1 Introduction to Vegetable Grafting

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1.1 Importance and Use of Vegetable Grafting

1.1.1 Historical perspective

Grafting is the art of joining together two plant parts (a rootstock and a scion) by means of tissue regeneration, in which the resulting combination of plant parts achieves physical reunion and grows as a single plant (Janick, 1986). It is a centuries-old technique but a relatively new one in vegetable cultivation. Various references to fruit grafting appear in the Bible and in ancient Greek and Chinese literature, suggesting that grafting was used in Europe, the Middle East and Asia by the 5th century BC (Melnyk and Meyerowitz, 2015). Grafting occurs commonly in nature, and the observation of natural grafts may have inspired human use of this technique in horticulture thousands of years ago (Mudge *et al.*, 2009).

Grafting of fruit trees has been practised for thousands of years, but in vegetables this technique is a relatively new one. Self-grafting was used as a technique to produce large-sized gourd fruits, as reported in a Chinese book written in the 5th century and a Korean book written in the 17th century (Lee and Oda, 2003). However, commercial grafting of vegetables only originated in the early 20th century with the aim of managing soilborne pathogens (Louws *et al.*, 2010).

Scientific vegetable grafting was first launched in Japan and Korea in the late 1920s by grafting watermelon on to gourd rootstocks to avoid soilborne diseases (Ashita, 1927; Yamakawa, 1983). This new technique was disseminated to farmers in Japan and Korea by the agricultural extension workers. In the early 1930s, the commercial use of grafted transplants was started in Japan by grafting

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watermelon on to bottle gourd (*Lagenaria siceraria* (Mol.) Standl) and summer squash (*Cucurbita moschata* Duch.) to induce resistance to Fusarium wilt (Oda, 2002; Sakata *et al.*, 2007, 2008). Grafting of cucumber to reduce soilborne diseases and to enhance scion vigour is believed to have started in the 1920s but was not applied on a commercial scale until the 1960s (Sakata *et al.*, 2008).

Among the Solanaceae crops, aubergine (*Solanum melongena* L.) was first grafted on to scarlet aubergine (*Solanum integrifolium* Lam.) in the 1950s (Oda, 1999). Similarly, grafting of tomato (*Solanum lycopersicum* L.) was started in the 1960s (Lee and Oda, 2003). In the 1950s, the rapid development of protected cultivation with the use of greenhouses or tunnels for offseason vegetable production and intensive cropping patterns changed the existing crop rotation system; consequently, farmers became dependent on grafting to control soilborne pathogens and other pests (Kubota *et al.*, 2008; Lee *et al.*, 2010).

Scientific studies investigating and developing rootstocks was initiated in the 1960s in Korea. By 1990, the percentage of grafted Solanaceae and Cucurbitaceae (e.g. cucumber, melon, aubergine, tomato) had increased to 59% in Japan and 81% in Korea (Lee, 1994). Currently, most greenhouse-cultivated cucurbits are grafted in China, Japan, Korea, Turkey and Israel, while grafted vegetables are cultivated on a commercial scale in more than 20 countries worldwide (Table 1.1).

1.1.2 Purpose and scope

Although vegetable grafting in ancient times was intended mainly to produce large-sized gourds for rice storage (Hong, 1710; PSNCK, 1982), it expanded rapidly in many countries to control soilborne pathogens (e.g. root-knot nematodes) and foliar pathogens, to enhance plant vigour, to extend the harvesting period, to increase yield and fruit quality, to prolong postharvest life, to increase nutrient uptake, to allow tolerance to low and high temperatures, to cope with salinity and heavy-metal stress, and to increase tolerance to drought and waterlogging (Table 1.2; *see* Chapters 6 and 7, this volume).

As well as myriad applications in advancing sustainable crop production, grafting can be used as a tool in both breeding and research. Recently, a group of researchers from Germany working on tobacco published a unique way of producing new allohexaploid tobacco species by using the graft site as propagation

Table 1.1. Main countries where grafted vegetables are produced and/or cultivated on a commercial scale.

Continent	Countries
East Asia	China, Japan, Korea, the Philippines
Europe	Spain, Italy, the Netherlands, France, Greece, Cyprus, Belgium, Portugal, Germany, Croatia, Bosnia and Herzegovina
Middle East and North Africa	Turkey, Israel, Morocco, Egypt, Iran, Algeria
Americas	Mexico, Canada, the USA, Argentina

Table 1.2. Benefits of vegetables grafting.

Benefit	Crop	Reference
Disease resistance to soilborne pathogens and foliar pathogens	Tomato, watermelon, aubergine, artichoke, cucumber, pepper, melon	Black *et al*. (2003); Bletsos *et al*. (2003); Bletsos (2005, 2006); Sakata *et al*. (2006, 2007, 2008); King *et al*. (2008); Lee *et al*. (2010); Louws *et al*. (2010); Kousik *et al*. (2012); Jang *et al*. (2012); Temperini *et al*. (2013); Gilardi *et al*. (2013a,b); Vitale *et al*. (2014); Arwiyanto *et al*. (2015); Miles *et al*. (2015); Shibuya *et al*. (2015); Suchoff *et al*. (2015)
Nematode resistance	Tomato	Dong *et al*. (2007); Lee *et al*. (2010); Louws *et al*. (2010)
Salt tolerance	Cucumber, pepper, watermelon, tomato	Huang *et al*. (2009); Colla *et al*. (2010, 2012, 2013); Huang *et al*. (2010, 2013a); Lee *et al*. (2010); Schwarz *et al*. (2010); Fan *et al*. (2011); Yang *et al*. (2012, 2013); Wahb-Allah (2014); Penella *et al*. (2015); Xing *et al*. (2015)
High- and low-temperature tolerance	Tomato, pepper, cucumber	Venema *et al*. (2008); Li *et al*. (2008); Lee *et al*. (2010); Schwarz *et al*. (2010); López-Marín *et al*. (2013)
Drought tolerance	Pepper, tomato	Lee *et al*. (2010); Schwarz *et al*. (2010); Penella *et al*. (2014); Wahb-Allah (2014)
Flooding tolerance	Tomato	Lee *et al*. (2010); Bhatt *et al*. (2015)
Nutrient uptake	Watermelon, tomato, melon	Kim and Lee (1989); Ruiz *et al*. (1997); Lee *et al*. (2010); Colla *et al*. (2010b, 2011); Huang *et al*. (2013b, 2016a,b); Schwarz *et al*. (2013); Huang *et al*. (2016a,b); Nawaz *et al*. (2016)
Yield increase	Watermelon, melon cucumber, tomato, aubergine, pepper, artichoke	Jeong (1986); Ruiz *et al*. (1997); Nisini *et al*. (2002); Colla *et al*. (2008); Huang *et al*. (2009); Lee *et al*. (2010); Gisbert *et al*. (2011); Moncada *et al*. (2013); Tsaballa *et al*. (2013); Temperini *et al*. (2013)
Fruit quality improvement	Tomato, cucumber, aubergine, pepper, melon, watermelon	Jeong (1986); Proietti *et al*. (2008); Huang *et al*. (2009); Lee *et al*. (2010); Rouphael *et al*. (2010); Gisbert *et al.* (2011); Zhao *et al*. (2011); Condurso *et al*. (2012); Krumbein and Schwarz (2013); Moncada *et al*. (2013); Tsaballa *et al*. (2013); Verzera *et al*. (2014); Kyriacou *et al*. (2016)
Scion vigour improvement	Cucumber	Jeong (1986); Lee *et al*. (2010)
Reproductive growth promotion	Cucumber	Jeong (1986); Lee *et al*. (2010)
Shelf-life/ postharvest life improvement	Melon	Zhao *et al*. (2011)

Continued

Table 1.2. Continued.

