Tomato

General information

Tomato (Solanum lycopersicum) is one of the most important and widely cultivated vegetable crops in the world. Grafting onto resistant rootstocks was first introduced to vegetable production in Japan and Korea in the late 1920s as a strategy against Fusarium wilt and other diseases (Tateishi, 1927). In North America, innovations in tomato grafting occurred during the 1930s and 1940s when tomato was grafted onto jimson weed (Datura stramonium L.) as a method for root-knot nematode control. However, the practice was discontinued due to evidence of the transport of alkaloids to the fruit from the rootstock (Lowman and Kelly, 1946; Peacock et al., 1944).

Grafting has gained popularity as a method to manage plant diseases previously controlled by soil fumigation with methyl bromide. Some of the most significant soil-borne pest problems for which resistant rootstocks may be beneficial include root-knot nematodes (Meloidogyne spp.; Kokalis-Burelle and Rosskopf, 2011; Barrett et al., 2012a), Verticillium wilt (Verticillium albo-atrum and V. dahliae), and southern blight (Athelia rolfsii anamorph Sclerotium rolfsii) (Rivard et al., 2010).

Bacterial wilt caused by Ralstonia solanacearum is a significant concern for tomato producers in many regions. Rivard and Louws (2008) have reported inadequate control of bacterial wilt with soil fumigants such as methyl bromide, chloropicrin, and a combination of chloropicrin and 1,3-dichloropropene. The pathogen has a wide host range and persists in the soil for long periods of time, making crop rotation ineffective, and forcing farmers to abandon fields as losses can rapidly reach 100%. Additionally, tomato varieties with resistance to bacterial wilt often produce small, unmarketable fruit. Thus, some resistant tomato cultivars are used as rootstocks, making grafting an important
option to manage bacterial wilt for the tomato industry. For some diseases, rootstocks may have to be selected with resistance to a specific race of the pathogen. This is the case for rootstocks resistant to *Fusarium oxysporum* f. sp. *lycopersici* (Fol), the cause of Fusarium wilt in tomato. Many of the rootstocks that are commercially available have resistance to races 1 and 2 of this pathogen, but few have resistance to race 3 of Fol, which is more limited in its distribution but is becoming increasingly more common, particularly in the southeastern United States. One commonly available rootstock, interspecific hybrid ‘Maxifort’ (*S. lycopersicum × S. habrochaites*), has resistance to Fol races 1 and 2 as well as crown rot, *F. o.* f. sp. *radici-lycoperisici*.

Tomato can be impacted by a number of abiotic stressors that grafting can ameliorate. Salinity, for example, has become a worldwide agricultural concern. Salt tolerant rootstocks have the potential to overcome osmotic stress, ion toxicity, and nutrient imbalances under high salinity (Colla et al., 2010). Under experimental conditions, grafted tomato plants resulted in 40-80% increase in yield compared to non-grafted or self-grafted plants at 50 mM NaCl (Santa-Cruz et al., 2002; Estañ et al., 2005; Martinez-Rodrigues et al. 2008). Interestingly, the scion and rootstock selection both have an influence on tolerance to salinity as well as on the mechanism of tolerance (Di Gioia et al., 2013; Giuffrida et al., 2014). In addition to salinity, the use of tomato rootstocks that are interspecific hybrids or wild accessions of *S. habrochaites*, a high-altitude wild tomato relative, has the potential to improve root growth and yield under sub-optimal (15 °C) temperatures (Venema et al., 2008). Similarly, but not as extensively studied, is the development of tomato rootstocks that maintain fruit yield under drought conditions and high temperature (Schwarz et al., 2010). Commonly, grafted tomato is used to increase plant vigor and yields and to extend harvest periods in protected cultivation (Kubota et al., 2008; Lee, 1994).

Grafting tomato has become essential for many heirloom tomato growers. Heirloom tomatoes lack resistance to soil-borne diseases and are typically heterogeneous because they are open-pollinated. Grafting allows for disease resistant rootstocks with improved plant vigor and disease resistance to be paired with scions that maintain high fruit quality and the desirable flavor associated with heirloom varieties (Rivard et al., 2011).

