AN OVERVIEW: TECHNICAL APPLICATION AND ECONOMIC BENEFITS OF GLOBAL VEGETABLE GRAFTING

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ABSTRACT

Driving forward towards an advanced horticultural industry, vegetable grafting has reached a milestone through modern and innovative techniques which came all the way from ancient wisdom. Three methods including hole insertion grafting, tongued approach grafting and splice grafting are recommended for manual and/or automated graftage in cucurbits and solanaceous crops. Based on the actual requirement of growers or nurseries, such techniques obviously solve transplant production problems with minimum impact on the environment. Recommended rootstock-scion combinations include cucurbits grafted onto squash / figleaf gourd and balsam pear grafted onto sponge gourd as well as tomato grafted onto eggplant / tomato. The latest updated information concerning the progress of the nature of grafting and its improvement with various techniques as well as global marketing status of rootstock seeds were briefly reviewed in this study.

Keywords: Grafting, Scion, Rootstock, Cucurbit, Solanaceae, Market Demand, Nursery

INTRODUCTION

Grafting techniques originated in China as early as 1560 B.C., and boomed in the Roman era (Hartmann et al., 2011), numerous different skills have been fully described in the literatures and until now, are widely used in the horticultural industry. An approach of two (or more) diverse living plant tissues joining together and developing as a new composite plant can be considered as a grafting method. The graft partners include a shoot system (scion) and a root system (rootstock) to take advantage of their superior properties for better adaptation with wide range growing conditions. For cucurbits and solanaceous crops, hole insertion grafting, tongued approach grafting and splice grafting are the most common used methods for manual and/or automated graftage.

Nowadays, various rootstocks for grafted vegetable seedlings are mainly used in Asia and in some European countries with more intensive farming on limited land to improve plant yield, control diseases, enhance tolerance to temperature and increase nutrient uptake; whereas the phenomenon is not often found in the U.S. until recent decades, because of crop rotation being practiced on affordable land under cost consideration (Core, 2005). The objective of this study gives a general idea of the current status of industrial grafting techniques of vegetable crops and the global trend of seed markets used for rootstocks.

TECHNICAL APPLICATION

Grafting purposes
Soil-borne diseases, such as Fusarium wilt in cucurbits as well as bacterial wilt and nematodes in Solanaceae, are inevitable particularly in an intensive cropping situation or in open field production with seasonal flooding (Black et al., 2003). Though grafting is the most expensive propagation technique, some vegetable nurseries continue to utilize such a viable method to improve crop quality, yield and better adaptation. In principle, the practical benefits are that vegetable crops grafted on to the disease-tolerant rootstocks can not only be used for integrated pest management but also for reduction in the application of pesticides and soil fumigants (Lee, 1994). For example, cucumber scions are grafted onto figleaf gourd (Cucurbita ficifolia) rootstocks to improve resistance of soil fungal diseases and enhance cold tolerance (Lee, 2003).
**Grafting methods**

Some of the most important grafts for cucurbits and solanaceous vegetables include hole insertion grafting (or terminal / top insertion grafting), tongued approach grafting, and splice grafting (also known as one cotyledon grafting, slant grafting, or Japanese tube grafting) (Hartmann *et al.*, 2011).

In general, watermelon plants prefer the “hole insertion grafting” which removes the true leaf from the rootstock along with the growing point. A bamboo needle is then used or a 1.4-mm size is drilled a bit to open a slit along one side on the hypocotyl of the rootstock, and then a scion is inserted with about 40-degree-angle cut on both end into the rootstock (Hassell *et al.*, 2008).

Cucumber and melon plants use “tongued approach grafting” which includes two stems cut on an angled slit on the rootstock and a downward angled slit on the scion, which provide a tongue-like slit on each stem. A graft union can be obtained after interlocking and sealing these tongues. When both rootstock and scion develop well, the top of the rootstock is cut off five days after grafting, and the bottom of the scion is cut off seven days after the top of the rootstock is removed (Hassell *et al.*, 2008).