Benefit	Crop	Reference
Heavy metals/ organic pollutants tolerance	Cucumber, tomato	Rouphael *et al*. (2008); Lee *et al*. (2010); Schwarz *et al.* (2010); Zhang *et al*. (2010a,b, 2013); Kumar *et al*. (2015a,b)
Extension of harvesting period	Cucumber	Jeong (1986); Itagi (1992); Ito (1992); Lee *et al*. (2010)
Weed control/ management	–	Dor *et al*. (2010); Louws *et al*. (2010)
Production of new species (tetraploid)	Tobacco	Fuentes *et al*. (2014)

material *in vitro* (Fuentes *et al*., 2014); in this case, grafting can be seen as a breeding tool to generate novel genetic combinations – in a process that is conceptually similar to protoplast fusion – by hybridization at the cellular level, bypassing sexual compatibility barriers (*see* Chapter 3, this volume). Independent breeding for rootstock and scion traits can also make 'trait stacking' in breeding programmes generally easier. Researchers have used reverse genetics and grafting to investigate root-to-shoot signalling: by grafting genetically defined and distinct rootstocks and scions, it is possible to assign the origins of physiological functions to one or the other, and to study the movement between roots and shoots of specific biomolecules (e.g. phytohormones, metabolites, small RNAs) and the consequent effects on root and shoot phenotypes (*see* Chapter 4, this volume). For example, the extent and impact of abscisic acid (Holbrook *et al*., 2002) and cytokinin (Ghanem *et al*., 2011) in root-to-shoot signalling became apparent through grafting with mutant and transgenic rootstocks. Also, by grafting hundreds of different rootstock genotypes from a genetically defined population to a common scion, it is possible to identify new genetic loci and processes that control rootstock traits by forward genetics (Asins *et al*., 2015); this can advance scientific understanding and provide molecular markers for rootstock breeding. Finally, fundamental studies can also be carried out in the graftable dicotyledonous model plant *Arabidopsis thaliana*, such as how the graft junction is formed and the fundamental process of vascular regeneration following wounding (Melnyk *et al*., 2015).

In short, grafting is being used in different ways for economic, societal and environmental benefits, and to extend the depth of knowledge about fundamental process in plant science.

Commercial grafting is currently practised in watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai), melon (*Cucumis melo* L.), cucumber (*Cucumis sativus* L.), pumpkin (*C. moschata*), bitter gourd (*Momordica charantia* L.), tomato (*S. lycopersicum*), aubergine (*S. melongena*) and pepper (*Capsicum annuum* L.). However, grafting may also be used in other vegetables, such as artichoke (*Cynara cardunculus* subsp. *scolymus* (L.) Hegi) grafted on to cardoon (Temperini *et al*., 2013), or in different *Phaseolus vulgaris* L. graft combinations (Cichy *et al*., 2007), where the yield increased significantly compared with non-grafted plants (*see* Chapter 9, this volume).

From the grower's point of view, yield is the most important factor in the economics of farming. Grafting directly increases yield by invigorating scions, increasing resource use efficiency (e.g. water, fertilizer), and extending the harvest period. Additionally, it helps to reduce the costs involved in plant protection measures compared with the use of self-rooted vegetables. An overview of reported percentage yield increases among various vegetables is summarized in Table 1.3.

1.1.3 Growing areas and plantlet production

Statistics about the cultivation and use of grafted vegetables worldwide are difficult to obtain and are often not updated as the use of grafted vegetables continues to increase. The trend for grafted vegetable production varies widely from country to country, and even within a country. The largest market for grafted vegetable crops is East Asia because of the high concentration of cucurbits in general and the high concentration of grafted plants in particular. For example, 99% of watermelons are grafted in Korea, 94% in Japan, and 40% in China. In contrast, solanaceous crops are less frequently grafted: about 60–65% of tomatoes and aubergines, and 10–14% of peppers. Under protected cultivation, the percentage is higher, and almost all cucumbers, watermelons, and tomato are grafted under these conditions. A similar high ratio of grafted plants compared with non-grafted can be found in Mediterranean countries, particularly those with high production areas, such as Spain, Italy, Turkey and Israel. In the Netherlands, nearly all the tomatoes produced in soil-less culture are grafted on to vigorous rootstocks to increase or at least secure the yield. In France, tomatoes and aubergines in particular are grafted to enhance resistance to soilborne pathogens and nematodes. Currently, grafting is expanding in many countries worldwide, particularly in eastern Europe, North and South America, India and the Philippines. The market for grafted vegetables in North America was first advanced in Canada by the Dutch, who introduced

Table 1.3. Yield increase of grafted plants in comparison with non-grafted or self-grafted plants in different vegetable crops.

Vegetable	Yield increase (%)	Reference
Melon	3.4–92	Ruiz *et al*. (1997); Lee *et al*. (2010); Condurso *et al*. (2012); Verzera *et al*. (2014); Salar *et al*. (2015); Han *et al*. (2015); Mohammadi *et al*. (2015); Esmaeili *et al*. (2015)
Watermelon	22.7–43.0	Mohamed *et al*. (2014); Soteriou *et al*. (2015)
Cucumber	8.8–57.0	Rouphael *et al*. (2008); Colla *et al*. (2012, 2013); Farhadi and Malek (2015); Gao *et al*. (2015)
Pepper	9.2	Jang *et al*. (2012)
Aubergine	27.7	Gisbert *et al*. (2011)
Tomato	5.4–80.3	Chung and Lee (2007); Schwarz *et al*. (2013); Wahb-Allah (2014); Bhatt *et al*. (2015); Boncato and Ellamar (2015); Suchoff *et al*. (2015)
Artichoke	21.7	Temperini *et al*. (2013)

grafting in tomato to increase yield under greenhouse conditions. Similarly, in Mexico grafting was introduced first in tomato and later in other vegetable crops.

Canada and Mexico currently have several large-scale grafting nurseries producing millions of grafted plants annually. As import of tomato plants from Mexico is prohibited in the USA, Canadian nurseries have been the only source of grafted plants until recently. More recently, nurseries in the USA have started grafting vegetables, and a large international nursery announced its plan to build the first North American operation. In most countries where grafted vegetables are cultivated, plantlets are produced by commercial nurseries based on growers' needs. In China alone, more than 1500 commercial nurseries are producing grafted transplants. In a small number of countries, particularly with small farm sizes and poor growers, grafted transplants are self-produced by the growers or imported from neighbouring countries. International trading of grafted vegetable transplants is rapidly increasing, but the majority of grafted transplants are still produced by the grower. In nurseries with a high production volume, fully automatic machines (grafting robots) may also be used, as occurs in the Netherlands and Korea.

1.2 The Process of Vegetable Grafting

The grafting process comprises four main steps (Fig. 1.1): (i) selection of the rootstock and scion cultivars; (ii) plantlet production and creation of the physical union by physical manipulation; (iii) healing of the graft union; and (iv) acclimatization of the grafted plants (Lee and Oda 2003; Lee *et al.*, 2010).

1.2.1 Selection of rootstock and scion cultivars

Selection of the correct rootstock and scion cultivars is a critical step for the success of grafted vegetable production. The seed of the scion cultivar is selected on the basis of purity, viability, yield, fruit quality and market demand. Rootstock cultivars are selected based on purity, viability, resistance to diseases, compatibility with the scion cultivar, and adaptability to local soil and environmental conditions.

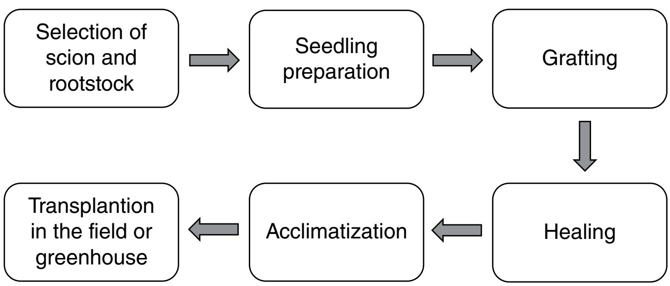

Fig. 1.1. Production process of grafted vegetable plantlets.

The public sector and private seed companies have introduced a number of high-yielding scion and rootstock cultivars with desired characteristics, such as resistance to diseases and nematodes, and tolerance to salinity, drought, flood, heat and chilling stress. Seed companies are aware that it is important that the rootstocks they breed do not impair fruit taste or quality. Thus, growers have a wide range of cultivars from which they can select rootstocks for Cucurbitaceae and Solanaceae crops in accordance with their own requirements. Cucurbit rootstock breeding work is concentrated mainly in China, Korea and Japan. The number of registered cucurbit rootstocks is increasing continuously because of the increased popularity of cultivation of grafted plants (Kato and Lou 1989; Ko, 1999; Lee *et al*., 2008). According to one estimate in China, over 600 Cucurbitaceae rootstocks are in trials at various stages, although only a few are released each year (King *et al*., 2010).

