

Soil-borne pathogens can be defined as pathogens that cause plant diseases via inoculums that come to the plant by means of soil. The most familiar diseases caused by soil-borne pathogens are most likely rots that affect below ground tissues including seed decay, damping off of seedlings, root and crown rots and vascular wilts initiated through root infection. Soil-borne plant pathogens are *Rhizoctonia* spp., *Fusarium* spp., *Verticillium* spp., *Sclerotinia* spp., *Pythium* spp., *Phytophthora* spp., *Ralstonia solanacearum* and root knot nematode. Soil-borne diseases are considered a serious limitation to crop production and about 68 % of the yield losses in vegetables are reported under continuous cropping. Several diseases caused by the soil-borne pathogens are difficult to predict, detect and diagnose. Additionally, the soil environment is extremely complex, creating it a challenge to know all the aspects of the diseases caused by soil-borne pathogens. They usually survive for long periods in host plant debris, soil organic matter, free-living organisms or resistant structures like microsclerotia, sclerotia, chlamydospore, oospores or nematode cysts or as mycelium, bacterial ooze in the infected plant debris. These pathogens are particularly challenging because they usually survive in soil for several years and each vegetable crop may be susceptible to several species

(Yadav 2020) [63]. A significant crop loss caused by soil-borne diseases aggravated by successive cropping was avoided by the production of vegetables with grafted seedlings. In several fruit-bearing vegetables like watermelon, cucumber, melon, tomato, eggplant and pepper, the utilisation of grafted seedling has become increasingly popular. Grafting is an environment-friendly approach that is employed to manage soil-borne diseases and thereby to increase the yield of susceptible cultivars (Lee and Oda 2003) [37]. This method is eco-friendly for sustainable vegetable production by using resistant rootstock; it reduces dependence on agrochemicals (Rivard and Louws 2008) [51] to mitigate the soil-borne problems. Additionally, grafting provides advantages to manage abiotic stress, to reduce reliance on chemical and fertiliser inputs, and to boost fruit quality (Colla *et al.* 2010, Proietti *et al.* 2008 & Rouphael *et al.* 2008) [13, 48, 14].

The first attempt in vegetable grafting was performed in Japan and Korea in the late 1920s with watermelon (*Citrullus lanatus*) grafted onto pumpkin (*Cucurbita moschata*) rootstock to confer resistance to *Fusarium* wilt in water melon production (Lee 1994) [36]. Soon after, watermelons (*Citrullus lanatus*) were grafted onto bottle gourd (*Lagenaria siceraria*) rootstocks for combating *Fusarium* wilt. Eggplant (*Solanum melongena*) was grafted onto scarlet eggplant (*Solanum integrifolium* Poir.) in the 1950s for managing Bacterial wilt. Since, then the cultivated area of grafted vegetables, as well as different types of vegetables being grafted, has consistently increased. Recently most of the watermelons, musk melons, (*Cucumis melo*) cucumber (*Cucumis sativus* L.), tomato and brinjal in Korea and Japan are grafted before being transplanted to the main field or green houses. In Japan (92%), Korea (98%) and China20%), major share in watermelon production is from grafted seedlings. In Europe, Spain is leading in grafted seedlings production with 129 million grafted seedlings followed by Italy (47 million grafted seedlings) and France (28million grafted seedlings). Grafting as a technology for the commercial production of vegetables was lateron adopted by many countries in Europe, Middle East, Northern Africa, Central America and other parts of Asia (Kubota *et al.* 2008) [35].

In India, grafting work has been initiated in IIHR Bangalore by Dr RM Bhatt and his Associates onthe identification of rootstocks for waterlogged conditions. NBPGR regional station, Thrissur, Kerala have done work on Cucurbit grafting to increase its production by taking *Momordica cochinchinensis*, a dioecious plant and success was 98%. CSKHPKV, Palampur started work on grafting and identified more than22 rootstocks of brinjal, chilli, tomato and cucurbits for imparting resistance to bacterial wilt and nematodes. The Department of Vegetable Crops, Horticultural College and Research Institute, TNAU, Coimbatore, Tamil Nadu initiated research on vegetable grafting in brinjal to mitigate root-knot nematode (*Meloidogyne* spp.) and dry root rot (*Macrophomina phaseolina*) incidence during 2008. The technology was standardised and released during the year 2016. Currently, the department is producing grafted brinjal plants and supplying to the farmers on request basis @ 7 Rs per graft. Some private players are also involved in grafting. One amongst them is 'VNR Seed Private Limited' in Chhattisgarh which is supplying grafted brinjal, tomato, cucumber, muskmelon and watermelon seedlings resistant to bacterial wilt to farmers. The other seed companies are Namdhari Seeds Pvt. Ltd., Bangalore, Jarvi Seeds Pvt. Ltd., Bharuch, Gujarat, and 'Takii Seed India Private Limited (Pugalendhi *et al.* 2019) [47].