Tomato plants are produced by “splice grafting” which is done by a single slanting cut, removal of one rootstock cotyledon attached with the growing point. The scion is then cut and matched with the two cut surfaces together, are held with a grafting clip or silicone sleeve (Hassell *et al.*, 2008). The aforementioned methods are mainly used for grafting disease-resistant rootstocks in vegetable crops and illustrated in Fig. 1.

![Common grafting methods](image_url)

Fig. 1. Common grafting methods used for cucurbits and solanaceous vegetables.  (A) Hole insertion grafting, (B) Tongued approach grafting, (C) One cotyledon grafting which is a form of splice grafting (Illustrations courtesy R. L. Hassell, Hartmann *et al.*, 2011).
To avoid any failure in the propagation of hybrid tomato and pepper cultivars, it is preferable to keep one or more scions from a single seedling. Success depends on whether the cut surfaces are securely matched with clean equipment to avoid unnecessary infections. Grafted plants are generally healed and acclimatized under cover in shade and high relative humidity (>85% RH), which gradually reduced over a period of about a week (Black et al., 2003).

**Graft incompatibility**

Unfavorable physiological responses between the grafting partners, pathogen-induced, or anatomical aberration have been known and discussed to influence graft union success, which can be easily understood as the fundamental biology of grafting and the causes of graft incompatibility to boost new breeding of superior cultivars with wide adaptation for rootstock markets in vegetable crops (Hartmann et al., 2011).

In vegetable crops, grafting is genetically limited to the dicotyledons. This is because vascular bundles in monocotyledons are scattered throughout the stem, instead of the continuous vascular cambium in dicotyledons (Hartmann et al., 2011).

Over the past years, specific vegetable cultivars are bred and used as rootstocks, and some successful crop combinations are commercially applied, such as inter-generic grafting with cucumber onto figleaf gourd, watermelon grafted onto bottle gourd (or squash), melon grafted onto white (or wax) gourd as well as inter-specific grafting between tomatoes and tomato grafted onto eggplant (Table 1).

### Table 1. Recommended scion and rootstock combinations used for vegetable grafting (Passam, 2003; with some modification).

<table>
<thead>
<tr>
<th>Scion</th>
<th>Rootstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watermelon (Citrullus vulgaris syn. C. lanatus)</td>
<td>Bottle gourd (Lagenaria siceraria)</td>
</tr>
<tr>
<td></td>
<td>White gourd (Benincasa hispida)</td>
</tr>
<tr>
<td></td>
<td>Pumpkin / Winter squash (Cucurbita spp.)</td>
</tr>
<tr>
<td>Melon (Cucumis melo)</td>
<td>White gourd (Benincasa hispida Cogn.)</td>
</tr>
<tr>
<td></td>
<td>Pumpkin / Winter squash (Cucumis spp.; Cucurbita spp.)</td>
</tr>
<tr>
<td>Cucumber (Cucumis sativus L.)</td>
<td>Figleaf gourd (Cucurbita ficifolia)</td>
</tr>
<tr>
<td>Balsam pear / Bitter gourd (Momordica charantia)</td>
<td>Sponge gourd (Luffa cylindrica)</td>
</tr>
<tr>
<td>Aubergine / Eggplant / Brinjal (Solanum melongena L.)</td>
<td>Chinese scarlet eggplant / Tomato-fruit eggplant (Solanum integrifolium)</td>
</tr>
<tr>
<td></td>
<td>Wild eggplant / Thai pea-eggplant (Solanum torvum)</td>
</tr>
<tr>
<td></td>
<td>Aubergine / Eggplant / Brinjal (Solanum melongena L.)</td>
</tr>
<tr>
<td>Tomato (Lycopersicon esculentum)</td>
<td>Tomato (Lycopersicon esculentum)</td>
</tr>
<tr>
<td></td>
<td>Aubergine / Eggplant / Brinjal (Solanum melongena L.)</td>
</tr>
</tbody>
</table>

**Graft flaws**

Sometimes poor grafting gets the cambial regions of both rootstock and scion out of alignment, so that graft union formation from the scion may be initiated and developed. Once high temperature and high transpiration occurs, water movement through rootstock can not be supplied, and thus the scion subsequently dies. Other operating errors which led to graft failure include uneven cut, use of desiccated scion, and improper way of holding between the grafting partners (Hartmann et al., 2011).