1.2.2 Overview of grafting methods

Different grafting methods are selected depending on the type of crop, the farmer's previous technical experience, personal choice, the number of grafts required, the purpose of grafting, plantlet production (own use or commercial), access to labour, and the availability of machinery and infrastructural facilities (Lee *et al*., 2010). In general, grafting methods can be divided into two categories: (i) manual grafting, where most of the grafting process is performed manually; and (ii) mechanical grafting, where machines (robots) are used to carry out the main grafting processes.

Although many machines and grafting robots have been developed, manual grafting is still the most popular and widely used method (Lee *et al*., 2010). In manual grafting, a number of methods are used for the process and described in detail in the following sections (*see* Plate 1).

Hole insertion

Hole insertion grafting is preferred for grafted watermelon transplant production in many areas because the size of watermelon seedlings is relatively small compared with the rootstock (bottle gourd or squash). In this method, rootstock seeds are sown 7–8 or 3–4 days earlier than the watermelon seeds for the bottle gourd and squash rootstock seeds, respectively. Grafting is performed 7–8 days after watermelon seed sowing. In the case of tomato and aubergine, rootstock seeds are sown 5–10 days before sowing the scion seeds, and grafting is performed 20–25 days after sowing the scion seeds (Lee *et al*., 2010). At the time of grafting, both rootstock and scion seedlings should be uniform, healthy and vigorous.

For graft operation, the true leaves and growing point of the rootstock are carefully and completely removed just above (Plate 1a) or sometimes below (Plate 1b) the cotyledonary leaves, and a slanting hole is made with a wooden or plastic gimlet. The hypocotyl portion of the scion is prepared by making a slanting cut with a tapering end for easy insertion (*see* Plate 1a). Care must be taken during insertion of the scion into the rootstock to avoid insertion of the scion into the rootstock hypocotyl cavity, because this will strongly affect the reunion, and at a later point, adventitious roots from the scion will grow through the rootstock cavity and reach the soil, thus ultimately minimizing the purpose of using a rootstock.

This method is very popular in China, because it results in a strong union and vascular connection compared with the tongue grafting approach, and additional labour for clipping, transplanting, cutting and clip removal is not required (Oda, 1994). However, sometimes parallel growth of the rootstock along with that of the newly grafted scion starts just above the cotyledonary leaves, so these offshoots need to be removed. Plate 2 shows an example of grafted watermelon transplants produced by the hole insertion method.

Tongue grafting

A rootstock and scion of equal size are used for tongue approach to grafting. Therefore, in order to attain plants of a uniform size, the seeds of scion cultivars (e.g. watermelon, cucumber, melon) are sown 5–7 days earlier compared with the rootstock seeds. The growing point and the true leaves are carefully and completely removed from the rootstock and a downward-slanting cut is made in the hypocotyl while an upward-slanting cut is made on the hypocotyl of the scion. The angle of cut is made at 30–40° in relation to the perpendicular axis. When removing the growing point of the rootstock, one cotyledonary leaf is often also removed to ensure complete removal of the growing point and to avoid crowding in limited growing space. The cut region on the scion is inserted into the rootstock (*see* Plate 1c), after which specially designed grafting clips are placed at the graft point to hold it firmly in place. The grafted rootstock and scion are immediately planted in pots. The plants are placed under partial shade conditions for 1–2 days after which they can be placed under normal greenhouse conditions. After 10–12 days, the lower hypocotyl portion of the scion of several plants is cut to see the response of the plants; if the graft union has been successful, the scions will continue to grow, but if the union is incomplete or partially complete, the scions will wilt or show restricted growth. These results are used to judge the overall response of the plants. The clips are removed before transplanting the plants.

An experienced person can perform about 800 grafts per day (Lee *et al.*, 2010). Therefore, this ancient method of vegetable grafting is rarely used by professional seedling growers compared with other methods as more labour is required for cutting the scion again for testing and adding the clips (which also need to be removed before transplanting) and more space is needed to grow the plantlets. Moreover, frequent rooting from the scion occurs under field conditions, especially if the plantlets are planted deep in the ground (Lee, 1994).

Splice grafting

This method, also known as tube grafting or one-cotyledon splice grafting, is the most widely used and preferred method by growers and commercial grafted transplant producers. It can be performed in most vegetables by hand or by machines/robots. In this method, the growing point and one cotyledonary leaf of the rootstock are removed by performing a slanted cut (35–45°) and a prepared scion is matched to it (*see* Plate 1d, e and j). This method is popular in cucurbits and solanaceous crops. Grafted watermelon transplants processed by this method are shown in Plate 3) and pepper transplants in Plate 4). To hold the graft site, a grafting clip, pin or tube (an elastic tube with a slit on one side) is used. For Solanaceae crops, grafting is performed at lower epicotyls of the rootstock.

The main features of the hole insertion, tongue and splice grafting methods are compared in Table 1.4.

Cleft grafting

Cleft grafting is also called apical or wedge grafting. In this method, the rootstock seedling is decapitated and a 0.5–1.5 cm vertical cut is made in the centre of the stem along the stem axis. The scion is pruned to one to three true leaves, and the lower stem end is given a slanted cut from both sides to form a wedge. This wedge-shaped scion is inserted into the slit made on the rootstock and a clip is placed to hold the rootstock and scion together (*see* Plate 1f and g). Various types of grafting clips in different sizes are available for this purpose.

In this method, the scion is tightly held by the rootstock compared with other methods, so clips may not be necessary and grafting tape, wax tape or Parafilm

Table 1.4. Comparison of the different grafting methods.

Hole insertion grafting	Tongue grafting approach	Splice grafting, tube grafting or one-cotyledon splice grafting
Strong vascular connection	Weak vascular connection	Very strong vascular connection
Trained workers required to accomplish the task	Less trained workers can successfully graft by this method	Trained workers required to accomplish the task
Grafting machine not available	Grafting machine available	Grafting machine available
Grafting clips not required	Grafting clips required	Grafting clips, pins and tubes required to hold the graft union
Labour for clipping, transplanting, cutting and clip removal not required	Labour for clipping, transplanting, cutting and clip removal not required	Labour for clipping, transplanting, cutting and clip removal may be required
Offshoot removal required	Offshoots removal required	Offshoots removal often not required
Scion does not need to be planted with the rootstock during the healing process	Scion needs to be planted with the rootstock during the healing process	Scion does not need to be planted with the rootstock during the healing process
Less space required during the healing process	More space required during the healing process	More space required during the healing process
Less labour-intensive	Most labour-intensive	More labour-intensive
Environmental control (high humidity) required during the healing process	No strict environmental control (high humidity) required during the healing process	Careful environmental control (high humidity) required during the healing process
Can be used mainly in cucurbits	Can be used in both solanaceous crops and cucurbits	Can be used in solanaceous crops, cucurbits and other minor crops

may be used to hold the scion. However, the grafting process takes more time than splice grafting, and sometimes rootstock stems split completely during the grafting process. Cleft grafting is relatively difficult to perform in vegetables compared with woody tree species, so this method is confined to several Solanaceae crops such as aubergine and chilies (*see* Plate 5) (Lee *et al.*, 2010; Johnson *et al.*, 2011), while it is rarely used in cucurbits.

Pin grafting

Pin grafting is similar to splice grafting, the only difference being that specially designed pins are used instead of clips to fix the grafted position of the scion and rootstock (*see* Plate 1h and i). These pins are made of a natural ceramic material so that they can remain within the plant without causing problems. The Takii Seed Company in Japan has designed ceramic pins of 15 mm length and 0.5 mm width with a hexagonal cross-section. This method saves time and labour, as clips need removal while pins do not. However, the ceramic pins are costly and are used only once as they are not removed, while clips can be reused for the grafting process. Recently, it has been found that rectangular-shaped bamboo or wooden sticks can be used as a replacement for ceramic pins. Careful environmental control is necessary for the success of a graft union. Rootstock suckers/offshoots may emerge during the healing stage of this method, or even under field conditions, and need removing.