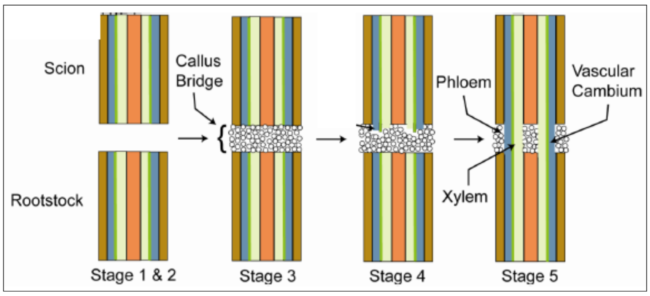
Recently, with emphasis on multi tactic approaches to manage soil-borne pathogens vegetable grafting has emerged as a very important integrated pest management to manage soil-borne diseases of vegetable crops. Among vegetable crops, grafting is commonly and economically practiced in solanaceous and cucurbitaceous vegetables *viz.*, Tomato (*Solanum lycopersicum* L.), Eggplant (*S. melongena* L.), Sweet pepper, Watermelon [*Citrullus lanatus* (Thunb.) Matsum. And Nakai], Melon (*Cucumis melo* L.), Bitter gourd (*Momordica charantia*), and Cucumber (*C. sativus* L.). In this review, the information on purpose, prospects and methods of grafting, defense mechanisms in disease resistance of grafted vegetables and soil-borne pest and disease management in the vegetable crops were described hereunder.

## What is Grafting?

Grafting is a method of asexual propagation where two living plant parts (the rootstock and scion) are united together so that vascular continuity is established between them and the resulting genetically composite organism functions as a single plant (Mudge *et al.* 2009) [43].

## The principle stages to graft union formation are

1. Lining up the vascular cambium.
2. A wound response.
3. Callus bridge formation.
4. Xylem and phloem differentiation into a new vascular cambium.
5. Secondary xylem and phloem development across the graft.



## Basic prerequisites of grafting

a. Root stocks: Select the plants that have desirable underground traits such a as vigorous root system, resistance against soil-borne diseases and enhanced nutrient uptake.
b. Scions: Select the plants that have desirable aboveground traits such as enhanced yield, fruit size, fruit quality and other horticultural traits.
c. Their Compatibility: Compatibility generally means the establishment of a successful callous formation between scion and root stock and rebuilding of vascular bundles i.e. cambium formation between the graft union as well as extended survival and proper functioning of the composite, grafted plant.
d. Grafting Aids; i. Grafting secateurs, ii. Grafting knives, iii. Grafting blades, iv. Grafting pins, v. Grafting waxes, vi. Grafting clips, vii. Grafting tubes etc.
e. Screen house: Used for growing seedlings prior to grafting. They are usually constructed with 60-mesh nylon net with double doors. The upper half should be covered with a separate UV resistant polyethylene to prevent UV light penetration.
f. Healing chamber/Grafting chamber: Used for establishment of successful graft union that minimises

water stress by reducing transpiration, maintains a temperature of 25- 30 ºC, high relative humidity of 95% and low light intensity of 3-5 lux. In this chamber, grafts should be kept for 5-7 days

g. Acclimatisation chamber: It is used for hardening the grafted seedling prior to transplanting and to prevent leaf burning and wilting of the just healed seedlings. A grafted seedling takes 7 to 10 days for acclimatisation as hardening treatment.

## Grafting methods in Vegetables

a. **Cleft grafting/Wedge grafting:** The rootstock (at the four to five-leaf stage) stem are cut horizontally with 2-3 leaves remaining on it and 0.5 cm long vertical incision is created into the middle of the rootstock. The scion stem is cut into a 0.5 cm long wedge with 2-3 leaves remaining on the stem and is inserted into the vertical incision in the rootstock and the joint is secured by the help of grafting clips. Tomato plants are primarily grafted by conventional cleft grafting.

b. **Tongue approach grafting/ side grafting (TAG):** The matching 45° incisions are made in scion and rootstock stems, approximately ¾ through the stem, to form “tongues”. The stem tongues are joined along in order that the cut surfaces are in contact. Parafilm is wrapped tightly around the graft union to prevent moisture loss. After five days, the rootstock top and the scion roots are cut off from the grafted plant such that the two are completely separated within 3 days.

c. **Tube grafting/ japanese grafting (TG):** This method makes possible to graft small plants grown in plug trays two or three times quicker than the conventional method and also suitable when rootstock and scion are of same size. Cut rootstock beneath cotyledons in a 45° or sharper angle. Prepare the scion with matching hypocotyl width cut in the same angle at about 5- 10 mm below the cotyledons. Place one tube a halfway down on top of the cut end of rootstock hypocotyl. Insert the scion into the grafting tube in order that cut surface aligns perfectly with that of rootstock.