### Table 1. Commonly used rootstock cultivars for tomato, and their disease resistance/susceptibility.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Tomato Mosaic Virus</th>
<th>Fusarium Crown Rot (Fusarium oxysporum f.sp. radici-lycoperisici)</th>
<th>Fusarium Wilt (Fusarium oxysporum f. sp. lycopersici)</th>
<th>Verticillium Wilt (Verticillium albo-atrum &amp; V. dahliae)</th>
<th>Bacterial Wilt (Ralstonia solanacearum)</th>
<th>Root-knot Nematodes (Meloidogyn e spp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor-T</td>
<td>R</td>
<td>N/A</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Arnold</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>N/A</td>
<td>R</td>
</tr>
<tr>
<td>Beaufort</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>N/A</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Body</td>
<td>R</td>
<td>N/A</td>
<td>S</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Estamino</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Maxifort</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>S</td>
<td>R</td>
</tr>
<tr>
<td>Multifort</td>
<td>S</td>
<td>R</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>RT-04-105T</td>
<td>S</td>
<td>R</td>
<td>R</td>
<td>S</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>RT-04-106T</td>
<td>R</td>
<td>S</td>
<td>R</td>
<td>S</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>

R = Resistant, S = Susceptible, N/A = not characterized
Some commonly used rootstock cultivars and their disease resistance/susceptibility are listed in Table 1. There are approximately 60 rootstocks commercially available for tomato grafting, consisting of primarily hybrid tomato rootstocks and interspecific hybrid tomato rootstocks. Availability of rootstocks changes regularly, and an extensive list is available on the vegetable grafting research-based information portal www.vegetablegrafting.org, under Resources (http://www.vegetablegrafting.org/wp/wp-content/uploads/2015/02/usda-scri-tomato-rootstock-table-feb-15.pdf).

Choosing the rootstock and scion
When grafting tomato, careful rootstock selection, timing, and attention to healing and planting in the field are essential for successful production of healthy transplants. Rootstocks that are specifically chosen for disease resistance should be selected based on disease pressure at the planting location. Assistance in the identification of diseases can be obtained by contacting your county extension agent or contacting a local plant disease diagnostic facility (https://www.apsnet.org/members/directories/Documents/SoilLabsandPlantClinics.pdf). Scions are chosen based on desired fruit characteristics and quality. Scion and rootstock compatibility is important when selecting plant material. One important consideration, particularly when using heirloom tomato cultivars as the scion, is the presence or absence of genes for resistance to Tomato mosaic virus (ToMV).

Many hybrid rootstocks have Tm-2 or Tm-2\textsuperscript{2} resistance genes that provide resistance to most known ToMV isolates, while heirloom scions have none or “low” resistance conferred from the Tm-1 gene. When scion and rootstock do not have the same genes for resistance, grafted tomato are more likely to fail when infected with ToMV (Yamakawa, 1982). This is a critical consideration for selecting rootstocks for heirloom tomato, and more information can be found in Rosskopf et al. (2013).

Grafting method, equipment, and procedures
Splice grafting, also known as “Japanese top-grafting” or “tube-grafting,” is the most commonly used technique when grafting Solanaceous crops. Cleft and side grafting are the other two main grafting techniques used to graft tomato.

Before starting to graft, it is important to arrange a clean and functional grafting area and make sure you have all the required equipment and tools:
- Healing chamber
- Disposable razor blades or scalpels to cut scion and rootstock plants.
- Silicone grafting clips to secure the rootstock and scion together and minimize water loss at the graft union.
- Antibacterial soap to sanitize hands.
- Spray bottles to mist plants with water during the grafting process.

Sanitation is extremely important for successful grafting, as plant pathogenic bacteria and viruses can be passed plant-to-plant from hands, cutting surfaces, and tools. Therefore, particular care is required in cleaning the

Figure 1. Tomato seedlings ready for grafting. (Photo by Erin Rosskopf)
grafting area and cleaning or changing razor blades frequently.