Mechanical grafting

Grafting machines or robots are increasingly being used for the grafting process. The first robotic 'one-cotyledon grafting system' was developed in the 1980s by Iam Brain in Japan for cucurbit vegetables. The prototype was developed in 1987 and then adapted in 1989 (Ito, 1992; Kubota *et al.*, 2008). It takes 4.5 s to make a graft, and the success rate is 95%. The technologies used in this robot were shared with agriculture machinery companies and a prototype semi-automatic grafting system was developed in Korea. Several grafting robots were developed by the Rural Development Administration of Korea and were provided to plug seedling nursery growers at a relatively low price. By 2001, three grafting robots had been developed in Korea. The simple and economical grafting machine developed by the Yopoong Company was provided for local growers and has been exported to Asian countries for more than a decade. Another semi-automatic grafting machine was developed by a private company in Korea and provided to growers. This semi-automatic multifunctional machine was adopted by many countries because of its reasonable price, adjustability and convenient handling (*see* Plate 14)

In the Netherlands, a fully automatic grafting robot with a capacity of 1000 grafts h^{-1} has been developed and used for tomato; similarly, another fully automatic grafting robot has been developed in Japan with a capacity of 750 grafts h^{-1} and a success rate of 90%. Currently, a total of six models of semi- or fully automatic grafting robots are available in the market; three of these models have been developed in Japan, and one each in Korea, the Netherlands and Spain, as described in Table 1.5. According to a published report (http://jhawkins54.typepad.com/files/vegetable-grafting-1.pdf, accessed 24 November 2016), at least two companies are producing mechanically grafted transplants in the USA. The use

Table 1.5. Features of grafting robots available in different countries. (From http://cals.arizona.edu/grafting/grafting-robots, accessed 24 November 2016.)

Make	Country of origin	Distribution	Suitability	Properties/characteristics/ specifications
Helper Robotech (semi-automated machine)	Korea	Distributed to Asia, Europe and North America	Cucurbits and tomato	The first model that can graft both cucurbits and tomato. Widely marketed in Asia and North America. Produces 650–900 grafts h^{-1} at ≥95% success rate. Needs two to three workers to operate the machine.
Iseki (semi-automated machine)	Japan	Distributed to Asia and Europe	Cucurbits	Introduced to the Asian and European market. One machine has been introduced in the USA for trial use. Produces 900 grafts h^{-1} at ≥95% success rate. Needs two to three workers to operate the machine.
Iseki (semi-automated machine)	Japan	Distributed to Asia	Tomato and aubergine	Produces 800 grafts h^{-1} at ≥95% success rate. Seedling size required for grafting was too large for Japanese standard, limiting the market. However, the seedling size is acceptable for USA standard. Needs two to three workers to operate the machine.
Iseki (fully automated machine)	Japan	–	Cucurbits	Introduced in Japanese market in 2009. Produces 800 grafts h^{-1} at ≥95% success rate. A tomato model is also under development at IAM BRAIN[a]. Only one person needed operate the machine.
ISO Group (fully automated machine)	The Netherlands	–	Tomato and aubergine	Introduced in 2009. Produces 1000 grafts h^{-1}. A semi-automated model is also available that requires manual feeding of plants into the system.
Conic System (semi-automated machine)	Spain	–	Tomato	A semi-automated robot to cut tomato scions and rootstocks at a selected angle. Produces 400–600 grafts h^{-1}. Only one person needed to operate the machine.

[a]Institute of Agricultural Machinery Bio-oriented Technology Research Advancement Institution, Japan.

of grafting machines and robots is increasing; Korea exported 32 grafting robots to different countries around the world between 2011 and 2013.

1.2.3 Preference of grafting method for different species

Curcubits

In Japan, grafted watermelon transplants are produced mainly by hole insertion grafting, while for cucumber, individual farmers produce grafted transplants for their own use by the tongue grafting approach. Commercial growers prefer splice grafting for curcubits (Lee *et al.*, 2010). In a recent study conducted in Egypt, Mohamed *et al.* (2014) concluded that, for watermelon, grafted transplants produced using the tongue grafting approach were better compared with those produced by hole insertion and splice grafting under the prevailing cultural and environmental conditions. A table-top grafting machine is available for the tongue grafting approach and is small, handy and easy to operate. However, the tongue grafting approach is considered a simple and basic grafting method, so these machines are now used only by a limited number of growers on a small scale in Korea.

Solanaceous crops

Individual farmers produce grafted aubergine transplants by a number of grafting methods of their own choice, while commercial growers generally adopt splice grafting. According to a published report (http://jhawkins54.typepad.com/files/vegetable-grafting-1.pdf, accessed 24 November 2016), cleft grafting is used routinely for the production of grafted tomato, pepper and aubergine transplants, although Johnson *et al.* (2011) reported that splice grafting is the most commonly used method (95%) for aubergine and tomato in the USA. Generally, less experienced and small farmers prefer the tongue grafting approach, while professional and commercial plantlet producers use splice grafting for most of their grafted vegetables. The quality of grafted transplants produced by splice grafting is considered to be better than those produced by tongue grafting (Lee *et al.*, 2010).

Other crops

Grafting is also reported in other vegetables, although only with local importance (*see* Chapters 2 and 9, this volume). Temperini *et al.* (2013) grafted artichoke (*C. cardunculus* subsp. *scolymus*) on to cardoon by cleft grafting and observed that grafting increased the yield. Similarly, Chinese cabbage (*Brassica rapa* ssp. *pekinensis* (Lour.) Kitam, inbred line) was grafted on to three *Brassica* rootstocks (mustard, turnip and broccoli) by cleft grafting to perform gene expression studies (Mun *et al.*, 2015). Although there is limited data on grafting in other vegetables, cleft grafting seems to be the most appropriate method.

1.2.4 Post-graft healing environment

Figure 1.2 presents a typical time line for graft production (http://www.ces.ncsu.edu/fletcher/programs/ncorganic/research/grafting_techniques.pdf,

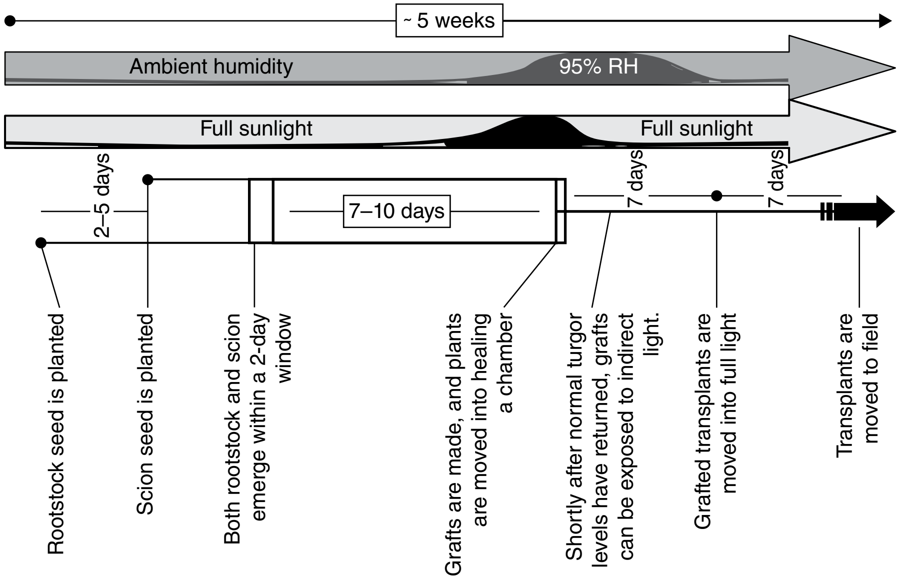

Fig. 1.2. A typical time line for graft production. RH, relative humidity. (Courtesy of C. Rivard and F. Louws, North Carolina State University, Raleigh, USA).

accessed 24 November 2016). Proper care of newly grafted transplants is necessary to secure a higher success rate for the grafting process. In the case of hole insertion grafting, splice grafting, cleft grafting and pin grafting, a very high humidity (95%) is required during the first 48 h when the temperature should be maintained at 27–28°C (82°F). Later, the plantlets can be shifted to a normal greenhouse environment (Guan and Zhao, 2014). Loss of water from the scion during the first 2 days may lead to wilting of the scion and ultimately failure of the grafting process; therefore, a high humidity is required to prevent water loss. Normally, grafted transplants are covered for 5–7 days after grafting with black plastic sheeting or 0.01 mm black polyethylene film to increase humidity, reduce light intensity and promote the healing process (Denna, 1962). However, prolonged covering of grafted transplants leads to unfavourable stem elongation and the plants become spindly, so proper care should be taken to avoid this.