d. **Hole insertion grafting (HIG):** When scion and rootstock have hollow hypocotyls, this methodology is preferred. A hole in the rootstock is created for insertion of the scion. The scion is then inserted in the hole in the rootstock and the joint is secured by the help of grafting clips.

e. **Slant grafting/ one cotyledon grafting:** Recently, it has been adopted by commercial seedling nurseries because it is applicable to most vegetable crops and mainly developed for robotic grafting. Grafting can be done by creating slant cuts on both rootstock and scion by retaining only one cotyledon leaf on the rootstock.

f. **Pin grafting:** It is same as the slant grafting. In this method, instead of grafting clips, specially designed pins are used to hold the grafted position. The size of the ceramic pin is nearly about 15 mm long and 0.5 mm in diagonal width of the hexagonal cross-section. The pins are made from natural ceramic; therefore, it can be left on the plant without any problem. The price of the ceramic pin is fairly high so that alternative to it is being needed. Experimental results revealed that bamboo pins, rectangular in cross-sectional shape, could successfully replace the expensive ceramic pins at a much lower price.

## Defence mechanisms in disease resistance of grafted vegetables

a. **Inherent resistance within Rootstocks as the first line of defence:** Because grafting is used mainly for combating soil-borne diseases, the defence mechanisms are usually associated with inherent resistance within rootstocks (King *et al*.., 2008) [33]. Rootstock selection and breeding has targeted both non-host and host resistance.

**Using non-host resistance:** Non-host disease resistance refers to the resistance provided by all members of a plant species against all races of a certain pathogen and itis often considered the most common and durable disease resistance (Mysore and Ryu, 2004) [44].

**Breeding host-resistant rootstocks:** Host resistance can be generally classified into two categories: vertical resistance (resistance is governed by single genes) and horizontal resistance (resistance is controlled by multiple genes). Oftentimes, the horizontal resistance can be accidentally lost by continuous selection for horticultural characteristics. Several cucurbitaceous and solanaceous rootstocks are selected from wild germplasm, and therefore theyare more likely to maintain non-differential/horizontal resistance to a wide range of pathogens.

b. **Shift of rhizosphere microbial diversity as a result of Grafting:** Rhizosphere microorganisms can play essential roles in suppressing soil-borne diseases through a variety of mechanisms like nutrient competition, antagonism, and parasitism. Exploring rhizosphere microbial diversity associated with plant species and genotypes, therefore, is another approach to understanding soil-borne disease incidence and severity (Broeckling *et al.* 2008, Garbeva *et al.* 2004 and Yao and Wu 2010) [7, 21, 64].

c. **Contributions of Vigorous Root Systems of Grafted vegetables to plant defence:** Soil-borne pathogens typically infect and damage plant roots, and, as a result, plant nutrient and water uptake can be affected. Thus, root system size and vigour are related to resistance to soil-borne diseases. Additionally, to specific disease resistance, they are characterised by large and vigorous root systems (Davis *et al.* 2008 and Lee 1994) [17, 36]. Several rootstocks developed for vegetable grafting were selected or bred from wild genotypes.

d. **Grafting-induced Systemic Defense:** A diverse range of defence responses are activated by plant-pathogen recognition. These responses is an accumulation of reactive oxygen species (ROS), expression of pathogenesis related genes, phytoalexins, production of antimicrobial compounds, synthesis of nitric oxide and hypersensitive responses (Buchanan *et al.* 2000) [8].

## Success stories of Grafting as an effective approach to manage various soil-borne diseases in vegetables

### 1. *Verticillium* wilt

Grafting has been frequently used to manage *Verticillium* wilt (VW) in tomato and eggplant and less frequently in cucurbit production. *V. dahliae* is the primary pathogen of concern, although there are reports of *V. alboatrum*. These two distinct taxa differ in several ways: *V. dahliae* produces microsclerotia able to persist in soils or plant debris for up to 14 years and is active above 30 ºC whereas *V. alboatrum* does not produce microsclerotia, produces melanised hyphae that able to persist in soils or debris for 2–5 years, and is not active above 30 ◦C (Klosterman *et al.* 2009) [34]. *V. dahliae* poses serious problems on a wide diversity of vegetable crops because of its biology and ecology.