**Successful grafting**

Success in grafting relies on the quality and selection of both rootstock and scion materials, and craftmanship as well as the proper care for the grafted plant. There are some critical considerations required for successful grafting, including: (1) Whether both rootstock and scion are compatible or not; (2) Whether both cut surfaces of vascular cambiums on rootstock and scion are held properly or not? (3) Whether the grafting operation is done when both rootstock and scion are raised with one or two true leaves or not; (4) Whether all cut surfaces are well-protected from drying out, right after finishing the grafting operation; and (5) Whether the aftercare for new grafts is continuous given till healing and acclimatization are completed or not? (Hartmann et al., 2011).
**Grafting automation**

To relieve the burden of labor shortages and the growers’ demands during the busy season, efforts have been made to mechanize these labor-intensive and time-consuming manual processes. Japan is the first country in the world that invented vegetable grafting robots. A prototype of a grafting robot was initially developed for cucurbits (Onoda et al., 1992). In recent decades, several models for both semi and/or fully automated vegetable grafting robots have been commercialized by different agricultural machine companies in Japan, Korea, Spain and the Netherlands. Automated operations of vegetable grafting done by one or two persons use rootstock/scion feeder, plastic grafting clips / elastic plastic tube, or adhesives to connect the grafted partners. Such a modern technology has been applied for the commercial greenhouse production of cucurbits and solanaceous vegetable crops, particularly in Japan, Korea and Europe.

**Chemical application**

To be centered in the concept of integrated pest management, grafting is not the only way to resist pathogen and nematodes in horticultural practices. Compared to the eco-friendly alternatives with some use restrictions, methyl bromide was firstly used in France as a soil fumigant in the 1930s, and has been proven to be the most consistently effective way to eliminate nematodes, fungi, insects and weeds for cucumber, tomato and peppers (Rosskopf et al., 2005). Regarding environmental issues, an international treaty banning methyl bromide was signed in 1987 to protect the atmospheric ozone layer without thinning. This was adapted by developed countries under the Montreal Protocol in 2005 (Meadows, 2013).

Fatty alcohol (C_{10} or a mixture of C_{6}-C_{12} saturated fatty alcohol) is one of practical methods and acts by giving contact kill onto tobacco suckers. Recently, Daley and Hassell (2014) reported that application of fatty alcohol compounds onto shoot apical meristems of the rootstock could control their regrowth, so as to decrease the cost of grafted watermelon transplant production with less labor. At the optimal concentration (7±0.5\%) of fatty alcohol, no harm was observed during the grafting procedures. Likewise, application of fatty alcohol at effective concentration (10-15\%) onto the target buds could inhibit redundant axillary shoots close to growing out tomato rootstock cotyledons (Eguchi and Kubota, 2015). Such a chemical application can relatively reduce transplant production cost and labor of commercial grafted watermelons and tomatoes.

**ECONOMIC BENEFITS**

**Vegetable rootstock**

For vegetable crops, watermelon grafted onto squash rootstocks was initially reported in 1927, and scarlet eggplant (Solanum integrifolium) rootstock was introduced into the production of eggplants in the 1950s (Oda, 2008). In Taiwan, grafted seedlings of watermelon and tomato were commercially produced in the nursery dating back to the 1970s and 1980s, respectively.

So far, many rootstock cultivars have been developed and extensively used for cucurbits and solanaceous vegetable crops. Mohamed et al. (2012) compared the effects of watermelon ‘Aswan’ F1 hybrids grafted onto current commercial F1 rootstock cultivars (‘Nun 6001’, ‘Strongtosa’ and ‘Tetsukabuto’) on fruit yield and fruit weight with non-grafted plants during spring-summer season. Both rootstock ‘Nun 6001’ and ‘Tetsukabuto’ were significantly higher than ‘Strongtosa’ and control on fruit yield and fruit weight in 2011. Compared to the variances of rootstock ‘Nun 6001’, those of rootstock ‘Tetsukabuto’ occurred in 2010 might be greatly caused by environmental stress (Fig. 2).
Fig. 2. Effects of Watermelon ‘Aswan F1’ grafted onto various commercial rootstock squash F1 cultivars on (a) Fruit yield per plant, (b) Fruit yield per hectare, (c) Fruit weight during spring-summer season of 2010-2011. Values followed by the same letter are not significantly different at the 0.05% level of probability according to Duncan’s multiple range test (Mohamed et al. 2012).