Experienced growers can use plastic tunnels or chambers as healing chambers. However, on a smaller scale, farmers can use specially designed healing containers. In commercial nurseries, the grafted transplants are placed on greenhouse benches and the trays are sealed with 0.01 mm polythene film for 5–7 days to raise the humidity. Partial shading during the day time helps to improve the results. Several types of healing growth chambers with sophisticated controls (temperature and humidity) have been designed by different companies and are used by commercial nurseries in Japan, Korea (Lee *et al.*, 1998, 2008; Kawai *et al.*, 1996), China, Spain and the USA. Dong *et al.* (2015) reported that use of a healing room is becoming increasingly common in China and a 95% grafting success can be obtained on commercial scale using this method.

In a recent report, Li *et al*. (2015) found that the health and vigour of watermelon transplants grafted on to pumpkin and bottle gourd were affected by different light sources (combinations of light controlled by light emitting diodes or LEDs). They obtained healthy and vigorous plantlets under a light source with a red/blue ratio of 7/3 compared with white fluorescent light only. Although they did not comment on the effect of the light source on the healing process, it was apparent that different light sources affected the healing of the graft union. This needs further investigation.

Plants grafted using the tongue approach can attain a high graft success rate without strict humidity control. However, exposure of plantlets to direct sunlight during the healing process should be avoided.

1.3 Problems Associated with Vegetable Grafting

Various problems are associated with the production and management of grafted transplants. The technique is labour-intensive and specialized trained workers are required. It also requires time management for sowing of the rootstock and scion seeds, a controlled environment for graft healing, and efficient grafting machines and robots. Overgrowth of transplants under field conditions may occur, and the yield and quality of scion fruit may also be significantly affected (Huang *et al*., 2015). Sometimes rootstock–scion incompatibility is observed during the initial stages or after transplantation under field conditions. Careful selection of rootstock and scion combinations is required depending on the prevailing soil and environmental conditions of the area. Both rootstock and scion seeds are required, and hybrid and special types of seed can be costly. The rootstock suckers/offshoots that develop during the healing process or under field conditions (after transplanting) need removal. Moreover, grafting can increase the risk of pathogen spread, especially for seedborne pathogens (e.g. bacterial canker caused by *Clavibacter michiganensis* subsp. *michiganensis* in tomato, bacterial fruit blotch caused by *Acidovorax citrulli* in watermelon and melon, charcoal rot caused by *Macrophomina phaseolina* in melon and bottle gourd, and tomato mosaic virus and pepino mosaic virus infections in tomato) in the nursery. This is due to the use of two seeds for producing a grafted plant and to the use of cutting instruments in the grafting process. For the above reasons, it is important to adopt procedures for preventing the spread of pathogens in the nursery by using seeds that have been certified free of pathogens, and by the periodical disinfection of cutting instruments, the use of clean clothing and disinfected hands by the grafting workers, the periodical disinfection of grafting areas and plant growing environments, and the continuous monitoring of the phytosanitary status of seedlings. Despite vegetable grafting providing many job opportunities for the workforce, researchers have identified some problems directly related to the health of nursery workers. Manual grafting is the leading grafting method (Lee *et al*., 2010), and workers performing grafting within a greenhouse and growth chamber face the problems of heat stress and discomfort, especially during April–June, September and October (Marucci *et al*., 2012). Although the working conditions can be adjusted to a certain degree by cooling pads, fans and covering sheets, better facilities (air-conditioned environments) are still required for the welfare of workers. However, the intensity of these problems can be reduced considerably by careful management practices.

1.4 Conclusions

Commercial vegetable grafting has been practised for decades and the area used for grafted vegetables is increasing continuously. The main objective of grafting remains an increase in yield, especially under the high pressure from soilborne pathogens and nematodes and unfavourable environmental conditions (e.g. sub- and supra-optimal temperatures, salinity, drought). Future research should contribute towards improving grafting technologies and nursery management practices to ensure high-quality grafted transplants for growers. Nursery production and management is labour-intensive. To solve this problem, scientists must focus on developing and popularizing facilities, equipment and grafting robots to increase the efficacy of grafting and reduce labour costs. The trend for plug plantlet nurseries is increasing in developing countries. Thus, the use of precise seeders, carrier vehicles, germination rooms, plant growth chambers and acclimatization facilities for grafted transplants should lead to great improvement.

To improve seed germination, uniformity and seedling vigour, seed-priming techniques warrant attention. Similarly, storage technology for grafted transplants demands the consideration of researchers. The development of databases, software, mobile applications and crop models related to grafted vegetables will assist nursery managers and farming communities in the selection of suitable scion and rootstock cultivars, and will also provide guidelines for optimal management practices. Although some problems associated with grafting of vegetables remain, these are outweighed by the benefits attained through grafting, so this technique will continue to proliferate and be adopted worldwide.

References

Arwiyanto, T., Lwin, K., Maryudani, Y. and Purwantoro, A. (2015) Evaluation of local *Solanum torvum* as a rootstock to control *Ralstonia solanacearum* in Indonesia. *Acta Horticulturae* 1086, 101–106.

Ashita, E. (ed.) (1927) *Grafting of Watermelons* Korea (Chosun). *Agricultural Newsletter* 1, 9 (in Japanese).

Asins, M.J., Raga, V., Roca, D., Belver, A. and Carbonell, E.A. (2015) Genetic dissection of tomato rootstock effects on scion traits under moderate salinity. *Theoretical and Applied Genetics* 128, 667–679.

Bhatt, R.M., Upreti, K.K., Divya, M.H., Bhat, S., Pavithra, C.B. and Sadashiva, A.T. (2015) Interspecific grafting to enhance physiological resilience to flooding stress in tomato (*Solanum lycopersicum* L.). *Scientia Horticulturae* 182, 8–17.

Black, L., Wu, D., Wang, J., Kalb, T., Abbass, D. and Chen, J. (2003) Grafting tomatoes for production in the hot-wet season. AVRDC International Cooperators' Guide. AVRDC publication number 03-551. Available at: http://www.ces.ncsu.edu/fletcher/programs/ncorganic/research/grafting.pdf (accessed 30 April 2016).