Resistance to VW in tomato is conferred by the Ve locus that comprised of two open reading frames (Ve1 and Ve2) and widely introgressed into commercial tomato cultivars. Host resistance enabled the partitioning of the *V. dahliae* population into race 1 strains, controlled by the Ve locus, and all other strains (so-called race 2) able to overcome this specific resistance. In several cases, race 2 strains were indigenous in soils before the Ve locus was deployed. Resistance is not known or has been tough to introgress in other fruiting vegetables and resistance to race 2 in tomato is presently unknown. Although tomato rootstocks are effective (Liu *et al.* 2009 & Lockwood *et al.* 1970) [39, 40] to manage VW, the majority of reports used interspecific hybrids of *Solanum* [ISHs; *S. lycopersicum*× *Solanum* sp.; *Solanum lycopersicum*× *S. habrochaites*; syn. *Lycopersiciesculentum*× *L. hirsutum*] as rootstocks; also named as KNVF - K for corky root rot, N for root knot nematodes (RKN), V for Verticillium, and F for FOL resistance (Gindrat *et al.* 1976, Ginoux and Dauple 1982 & Ioannou 2001) [24, 25]. Eggplant grafted to the ISHs 'Brigeor F1' minimised the incidence of wilt to 20% compared to 96% in non-grafted controls and decreased the severity of VW from a rating of 2.4 to 0.3 using a 1–3 scale (Ioannou2001). *Solanum torvum* (Turkey berry) is often used as rootstock for eggplants and accounts for over 50% of the total acreage of grafted eggplants in Japan (Oda 1995) [45]. *S. torvum* rootstocks in Italy offered management of RKN however succumbed to VW after repeated cropping cycles (Garibaldi *et al.* 2005) [22]. In follow up work, eggplant grafted onto *S. torvum* had a wilt incidence of 20% compared to 97% wilt in non-grafted plants. In parallel research, *S. torvum* suppressed VW permitting mild symptoms; enhanced root biomass compared to non-grafted controls, and generated yields comparable to MeBr treatments (Bletsos 2006) [6]. This rootstock additionally offered greater resistance to VW than *S. sisymbriifolium*, the latter being intermediate between *S. torvum* and non-grafted controls with comparable yield benefits (Bletsos *et al.* 2003) [6]. *S. torvum* dramatically curtailed disease incidence and enhanced yield under thedual pressure of VW and RKN (Curuk *et al.* 2009) [16]. *S. torvum* has a Ve homologue (Fei *et al.* 2004) [19] however seems to possess a broader spectrum of tolerance than ISHs selections. *S. torvum* could also be restricted through regulation in certain countries or regions where it is considered a noxious weed.

## 2. Corky Root rot of tomato and eggplant

*Pyrenochaeta lycopersici* causes corky root rot, occurs in intensive tomato and eggplant production systems, particularly in cooler soils. Major gene resistance against this pathogen is still unknown. Susceptible eggplant 'Bonica F1' grafted to the ISHs 'Brigeor F1' reduced corky root rot incidence to 0%as compared to 100% incidence in non grafted control (Ioannou 2001) [32]. 'Beaufort' has been adopted to be used by organic tomato growers in Sweden to manage this disease (Hasna *et al.* 2009) [28].

## 3. Southern stem blight in tomato and eggplant

*Sclerotium rolfsii* can cause devastating crop losses on a wide diversity of fruiting vegetables. Tolerance has been discovered in eggplant rootstocks (Black *et al.* 2003) [4] and host resistance was recently documented in tomato (Rivard *et al.* 2010) [50]. The interspecific hybrids 'Maxifort', 'Beaufort' and 'Big Power' limited southern stem blight incidence from 0 to 5% whereas up to 79% ofthe non-grafted controls wilted in organic and conventional production systems (Rivard *et al.* 2010) [50].

## 4. *Fusarium* wilt of Tomato

Three genes I, I-2 and I-3 (I for immunity) govern monogenic resistance to the *F. oxysporum* f.sp. *Lycopersici* (*FOL*) races 0, 1 and 2. These genes are rapidly introgressed into commercial cultivars and widely deployed throughout most tomato production regions. Rootstocks commonly have the I and I-2 genes, and as race-2 becomes more predominant, there will be increased want for rootstocks with I-3 resistance (Chung *et al.* 1997) [9]. Resistance is usually complete when the host and parasite interact in a gene-for gene fashion, however instead of a hypersensitive response as in other pathosystems, resistance is mediated by callose deposition, phenolic accumulation and formation of tyloses and gels in the xylem vessels (Takken and Rep 2010) [58] restricting pathogen colonisation. In ISHs selections, resistant rootstocks harbored the pathogen at a far lower frequency than the susceptible non-grafted tomato (Harrison and Burgess 1962) [27]. The emergence of *F. oxysporum* f. sp. *radicislycopersici* (*FORL*), primarily in greenhouse production systems led to the need to graft favored scion cultivars onto resistant rootstocks (Thorpe and Jarvis 1981) [59]. Subsequently, *FORL* resistance (locus Frl) has been widely introgressed into commercial cultivars and normally used interspecific hybrids.

## 5. *Fusarium* wilt of watermelon

Host resistance has been used to manage *F. oxysporum* f. sp. *niveum* (*FON*) race 0 and 1 however all cultivars are sensitive to race2 (Miguel *et al.* 2004) [42]. *FON* races are highly specialised permittingnon-host resistance as a viable mechanism to limit disease damage (Yetisir *et al.* 2007, 2003) [66]. Therefore, interspecific and intergeneric grafting or the use of interspecific hybrids is often used for watermelon. Bottle gourd is the main rootstock used for watermelon in Japan, depending on the region of production (Sakata *et al.* 2007) [54]. The ISHc 'Shintoza' is preferred in Spain because it offers resistance to all races of *FON* and provides yield stability as assessed by the coefficient of variation over 8 years, compared to non-grafted plants (Miguel *et al.* 2004) [42].