When grafting, regardless of the method used, it is critically important to have good contact between the scion and rootstock vascular systems. This is accomplished by grafting plants with similar stem diameters. Plants should be grafted when plants have 2–4 true leaves and stem diameters between 1.5–2.5 mm (Fig. 1).

For this purpose, it is important to define the grafting timeline (Fig. 2).

Conduct a germination test several weeks prior to grafting in order to determine how long both the scion and the rootstock will take to reach the optimal size, and time seeding accordingly (Hu et al., 2016). Keep plants in a shaded area prior to grafting, and cease watering rootstock plants 12–24 hours prior to grafting.

Figure 3. Splice grafting tomato. (Photos by Cary Rivard)
Splice grafting is achieved by cutting the rootstock and scion stems at a 45° angle, putting the cut edges of the two plants together, and securing with a grafting clip (Fig. 3). It is important to cut the rootstock below the cotyledons to avoid unwanted rootstock regrowth, which would require additional pruning. The scion can be cut below or above the cotyledon, wherever the stem diameter best matches the rootstock.

Once the rootstock is cut, slip the silicon grafting clip onto the rootstock, followed by the scion, making sure that both stems are in tight contact with each other and no air is visible at the graft union. Mist plants frequently with water during the grafting process and place them in the healing chamber in the dark immediately after grafting (Fig. 4).

When adventitious roots from a non-resistant scion come into contact with infested soil, the plant can become infected. Recent research shows that growth of adventitious roots (Fig. 5) can be reduced by removing scion leaves prior to grafting (Meyer et al., 2016). At low humidity (<70%), removing 50% of the leaves reduced scion adventitious root formation; but at 95% humidity, removal of 90% of leaves was required to reduce adventitious root formation. However, when a less vigorous rootstock such as ‘Trooper Lite’ is used, and all true leaves are removed and only the cotyledons remain during grafting, tomato marketable yield is significantly reduced (Masterson et al., 2016).

Healing chamber
Construction of a healing chamber is essential when grafting any type of vegetable, and should be done in advance of grafting. The chamber’s main purpose is to allow the vascular tissue of the newly cut seedlings to reconnect for water and nutrient transport, and to gradually acclimate the plants to greenhouse conditions. To keep the scion from becoming water stressed, the scion’s transpiration rate is slowed during the healing process by increasing the humidity and decreasing the light for several days after grafting. Temperature, humidity and light levels in the healing chamber should remain constant to avoid stress on the plants. The chamber should be maintained be-
between 21 and 27 °C and 80-95% humidity, and light level should be low for 3-5 days (Fig. 2).

The lower the healing temperature, the longer the period of time required for the graft union to heal. Add water to the floor of the chamber or in pans to keep high relative humidity. Do not irrigate or mist plants, as excess water may pull the scion away from the rootstock due to high root pressure, and water on the leaves may accumulate in the grafting clip leading to rot. A cool-mist vaporizer can be used to provide humidity without increasing temperature, but is an added cost. Cover the chamber with plastic sheeting to maintain high humidity, and cover the plastic with dense shade cloth to block light from newly grafted plants.

Gradually acclimate plants to greenhouse conditions. Three days after grafting, open the healing chamber and mist the walls and floor with water. The healing chamber should be left closed and undisturbed for the fourth day, but remove the black cover from the front of the chamber. Increase light levels in the chamber each day so that on day 6 after grafting, the black cover is completely removed. Plants require at least two days at medium light and humidity before they can be moved to the greenhouse, where humidity is low and light levels are high.

In walk-in healing chambers, use fluorescent lights to increase light levels. On days 5, 6 and 7, open the plastic of the healing chamber for 30 minutes, 1 hour, and 6-8 hours, respectively; each day, add water to the floor before closing the chamber again. On day 8, remove plants from the healing chamber and place in the greenhouse. Although plants are fully acclimated, it may take an additional 5-6 days for the graft union to fully heal. It is therefore important to water plants from below to prevent any damage to the recently healed graft union. The grafting clip will gradually open as the stem grows, and will naturally fall off.

Figure 5. Comparison between a robust and high quality grafting union (left) and a poor quality tomato transplant with the development of adventitious roots from the scion (right). (Photos by Francesco Di Gioia)
About 14 days after grafting, plants are ready to be hardened and then transplanted to the field.