Rootstock breeding
Since the late 1990s, there have been a number of excellent rootstock cultivars being developed by Known-You Seed Co., Ltd. to improve the crop yield and overcome soil-borne diseases and nematodes. In cucurbits, watermelon ‘Knight’, bottle gourd ‘S-1’, winter squash ‘Strong Man’ and ‘Tetsukabuto’, figleaf gourd ‘White Skin’ as well as sponge gourd ‘Companion’ and F-1560 are widely used for nursery. In Solanaceae, tomato T-3047 as well as eggplant ‘Fond May’ and F-1954 are recommended for grafting use.
Rootstock industry

Due to increased disease attack and environmental tolerance, the maximum pest resistance package, seedling vigor and wide adaptability have become more important to develop a full range of rootstocks for the grafting market. Based on the recent market information, Raymond (2013) indicated that Europe (Italy, Greece and Spain) almost has taken 50% of grafted cucurbit crops. This was followed by Asia (Japan, Korea, Taiwan, China and probably including Middle East) and Africa (Morocco, Tunisia and Senegal) with about 25% for each. Besides, Europe (Spain, Netherlands, France and Italy) and Asia (Japan, Korea and Taiwan) have taken near to 40% of grafted Solanaceae crops in each, and the rest are Africa (Morocco and Tunisia) and North America (Mexico) with about 10% for each. In general, rootstock is a very important industry in Europe, regardless of whether they are cucurbits and/or solanaceous crops. However, the seed price is a key factor in entering the market, because of the keen competition in similar cultivars.

For current commercial rootstock squash cultivars, ‘Strong Man’ and ‘Tetsukabuto’ have been successfully introduced to the global markets over the past decade, such as Taiwan, China, the Middle East and Europe (Figure 3). Except 25 million seeds in 2011, the total annual quantity of rootstock squash ‘Strong Man’ was approximately 10 to 15 million seeds in the Greater China region. In Taiwan, ‘Strong Man’ is the most dominant cultivar used for grafting cucurbits, especially diploid watermelons. Though there is more market potential in China, limited market share (about four million seeds per year) of this cultivar could be steadily maintained on a highly competitive basis in recent three years (Fig. 3A). Compared to ‘Strong Man’, the total market demand of ‘Tetsukabuto’ is gradually rising up and has dramatically doubled since 2013, where there was a greater market potential in the Middle East during past three years (Fig. 3B).

In addition, current commercial sponge gourd cultivars used for rootstocks, such as ‘Companion’ and F-1560, mainly sell to the Greater China region (Figure 4). For ‘Companion’, the seed sales reached a stable fluctuation ranging from 350,000 to 450,000 seeds during 2009-2015 in Taiwan. This cultivar was then introduced to China in 2011, but performed dramatically due to scion and rootstock sold in pairs which were reflected on sales quantity (Fig. 4A). For F-1560, growers’ requirement declined in Taiwan during the past decade; however, it became very popular in China while it was introduced in 2011, boomed in 2013, reached the apex of one million seeds in 2014, and dropped in 2015 due to seed shortage (Fig. 4B). Interestingly, the sales of F-1560 performed diversely in different locations, which might be dependent on the usual grafting practice. The nurseries in Taiwan considered that slim stems are hard to operate while grafting and thus they prefer to use ‘Companion’ instead. However, F-1560 is more effectively resistant to Fusarium wilt, so its sales performance in China was overwhelmingly much better than that of ‘Companion’.