## 6. *Fusarium* wilt of melons

*F. oxysporum* f. sp. *melonis* (*FOM*) is restricted to melon and comprises4 races: 0, 1, 2 and 1.2. Race 1.2 includes variants that cause wilt and yellows (1.2w and 1.2y). Resistance has been obtainable in commercial F1 hybrids that contain the Fom-1 and Fom-2 dominant genes convening resistance to races 0 and 2 and 0 and 1, respectively, however complete resistance to race 1.2 has not been identified in *Cucumismelo*. The emergence of this race has driven the necessity for grafting in several regions of the world (Crino*et al.*2007, Herman and Perl-Treves 2007, Miguel 2004, Sakata *et al.* 2008 and Trionfetti Nisini *et al.* 2000) [54, 42]. Incomplete resistance to race 1.2 has created it necessary to introduce *Cucurbita moschata* and the ISHc *C. maxima* × *C. moschata* rootstocks (Sakata *et al.* 2008) [54] that offer broad spectrum resistance, have high grafting compatibility, and increase yield counting on the environmental conditions. However, specific combinations may negatively impact fruit yield or quality and so intraspecific grafts are preferred (Cohen *et al.*2002, Sakata *et al.* 2007 and Sakata *et al.* 2008) [55, 54]. Therefore, *C. melo* rootstocks are developed with moderate resistance (Crino *et al.* 2007, Hirai *et al.* 2002 and Perche pied *et al.*2005) and close to complete resistance (Herman and Perl-Treves 2007) to 1.2y and1.2w. *Benincasa cerifera* (syn. *B. hispida*) has been used often in Europe, however more recently the ISHc rootstocks gained importance (Miguel 2004) [42].

### 7. *Monosporascus* root rot and vine decline of melons

Vine decline of melons caused by *Monosporascus cannonballus* occurs in semi-arid and hot regions of melon and watermelon production and tends toward soils that are saline and alkaline (Cohen *et al.* 2007). The pathogen can prolifically form perithecia (persists in soils for long periods of time) in root cortical tissues giving a "pepper spot" appearance. The pathogen can cause a sudden wilt as fruit mature. All melon and watermelon selections are susceptible (Davis *et al.* 2008) [17], thus grafting has been viewed as a mechanism to limit crop losses (Cohen *et al.* 2007). *C. maxima* × *C. moschata* rootstocks provided the most effective results up to now. In Israel, 'TZ 148' conferred some benefit in melon production in certain seasons and in certain geographic locations (Cohen *et al.* 2005). Also in Israel, in another series of tests, the ISHc 'Brava' reduced melon vine decline 63-100% compared to the controls however failed to reduce symptoms in other experiments, probably because of high inoculum load (Edelstein *et al.* 1999). It was speculated that the grafted rootstock permitted buildup of inoculum over production seasons and an integrated approach with fumigation and grafting generated the best control (Edelstein *et al.* 1999). Under different environmental conditions and geographic locations, the ISHc 'Shintoza' rootstock used for grafting watermelon reduced ascospore density in the soil by approximately 4% compared to the initial inoculum levels in the beginning of the season (Beltran *et al.* 2008) [2]. Ascospore density raised by 5-63% favored by non-grafted watermelon and muskmelon plants.

The restricted increase of ascospore density was associated with decreased colonisation from 67 to 81% on non-grafted plants down to 21% on the rootstock roots. Likewise, perithecia were not found on the roots of the rootstock precluding ascospore formation and soil re-infestation. Grafted plants remained asymptomatic compared to 100% symptoms for non-grafted controls by the end of the season. Grafting onto *Cucurbita* rootstocks has become a crucial component of watermelon production where *M. cannonballus* occurs in open fields in Spain under reduced rotation programs (Beltran *et al.* 2008) [2]. A wild accession of *Cucumismelo* ssp. *agrestis* 'Pat 81' was highly resistant to *M. cannonballus* and when used as an intraspecific rootstock dramatically reduced disease incidence, comparable to the ISHc 'RS 841'and resulted in higher melon fruit quality (Fita *et al.* 2007) [20]. The success of managing *M. cannonballus* seems to be subject to environmental conditions, geographic location, scion used and inoculum load as these parameters impact the host-pathogen interaction under conditions where complete resistance is not operative in contrast to other pathosystems such as FW where stability of control is mediated by specific host resistance.