Bletsos, F.A. (2005) Use of grafting and calcium cyanamide as alternatives to methyl bromide soil fumigation and their effects on growth, yield, quality and Fusarium wilt control in melon. *Journal of Phytopathology* 153, 155–161.
Bletsos, F.A. (2006) Grafting and calcium cyanamide as alternatives to methyl bromide for greenhouse eggplant production. *Scientia Horticulturae* 107, 325–331.
Bletsos, F., Thanassoulopoulos, C. and Roupakias, D. (2003) Effect of grafting on growth, yield, and Verticillium wilt of eggplant. *HortScience* 38, 183–186.
Boncato, T. and Ellamar, J. (2015) Off-season tomato production: a new technology in Tarlac Province of Philippines. *Acta Horticulturae* 1086, 261–267.
Chung, H.D. and Lee, J.M. (2007) Rootstocks for grafting. In: *Horticulture in Korea*. Korean Society for Horticultural Science Technical Bulletin, Korea, pp. 162–167.
Cichy, K.A., Snapp, S.S. and Kirk, W.W. (2007) Fusarium root rot incidence and root system architecture in grafted common bean lines. *Plant Soil* 300, 233-244.
Colla, G., Rouphael, Y., Cardarelli, M., Temperini, O., Rea, E., Salerno, A. and Pierandrei F. (2008). Influence of grafting on yield and fruit quality of pepper (*Capsicum annuum* L.) grown under greenhouse conditions. *Acta Horticulturae* 782, 359–363.
Colla, G., Rouphael, Y., Leonardi, C. and Bie, Z. (2010b) Role of grafting in vegetable crops grown under saline conditions. *Scientia Horticulturae* 127, 147–155.
Colla, G., Cardona Suarez, C.M., Cardarelli, M. and Rouphael, Y. (2010c) Improving nitrogen use efficiency in melon by grafting. *Hortscience* 45, 559–565.
Colla, G., Rouphael, Y., Mirabelli, C. and Cardarelli, M. (2011) Nitrogen-use efficiency traits of mini-watermelon in response to grafting and nitrogen-fertilization doses. *Journal of Plant Nutrition and Soil Science* 174, 933–941.
Colla, G., Rouphael, Y., Leonardi, C. and Bie, Z. (2010a) Role of grafting in vegetable crops grown under saline conditions. *Scientia Horticulturae* 127, 147–155.
Colla, G., Rouphael, Y., Rea, E. and Cardarelli, M. (2012) Grafting cucumber plants enhance tolerance to sodium chloride and sulfate salinization. *Scientia Horticulturae* 135, 177–185.
Colla, G., Rouphael, Y., Jawad, R., Kumar, P., Rea, E. and Cardarelli, M. (2013) The effectiveness of grafting to improve NaCl and $CaCl_2$ tolerance in cucumber. *Scientia Horticulturae* 164, 380–391.
Condurso, C., Verzera, A., Dima, G., Tripodi, G., Crinò, P., Paratore, A. and Romano, D. (2012) Effects of different rootstocks on aroma volatile compounds and carotenoid content of melon fruits. *Scientia Horticulturae* 148, 9–16.
Denna, D.W. (1962) A simple grafting technique for cucurbits. *Proceedings of the American Society of Horticultural Sciences USA* 81, 369–370.
Dong, D., Cao, Z., Wang, X., Hu, J. and Gullino, M.L. (2007) Effect of nematode resistant rootstocks on growth characteristics and yields of tomato. *Acta Horticulturae Sinica* 34, 1305–1308.
Dong, W., Zhou, Z.C., Bu, Y.L., Zhuo, J.Q., Chen, L.Z. and Li, Y.Z. (2015) Research and application of grafted seedlings healing room. *Acta Horticulturae* 1086, 51–57.
Dor, E., Alperin, B., Wininger, S., Ben-Dor, B., Somvanshi, V.S., Koltai, H., Kapulnik, Y. and Hershenhorn, J. (2010) Characterization of a novel tomato mutant resistant to the weedy parasites *Orobanche* and *Phelipanche* spp. *Euphytica* 171, 371–380.
Esmaeili, M., Salehi, R., Taheri, M.R., Babalar, M. and Mohammadi, H. (2015) Effect of different nitrogen rates on fruit yield and quality of grafted and non-grafted muskmelon. *Acta Horticulturae* 1086, 255–260.
Fan, M., Bie, Z., Krumbein, A. and Schwarz, D. (2011) Salinity stress in tomatoes can be alleviated by grafting and potassium depending on the rootstock and K-concentration employed. *Scientia Horticulturae* 130, 615–623.
Farhadi, A. and Malek, S. (2015) Evaluation of graft compatibility and organoleptic traits of greenhouse cucumber seedlings grafted on different rootstocks. *Acta Horticulturae* 1086, 219–224.

Fuentes, I., Stegemann, S., Golczyk, H., Karcher, D. and Bock, R. (2014) Horizontal genome transfer as an asexual path to the formation of new species. *Nature* 511, 232–235.

Gao, Y., Tian, Y., Liang, X. and Gao, L. (2015) Effects of single-root-grafting, double-root-grafting and compost application on microbial properties of rhizosphere soils in Chinese protected cucumber (*Cucumis sativus* L.) production systems. *Scientia Horticulturae* 186, 190–200.

Ghanem, M.E., Albacete, A., Smigocki, A.C., Frébort, I., Pospíilová, H., Martínez-Andújar, C., Acosta, M., Sánchez-Bravo, J., Lutts, S., Dodd, I.C. and Pérez-Alfocea, F. (2011) Root-synthesized cytokinins improve shoot growth and fruit yield in salinized tomato (*Solanum lycopersicum* L.) plants. *Journal of Experimental Botany* 62, 125–140.

Gilardi, G., Gullino, M.L. and Garibaldi, A. (2013a) Critical aspects of grafting as a possible strategy to manage soil-borne pathogens. *Scientia Horticulturae* 149, 19–21.

Gilardi, G., Baudino, M., Moizio, M., Pugliese, M., Garibaldi, A. and Gullino, M.L. (2013b) Integrated management of *Phytophthora capsici* on bell pepper by combining grafting and compost treatment. *Crop Protection* 53, 13–19.

Gisbert, C., Prohens, J., Raigón, M.D., Stommel, J.R. and Nuez, F. (2011) Eggplant relatives as sources of variation for developing new rootstocks: effects of grafting on eggplant yield and fruit apparent quality and composition. *Scientia Horticulturae* 128, 14–22.

Guan, W. and Zhao, X. (2014) *Techniques for Melon Grafting*. Document no. HS1257, Horticultural Sciences Department, University of Florida, Florida.

Han, X.Y., Huang, Q.W., Kong, X.Y., Luo, F., Wang, S., Wan, S.L. and Lin, D.P. (2015) Effects of different stocks on the development and fruit quality of Hami melon. *Acta Horticulturae* 1086, 237–246.

Holbrook, N.M., Shashidhar, V.R., James, R.A. and Munns, R. (2002) Stomatal control in tomato with ABA-deficient roots: response of grafted plants to soil drying. *Journal of Experimental Botany* 53, 1503–1514.

Hong, M.S. (1710) Forest economics. 1, 38–39 (see PSNCK (1982) for translated version).

Huang, Y., Tang, R., Cao, Q. and Bie, Z. (2009) Improving the fruit yield and quality of cucumber by grafting onto the salt tolerant rootstock under NaCl stress. *Scientia Horticulturae* 122, 26–31.

Huang, Y., Bie, Z., He, S., Hua, B., Zhen, A. and Liu, Z. (2010) Improving cucumber tolerance to major nutrients induced salinity by grafting onto *Cucurbita ficifolia*. *Environmental and Experimental Botany* 69, 32–38.

Huang, Y., Bie, Z., Liu, P., Niu, M., Zhen, A., Liu, Z., Lei, B., Gu, D., Lu, C. and Wang, B. (2013a) Reciprocal grafting between cucumber and pumpkin demonstrates the roles of the rootstock in the determination of cucumber salt tolerance and sodium accumulation. *Scientia Horticulturae* 149, 47–54.

Huang, Y., Li, J., Hua, B., Liu, Z., Fan, M. and Bie, Z. (2013b) Grafting onto different rootstocks as a means to improve watermelon tolerance to low potassium stress. *Scientia Horticulturae* 149, 80–85.

Huang, Y., Kong, Q.S., Chen, F. and Bie, Z. (2015) The history, current status and future prospects of the vegetable grafting in China. *Acta Horticulturae* 1086, 31–39.

Huang, Y., Zhao, L.Q., Kong, Q.S., Cheng, F., Niu, M.L., Xie, J.J., Nawaz, M.A. and Bie, Z.L. (2016a) Comprehensive mineral nutrition analysis of watermelon grafted onto two different rootstocks. *Horticultural Plant Journal* 2, 105–113.

Huang, Y., Jiao, Y., Nawaz, M.A., Chen, C., Liu, L., Lu, Z., Kong, Q., Cheng, F. and Bie, Z. (2016b) Improving magnesium uptake, photosynthesis and antioxidant enzyme activities of watermelon by grafting onto pumpkin rootstock under low magnesium. *Plant and Soil* doi: 10.1007/s11104-016-2965-3.

Itagi, T. (1992) Status of transplant production systems in Japan and new grafting techniques. In: *Symposium on Protected Horticulture*. Horticultural Experimental Station, Rural Development Administration, Suwon, Republic of Korea, pp. 32–67 (in Korean).

Ito, T. (1992) Present state of transplant production practices in Japanese horticultural industry. In: Kurata, K. and Kozai, T. (eds) *Transplant Production System*. Kluwer Academic Publishers, Yokohama, Japan, pp. 65–82.

Jang, Y., Yang, E., Cho, M., Um, Y., Ko, K. and Chun, C. (2012) Effect of grafting on growth and incidence of phytophthora blight and bacterial wilt of pepper (*Capsicum annuum* L.). *Horticulture, Environment, and Biotechnology* 53, 9–19.

Janick, J. (1986) *Horticultural Science*, 4th edn. W.H. Freeman & Co., New York.