Fig. 3. Annual quantity of squash seeds used for rootstocks from 2006 to 2015: (A) ‘Strong Man’ sold to Taiwan and China. (B) ‘Tetsukabuto’ sold to the Middle East, Taiwan and Europe. (Source: Data compiled from Known-You Seed Co., Ltd.)

Fig. 4. Annual quantity of sponge gourd seeds used for rootstocks from 2006 to 2015: (A) ‘Companion’ sold to Taiwan and China. (B) F-1560 sold to the Middle East, Taiwan and Europe (Source: Data compiled from known-You Seed Co., Ltd.)

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In Fig. 5, eggplant rootstock cultivars are commonly used for grafting tomato in Taiwan, and ‘Fond May’ has been commercialized for the past decade. An excellent cultivar called F-1954 was successfully introduced to the market in 2015 and had taken parts of market share of ‘Fond May’, because of better disease resistance. A few local nurseries favored to graft with Tomato rootstock T-3047, because it does not only provide a superior grafting compatibility but also to avoid some symptoms of physiological disorder (such as blossom-end rot and small fruits) caused by eggplant rootstocks.

**Local nursery**

Owing to a severe threat of pathogens and nematodes under intensive farming, professional vegetable nurseries with manual operation in Taiwan have been springing up in recent decades. At present, watermelon and tomato are the major crops among grafted vegetables. To solve the pathogen and environmental stress, the Government, Academia and AVRDC–The World Vegetable Center in Taiwan have also been striving to develop some suitable methods used for vegetable grafting, particularly in smallholder farming systems.

Face to face interviews with local nurseries are able to easily touch the core problem and industry demand. Now, the peak season of vegetable grafting in Taiwan is from July to September every year. To avoid any delay of transplanting time, all nurseries have to do their best efforts and complete the
orders to ship out the grafted plants to growers on time. The maximum capacity of taking such orders is testing the managing wisdom of each nursery owner. Lack of sufficient experienced labor is the first problem that one can face up to the existing situation immediately, and subsequently numerous and spacious healing equipment are the next barrier for nursery, even though one has enough manpower to take all orders (personal communication).

Concerning the first issue, one may consider sorting it out using grafting robots. Indeed, grafting automation is by far the best solution to overcome the problem of labor shortage. However, the high cost of mechanization is scaring away potential buyers. Ideally, US$10,000 to US$15,000 per grafting robot will be helpful to expand the utilization of grafting automation for local nurseries. Yet, certain crop restriction on a single machine, such as stem diameter of scion and rootstock, replacement of different grafting tubes/links, and so on could also be doubtful. This is because nurseries need to take the orders from farmers of diverse crops to meet each grower’s demand, instead of doing one crop/cultivar only. As for the second concern, healing rooms are also a considerable investment for those nurseries with limited spaces.

Currently, the growers are better aware of the benefits in using grafted plants to ensure their harvest without being ruined by pests. By reducing regular practice of plowing to once a year (normally twice a year), the growers are willing to pay relatively high cost of grafted plants under successive planting conditions. Prior to the popularization of grafting automation, nurseries in Taiwan have found out some ways to balance the aforementioned problems: (1) It is required to make a forecast to seed companies at least one year ahead, so seed suppliers can arrange the production plan accordingly. (2) Though the labor hiring is concentrated on the peak season, it is better to keep employees’ jobs extended to a full year. As grafting demands never decline even in the off-season, various vegetable crops depending on their sowing time can be developed to maintain the persistent manpower and labor cost. (3) Mutual assistance is also very important between nurseries, reliable alliance partners can gain from dividing the orders.

CONCLUSION

Grafting acts synergistically on the rootstock-scion relationship and thus has greater benefits than the sum of its parts. However, the nature of the rootstock-scion relationship is very complex and a prediction of graft combinations even within the same species is still limited. Without any exception, any new rootstocks engaged with given scions rest on repeated trial-and-error processes. Since grafting is a repetitive and labor-intensive process, grafting automation can alleviate labor shortage for the vegetable nursery industry during the peak season. Yet, many nurseries are hesitating to invest such technical application owing to high cost of grafting robots. Ultimately, affordable equipment should expand future grafting possibilities.

REFERENCES