### 8. Bacterial wilt of solanaceous crops

Bacterial wilt (BW) caused by *Ralstonia solanacearum* (Rs) is among the most important bacterial diseases in several tropical and sub-tropical regions and is the focus of extensive grafting efforts in solanaceous vegetable crops. Infection usually causes complete plant collapse in prone cultivars. The bacteria can persist in the soil for several years, probably in association with a wide host range of plants including weed species. Soil disinfestation may reduce inoculum levels but the bacteria rapidly re-infest disinfested soils. Populations are extremely diverse in their virulence to rootstock selections within and across regions of vegetable production, limiting the effectively of deployed host resistance. Durable resistance against diverse pathogenic strains has been troublesome to identify and, in the case of tomato, resistance is closely linked to small fruit size.

A range of rootstocks are used to manage BW in tomato production systems. Hawaii 7998, Hawaii 7996 (*Solanum lycopersicum*) and CRA 66 (*S. lycopersicum* var. *cerasiforme*) accessions are open pollinated breeding line selections and have beenfavoured rootstocks in many regions of the world (Black *et al.* 2003 & Rivard and Louws 2008) [4, 51]. As an example, in eastern North Carolina plants grafted onto H7996 and CRA 66 exhibited no symptoms of wilt compared to 75–79% BW incidence using a non-grafted heirloom line (Rivard and Louws 2008) [51]. AlthoughH7996 and CRA 66 are among the most stable sources of resistance worldwide, strains able to cause wilt on these accessions are recorded (Jaunet and Wang 1999 & Lin *et al.* 2008). Likewise rootstock selections may offer resistance against a broad range of strains or to specific representative groups (Matsuzoe *et al.*1993).In Taiwan, eggplant rootstock (EG203) offered the highest level of resistance to the greatest diversity of strains tested followed byH7996 (Lin *et al.* 2008). The AVRDC recommends eggplant rootstocks for tomato production for BW resistance and in cases when flooding may occur, otherwise H7996 is suggested (Black *et al.* 2003) [4].

### 9. Root knot nematode pathogens

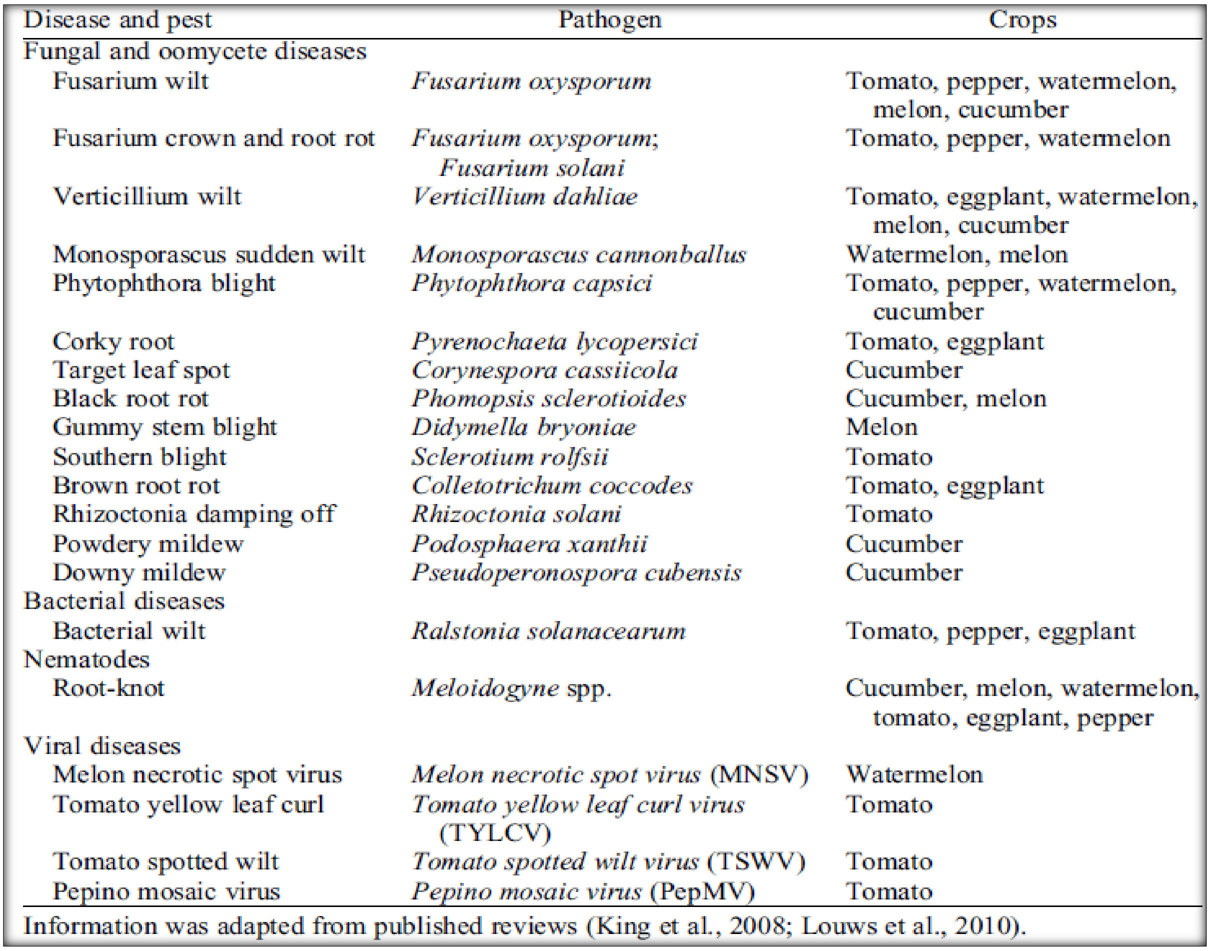
Root knot nematodes (RKN) are obligate endoparasites that have a broad host range, including weeds, and cause severe losses, particularly where vegetables are cropped intensively in sandy soils. Thefour main species encountered include *Meloidogyne incognita*, *M. arenaria*, *M. javanica* and *M. hapla* (*Mi*, *Ma*, *Mj*, *Mh*). Althoughcrop rotation with non-hosts and soil disinfestation/fumigation are effective, resistance is a preferred as a more sustainable tactic. Effective resistance (Mi locus) is routinely introgressed into several tomato cultivars and rootstocks. Resistance is knownto break down under high soil temperatures (above 28 ºC). But, resistance is differentially expressed in different genomic backgrounds, to different RKNspecies or populations within a species (Cortada *et al.* 2008, Rivard *et al.* 2010 & Verdejo-Lucas and Sorribas 2008) [50]. As an example, Rivard *et al.* (2010) [50] reported that under heavy natural Mi inoculum pressure and in hot soils, non-grafted tomatoes were severely galled whereas 'Maxifort' and 'Beaufort' had a low incidence of galling and 'Big Power' had trace amounts of galling in two consecutive years. All rootstocks suppressed the symptom incidence over the 1,3- dichloropropene fumigant standard. 'Big Power' also significantly minimised the population of nematodes to 40 juveniles per 500cm$^3$ soil at harvest and all other treatments, including fumigated soils, hadupto 2500 juveniles per 500cm−3 (Rivard *et al.* 2010) [50]. The capacity of 'Beaufort' to support Mi nematode reproduction was also observed in California (Lopez-Perez *et al.* 2006). 'Big Power' was found to have intermediate resistance to Mj whereas 'Maxifort' and 'Beaufort' were moderately resistant and numerous other interspecific hybrid rootstocks were highly resistant (Cortada *et al.* 2008) [14]. Resistance in an experimental ISHs rootstock (PG76) gradually became ineffective to an (originally) avirulent *Mj* population after three cycles of continuous production (Verdejo-Lucas and Sorribas 2008). This complicated interaction between production site, temperature effects, host genetics and RKN population presents a challenge to design IPM programs that offer yield stability in the presence of RKN populations. *S. torvum* and *S. peruvianum* also provide resistance to Mi (Rodriguez *et al.* 2009). RKN management in eggplant has been accomplished with the ISHs rootstock ‘Brigeor’ (Ioannou 2001) [32] and *S. torvum* (Curuk *et al.* 2009) [16] and the compatibility of eggplant on ISHs rootstock provides options for practitioners.