Jeong, S.J. (1986) Effects of several rootstocks on the growth, fruit yield and quality of two cucumber cultivars. Institute of Food Development, Kyung Hee University, Suwon, Korea. *Research Collection* 7, 67–76 (in Korean with English summary).

Johnson, S., Kreider, P. and Miles, C. (2011) Vegetable grafting eggplants and tomatoes. Washington State University Extension Fact Sheet, FS052E, Washington State University, Washington, DC.

Kato, T. and Lou, H. (1989) Effect of rootstock on the yield, mineral nutrition and hormone level in xylem sap in eggplant. *Journal of the Japanese Society for Horticultural Science* 58, 345–352.

Kawai, J., Onouti, N., Niwa, K. and Ito, T. (1996) The development of grafts for seedlings raised in cellular pots and simple acclimating equipment in tomato plants. Aichi Agricultural Research Center, Japan. *Research Bulletin* 28, 149–155 (in Japanese with English summary).

Kim, S.E. and Lee, J.M. (1989) *Effect of Rootstocks and Fertilizers on the Growth and Mineral Contents in Cucumber* (*Cucumis sativus* L.). Institute of Food Development, Kyung Hee University, Suwon, Korea. *Research Collection* 10, 75–82 (in Korean with English summary).

King, S.R., Davis, A.R., Liu, W.G. and Levi, A. (2008) Grafting for disease resistance. *HortScience* 43, 1673–1676.

King, S.R., Davis, A.R., Zhang, X. and Crosby, K. (2010) Genetics, breeding and selection of rootstocks for Solanaceae and Cucurbitaceae. *Scientia Horticulturae* 127, 106–111.

Kyriacou, M.C., Soteriou, G.A., Rouphael, Y., Siomos, A.S. and Gerasopoulos, D. (2016). Configuration of watermelon fruit quality in response to rootstock-mediated harvest maturity and postharvest storage. *Journal of the Science of Food and Agriculture* 96, 2400–2409.

Ko, K.D. (1999) Response of cucurbitaceous rootstock species to biological and environmental stresses. PhD thesis, Seoul National University, Seoul, Korea.

Kousik, C.S., Donahoo, R.S. and Hassell, R. (2012) Resistance in watermelon rootstocks to crown rot caused by *Phytophthora capsici*. *Crop Protection* 39, 18–25.

Krumbein, A. and Schwarz, D. (2013) Grafting: a possibility to enhance health-promoting and flavour compounds in tomato fruits of shaded plants? *Scientia Horticulturae* 149, 97–107.

Kubota, C., McClure, M.A., Kokalis-Burelle, N., Bausher, M.G. and Rosskopf, E.N. (2008) Vegetable grafting: history, use, and current technology status in North America. *HortScience* 43, 1164–1669.

Kumar, P., Lucini, L., Rouphael, Y., Cardarelli, M., Kalunke, R.M., and Colla, G. (2015a) Insight into the role of grafting and arbuscular mycorrhiza on cadmium stress tolerance in tomato. *Frontiers in Plant Science* 6, 477.

Kumar, P., Rouphael, Y., Cardarelli, M., and Colla, G. (2015b) Effect of nickel and grafting combination on yield, fruit quality, antioxidative enzyme activities, lipid peroxidation, and mineral composition of tomato. *Journal of Plant Nutrition and Soil Science* 178, 848–860.

Lee, J.M. (1994) Cultivation of grafted vegetables. I. Current status, grafting methods, and benefits. *HortScience* 29, 235–239.

Lee, J.M. and Oda, M. (2003) Grafting of herbaceous vegetable and ornamental crops. *Horticultural Reviews* 28, 61–124.

Lee, J.M., Bang, H.J. and Ham, H.S. (1998) Grafting of vegetables. *Journal of the Japanese Society for Horticultural Science* 67, 1098–1114.

Lee, J.M., Kubota, C., Tsao, S.J., Vinh, N.Q., Huang, Y. and Oda, M. (2008) Recent progress in vegetable grafting. In: *International Workshop on Development and Adaptation of Green Technology for Sustainable Agriculture and Enhancement of Rural Entrepreneurship*. IRRI, Los Banos, Laguna, Philippines, p. 21.

Lee, J.M., Kubota, C., Tsao, S.J., Bie, Z., Echevarria, P.H., Morra, L. and Oda, M. (2010) Current status of vegetable grafting: diffusion, grafting techniques, automation. *Scientia Horticulturae* 127, 93–105.

Li, J.-Y., Tian, H.-X., Li, X.-G., Meng, J.-J., and He, Q.-W. (2008) Higher chilling-tolerance of grafted-cucumber seedling leaves upon exposure to chilling stress. *Agricultural Sciences in China* 7, 570–576.

Li, X.E., Liu, F.Y., Huang, Y., Kong, Q.S., Wan, Z.J., Li, X. and Bie, Z. (2015) Growth and physiology of grafted watermelon seedlings as affected by different light sources. *Acta Horticulturae* 1086, 59–64.

López-Marín, J., González, A., Pérez-Alfocea, F., Egea-Gilabert, C. and Fernández, J.A. (2013) Grafting is an efficient alternative to shading screens to alleviate thermal stress in greenhouse-grown sweet pepper. *Scientia Horticulturae* 149, 39–46.

Louws, F.J., Rivard, C.L. and Kubota, C. (2010) Grafting fruiting vegetables to manage soil borne pathogens, foliar pathogens, arthropods and weeds. *Scientia Horticulturae* 127, 127–146.

Marucci, A., Pagniello, B., Monarca, D., Colantoni, A., Biondi, P. and Cecchini, M. (2012) The heat stress for workers during vegetable grafting in greenhouses. In: *International Conference RAGUSA SHWA*. Ragusa, Italy, pp. 321–328.

Melnyk, C.W. and Meyerowitz, E.M. (2015) Plant grafting. *Current Biology* 25, R183–R188.

Melnyk, C.W., Schuster, C., Leyser, O. and Meyerowitz, E.M. (2015) A developmental framework for graft formation and vascular reconnection in *Arabidopsis thaliana*. *Current Biology* 25, 1306–1318.

Miles, C., Wimer, J. and Inglis, D. (2015) Grafting eggplant and tomato for Verticillium wilt resistance. *Acta Horticulturae* 1086, 113–118.

Mohamed, F.H., Abd El-Hamed, K.E., Elwan, M.W.M. and Hussien, M.N.E. (2014) Evaluation of different grafting methods and rootstocks in watermelon grown in Egypt. *Scientia Horticulturae* 168, 145–150.

Mohammadi, H., Salehi, R. and Esmaeili, M. (2015) Yield and fruit quality of grafted and non-grafted muskmelon (*Cucumis melo* L.) affected by planting density. *Acta Horticulturae* 1086, 247–254.

Moncada, A., Miceli, A., Vetrano, F., Mineo, V., Planeta, D. and D'Anna, F. (2013) Effect of grafting on yield and quality of eggplant (*Solanum melongena* L.). *Scientia Horticulturae* 149, 108–114.

Mudge, K., Janick, J., Scofield, S. and Goldschmidt, E.E. (2009) A history of grafting. *Horticultural Reviews* 35, 437–493.

Mun, M., Yi, H., Nou, I. and Hur, Y. (2015) Grafting-induced gene expression change in *Brassica rapa* leaves is different from fruit trees. *Plant Breeding and Biotechnology* 3, 67–76.

Nawaz, M.A., Imtiaz, M., Kong, Q., Fei, C., Ahmed, W., Huang, Y. and Bie, Z. (2016). Grafting: a technique to modify ion accumulation in horticultural crops. *Frontiers in Plant Science* 7, 1457.

Nisini, P.T., Colla, G., Granati, E., Temperini, O., Crino, P., and Saccardo, F. (2002). Rootstock resistance to fusarium wilt and effect on fruit yield and quality of two muskmelon cultivars. *Scientia Horticulturae* 93, 281–288.

Oda, M. (1994) Effects of uniconazole and gibberellic acid application on elongation of hypocotyls and internodes in figleaf gourd for rootstock. *Japan Agricultural Research Quarterly* 28, 195–199.

Oda, M. (1999) Grafting of vegetables to improve greenhouse production. *Food and Fertilizer Technology Center Extension Bulletin* 480, 1–11.

Oda, M. (2002) Grafting of vegetable crops. *Scientific Report of the Graduate School of Agriculture and Biological Sciences, Osaka Prefecture University* 54, 49–72.

Penella, C., Nebauer, S.G., Bautista, A.S., López-Galarza, S. and Calatayud, A. (2014) Rootstock alleviates PEG-induced water stress in grafted pepper seedlings: physiological responses. *Journal of Plant Physiology* 171, 842–851.

Penella, C., Nebauer, S.G., Quinones, A., Bautista, A.S., López-Galarza, S. and Calatayud, A. (2015) Some rootstocks improve pepper tolerance to mild salinity through ionic regulation. *Plant Science* 230, 12–22.

Proietti, S., Rouphael, Y., Colla, G., Cardarelli, M., De Agazio, M., Zacchini, M., Rea, E., Moscatello, S. and Battistelli, A. (2008) Fruit quality of mini-watermelon as affected by grafting and irrigation regimes. *Journal of the Science of Food and Agriculture* 88, 1107–1114.

PSNCK (1982) *Forest Economics*. Rev. Korean edition of original writings of M.S. Hong. Proceedings of the Society of National Culture of Korea, Korea.

Rouphael, Y., Cardarelli, M., Rea, E. and Colla, G. (2008) Grafting of cucumber as a means to minimize copper toxicity. *Environmental and Experimental Botany* 63, 49–58.

Rouphael, Y., Schwarz, D., Krumbein, A. and Colla, G. (2010) Impact of grafting on product quality of fruit vegetables. *Scientia Horticulturae* 127, 172–179.

Ruiz, J.M., Belakbir, A., Lopez-Cantarero, I. and Romero, L. (1997) Leaf-macronutrient content and yield in grafted melon plants. A model to evaluate the influence of rootstock genotype. *Scientia Horticulturae* 71, 227–234.

Sakata, Y., Sugiyama, M., Ohara, T. and Morishita, M. (2006) Influence of rootstocks on the resistance of grafted cucumber (*Cucumis sativus* L.) scions to powdery mildew (*Podosphaera xanthii* U. Braun & N. Shishkoff). *Journal of Japanese Society for Horticultural Sciences* 75, 135–140.

Sakata, Y., Ohara, T. and Sugiyama, M. (2007) The history and present state of the grafting of cucurbitaceous vegetables in Japan.. *Acta Horticulturae* 731, 159–170.

Sakata, Y., Ohara, T. and Sugiyama, M. (2008) The history of melon and cucumber grafting in Japan. *Acta Horticulturae* 767, 217–228.

Salar, N., Salehi, R. and Delshad, M. (2015) Effect of grafting and nitrogen application on yield and fruit quality of grafted and non-grafted melon. *Acta Horticulturae* 1086, 225–230.

Schwarz, D., Rouphael, Y., Colla, G. and Venema, J.H. (2010) Grafting as a tool to improve tolerance of vegetables to abiotic stresses: thermal stress, water stress and organic pollutants. *Scientia Horticulturae* 127, 162–171.

Schwarz, D., Öztekin, G.B., Tüzel, Y., Brückner, B. and Krumbein, A. (2013) Rootstocks can enhance tomato growth and quality characteristics at low potassium supply. *Scientia Horticulturae* 149, 70–79.

Shibuya, T., Itagaki, K., Wang, Y. and Endo, R. (2015) Grafting transiently suppresses development of powdery mildew colonies, probably through a quantitative change in water relations of the host cucumber scions during graft healing. *Scientia Horticulturae* 192, 197–199.

Soteriou, G.A., Kyriacou, M.C., Siomos, A.S. and Gerasopoulos, D. (2015) Rootstock-mediated effects on watermelon ripening behavior and fruit physicochemical and phytochemical composition. *Acta Horticulturae* 1079, 707–714.

Suchoff, D., Gunter, C., Schulthesis, J. and Louws, F.J. (2015) On farm grafted tomato trial to manage bacterial wilt. *Acta Horticulturae* 1086, 119–127.

Temperini, O., Calabrese, N., Temperini, A., Rouphael, Y., Tesi, R., Lenzi, A., Carito, A. and Colla, G. (2013) Grafting artichoke onto cardoon rootstocks: graft compatibility, yield and verticillium wilt incidence. *Scientia Horticulturae* 149, 22–27.

Tsaballa, A., Athanasiadis, C., Pasentsis, K., Ganopoulos, I., Nianiou-Obeidat, I. and Tsaftaris, A. (2013) Molecular studies of inheritable grafting induced changes in pepper (*Capsicum annuum*) fruit shape. *Scientia Horticulturae* 149, 2–8.

Venema, J.H., Dijk, B.E., Bax, J.M., Hasselt, P.R.V. and Elzenga, J.T.M. (2008) Grafting tomato (*Solanum lycopersicum*) onto the rootstock of a high-altitude accession of *Solanum habrochaites* improves suboptimal-temperature tolerance. *Environmental and Experimental Botany* 63, 359–367.

Verzera, A., Dima, G., Tripodi, G., Condurso, C., Crinò, P., Romano, D., Mazzaglia, A., Lanza, C.M., Restuccia, C. and Paratore, A. (2014) Aroma and sensory quality of honeydew melon fruits (*Cucumis melo* L. subsp. *melo* var. inodorus H. Jacq.) in relation to different rootstocks. *Scientia Horticulturae* 169, 118–124.

Vitale, A., Rocco, M., Arena, S., Giuffrida, F., Cassaniti, C., Scaloni, A., Lomaglio, T., Guarnaccia, V., Polizzi, G., Marra, M. and Leonardi, C. (2014) Tomato susceptibility to Fusarium crown and root rot: effect of grafting combination and proteomic analysis of tolerance expression in the rootstock. *Plant Physiology and Biochemistry* 83, 207–216.

Wahb-Allah, M.A. (2014) Effectiveness of grafting for the improvement of salinity and drought tolerance in tomato (*Solanum lycopersicon* L.). *Asian Journal of Crop Science* 6, 112–122.

Xing, W.W., Li, L., Gao, P., Li, H., Shao, Q.S., Shu, S., Sun, J. and Guo, S.R. (2015) Effects of grafting with pumpkin rootstock on carbohydrate metabolism in cucumber seedlings under $Ca(NO_3)_2$ stress. *Plant Physiology and Biochemistry* 87, 124–132.

Yamakawa, B. (1983) Grafting. In: Nishi (ed.) *Vegetable Handbook*. Yokendo Book Company, Tokyo, Japan, pp. 141–153 (in Japanese).

Yang, Y., Wang, L., Tian, J., Li, J., Sun, J., He, L., Guo, S. and Tezuka, T. (2012) Proteomic study participating the enhancement of growth and salt tolerance of bottle gourd rootstock-grafted watermelon seedlings. *Plant Physiology and Biochemistry* 58, 54–65.

Yang, Y., Lu, X., Yan, B., Li, B., Sun, J., Guo, S. and Tezuka, T. (2013) Bottle gourd rootstock-grafting affects nitrogen metabolism in NaCl-stressed watermelon leaves and enhances short-term salt tolerance. *Journal of Plant Physiology* 170, 653–661.

Zhang, Z.-K., Liu, S.-Q. Hao, A.-Q. and Liu, S.-H. (2010a) Grafting increases the copper tolerance of cucumber seedlings by improvement of polyamine contents and enhancement of antioxidant enzymes activity. *Agricultural Sciences in China* 9, 985–994.

Zhang, Z.-K., Zhag, H.L., Huang, Z.-J., Chen, K. and Liu, S.-Q. (2010b) Grafting enhances copper tolerance of cucumber through regulating nutrient uptake and antioxidative system. *Agricultural Sciences in China* 9, 1758–1770.

Zhang, Z.-K., Li, H., He, H.-J. and Liu, S.-Q. (2013) Grafting raises the Cu tolerance of cucumber through protecting roots against oxidative stress induced by Cu stress. *Journal of Integrative Agriculture* 12, 815–824.

Zhao, X., Guo, Y., Huber, D.J. and Lee, J. (2011) Grafting effects on postharvest ripening and quality of 1-methylcyclopropene-treated muskmelon fruit. *Scientia Horticulturae* 130, 581–587.