RKN resistance is unknown in commercial cucurbits and so the seek for resistant rootstock has been a vital priority (Cohen *et al.* 2007) [23]. The ISHc rootstocks may offer some suppression of RKN (Giannakou and Karpouzas 2003) [38] but in general are considered susceptible (Besri and Rabat 2008). Bur cucumber and the African horned cucumber have the most effective nematode tolerance with promise for cucurbit grafting (Lee and Oda 2003) [37]. Cantaloupes (*Cucumismelo* L.) grafted on *C. moschata* reduced RKN (Mi race 3) galling incidence but did not limit final nematode populations in the soil whereas *C. metuliferus* rootstocks offered similar benefits and decreased nematode levels observed at harvest. The later rootstock allowed egg production and was thus considered moderately resistant (Siguenza *et al.* 2005). Bur cucumber is also effective for RKN management in cucumber and provide resistance to FW but is susceptible to damping off (Sakata *et al.* 2008) [55].

## 10. Soil-borne Virus pathogens

Grafting could be a common tool to study the transmissibility of viruses. Introgression of genes into rootstock for virus resistance to restrict transmission to the scion could be a priority goal. If rootstocks are more vulnerable than the scion the risk of virus infection isenhanced. Grafting could be a viable tactic to limit infection by soil-borne viruses. *Melon necrotic spot virus* (MNSV) is vectored by *Olpidium* sp and watermelon grafted on ISHc ‘RS841’ and ‘Shintosa Camelforce’ increased yield by up to 115% in infested soils compared to non grafted plants that had over 90% wilt when harvest commenced (Huitron-Ramirez *et al.* 2009). Rootstocks specifically bred for MNSV resistance are developed and deployed (Cohen *et al.* 2007 and Hirai *et al.* 2003) [60]. The etiology of a “collapse” in tomato has not been fully delineated but is related to *Pepino mosaic virus* (*PepMV*) and can be transmitted in nutrient solutions and possibly through root grafts and fungal vectors. Grafting on interspecific rootstock decreased yield losses due to *PepMV* compared to non-grafted plants (Miguel 2004 and Schwarz *et al.* 2010) [42].

**Table 1:** Diseases reported to be controlled by grafting in different vegetable crops



| Disease and pest | Pathogen | Crops |
|---|---|---|
| Fungal and oomycete diseases | | |
| Fusarium wilt | *Fusarium oxysporum* | Tomato, pepper, watermelon, melon, cucumber |
| Fusarium crown and root rot | *Fusarium oxysporum*; *Fusarium solani* | Tomato, pepper, watermelon |
| Verticillium wilt | *Verticillium dahliae* | Tomato, eggplant, watermelon, melon, cucumber |
| Monosporascus sudden wilt | *Monosporascus cannonballus* | Watermelon, melon |
| Phytophthora blight | *Phytophthora capsici* | Tomato, pepper, watermelon, cucumber |
| Corky root | *Pyrenochaeta lycopersici* | Tomato, eggplant |
| Target leaf spot | *Corynespora cassiicola* | Cucumber |
| Black root rot | *Phomopsis sclerotioides* | Cucumber, melon |
| Gummy stem blight | *Didymella bryoniae* | Melon |
| Southern blight | *Sclerotium rolfsii* | Tomato |
| Brown root rot | *Colletotrichum coccodes* | Tomato, eggplant |
| Rhizoctonia damping off | *Rhizoctonia solani* | Tomato |
| Powdery mildew | *Podosphaera xanthii* | Cucumber |
| Downy mildew | *Pseudoperonospora cubensis* | Cucumber |
| Bacterial diseases | | |
| Bacterial wilt | *Ralstonia solanacearum* | Tomato, pepper, eggplant |
| Nematodes | | |
| Root-knot | *Meloidogyne* spp. | Cucumber, melon, watermelon, tomato, eggplant, pepper |
| Viral diseases | | |
| Melon necrotic spot virus | *Melon necrotic spot virus* (MNSV) | Watermelon |
| Tomato yellow leaf curl | *Tomato yellow leaf curl virus* (TYLCV) | Tomato |
| Tomato spotted wilt | *Tomato spotted wilt virus* (TSWV) | Tomato |
| Pepino mosaic virus | *Pepino mosaic virus* (PepMV) | Tomato |

Information was adapted from published reviews (King et al., 2008; Louws et al., 2010).

## Precautions

To maximise the potency of the technique, an ideal co-ordination of the vegetative cycles should be achieved before the conjunction of the two plants. Expose seedlings to full sun and a few water stresses before grafting to keep the plants short and increase tolerance to water stress. Throughout grafting, the timing of the operations must be strictly controlled. Prepare grafts early or late in the day to avoid water loss. Appropriate sanitation measures need to be adopted (use of pest free high quality seeds and match scions and rootstocks of equal stem diameter). Cut them at a precisely identical angle. Graft in a location that is shielded from direct sunlight and away from greenhouse heater discharge. Confirm the cut surfaces keep good contact once the plants are clipped together so that they need the best chance of successfully connecting toeach other. Use physical barriers against virus vectors and specific pesticides against insects and fungi. Throughout the whole process the environmental conditions (temperature, humidity, composition of the substrate, sun radiation and ventilation) need to be optimised and controlled.

## Conclusions

Grafting is a rapid alternative management tool forsoil-borne diseases. Grafting can affect numerous quality aspects of vegetable crops still fits well into the organic and integrated crop production system. The utilisation of grafting as an integrated pest management tool to manage soil-borne pest and diseases are going to be helpful in the low input sustainable horticulture of the future when carried out with increasing knowledge regarding the biology, diversity and population dynamics of the pathogen. Large scale commercial production of vegetable seedlings is increasing quickly in several developed countries and this cause an increased commercial supply and use of grafted vegetable seedlings throughout the world. Further, inventions in mechanised and robotic grafting may be a bonus for this eco-friendly approach.

## Future prospects

Identification of compatible disease resistant rootstocks and healthy grafted seedlings at low price are the key points for wider use of vegetable grafting. Much researchis required to reduce post grafting losses. Besides, Availability of efficient grafting machines and grafting robots will increase grafting speed, the survival rate of grafted plants minimises the higher price of grafted seedlings and therefore can encourage the cultivation of grafted plants among small-scale farmers worldwide. Researches, extension specialists and seed companies ought to work along to integrate this modernised technology as an efficient tool for producing high-quality vegetables. There is a scope for vegetable breeders and private companies of India to develop resistant rootstocks. Sharpening of grafting skills and healing environment have to be standardised for its application on a commercial scale. Vegetable grafting can promote the production of organic produces which are the foremost concern of constomers.

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