**Using grafted plants**
Grafted tomato can be grown in the open field or under “protected” agricultural systems, including greenhouses and high tunnels. The use of high tunnels has increased considerably and allows farmers with small acreage to produce high-quality produce without the large investment of a greenhouse structure. High tunnels also allow for extended production seasons, allowing for earlier plantings and additional harvests and increased economic returns (Galinato and Miles, 2013). While high tunnels can protect tomato from wind and rain, which...
reduces exposure and infection by foliar pathogens, soil-borne diseases remain a problem, which can be alleviated through the use of a disease-resistant rootstock. Grafting an indeterminate tomato scion onto a vigorous rootstock makes it possible to extend the harvest period when environmental conditions are adequate. Grafted tomato plants are increasingly used also in soilless cultivation systems, where, under controlled conditions and with crop cycles extended up to one year, grafted plants can reach their full potential (Fig. 6).

An important factor limiting the extensive adoption of grafted plants is the high cost of grafted seedlings. A solution commonly adopted in commercial tomato production is the use of double-leader grafted seedlings (Fig. 7). The use of double-leader plants halves the plant number, substantially reducing the cost of the plant material.

To produce a double-stem plant, the healed and acclimated grafted seedling is pinched

---

Figure 8. Open-field fresh-market tomato production with a determinate cultivar and the “stake and weave” training system. (Photo courtesy of Francesco Di Gioia)

Figure 9. Grafted tomato plants with indeterminate scion grafted onto a vigorous rootstock raised vertically in a multi-tunnel greenhouse with a simple trellis. (Photo by Francesco Di Gioia)
back to the cotyledonary leaves, to induce the development of two lateral shoots. Plants are then maintained in the nursery for an additional 1 to 3 weeks (Kubota, 2008). Alternatively, a lateral shoot along with the main stem is maintained to form the two main producing shoots.

Cultural practices used in both high tunnels and open-field plantings with indeterminate scions may require modification to maximize productivity. For example, vigorous rootstocks may have increased nitrogen assimilation as well as reduced water usage (Djidonou et al., 2013). While grafting with determinate scions will still require 1-2 “suckering” events, season-long pruning is required with vigorous rootstocks coupled with indeterminate scions. The type of trellis system may also need to be modified.

While a “stake and weave” system is often used in open-field production with determinate varieties (Fig. 8), trellising is needed with indeterminate scions grafted onto a vigorous rootstock (Fig. 9). Trellis systems are attached to a secondary structure, not to the high tunnel hoops, because the trellis system will need to support a significant amount of weight. The trellis can be a single line (Fig. 9) or a woven support system (Fig. 10).

Regardless of the growing environment and system, it is critical that grafted plants are set high enough in the planting hole that the graft union is above the soil line (Fig. 7). Deep planting or having soil in contact with the graft union can negate the benefit of a resistant rootstock by allowing infection of the susceptible scion by soilborne pathogen propagules.

**Success stories**

Several soilborne diseases can result in complete crop loss when susceptible tomato cultivars are grown in infested fields. Two of the most devastating diseases, Fusarium wilt and bacterial wilt, can be successfully managed using resistant rootstocks. In a Florida study using a susceptible scion grafted onto multiple rootstocks with resistance to *R. solanacearum*, the incidence of bacterial wilt was significantly reduced when compared to the non-grafted and self-grafted plantings (Rivard et al., 2012). Total marketable tomato fruit yields using grafted plants increased by 25-99% depending on the severity of the disease (McAvoy et al., 2012). For growers who produce heirloom tomato, either in high
tunnels or open-field, the lack of resistance to soilborne diseases can result in a failed crop. Losses to Fusarium wilt in non-grafted ‘German Johnson’ (GJ) tomato in one field reached 50%, whereas GJ grafted onto ‘Maxifort’ plants experienced no symptoms of disease (Rivard and Louws, 2008). On three farms in Florida, where heirloom tomatoes are grown in both high tunnels and open-field, the incidence of Fusarium wilt had caused the growers to abandon these desirable varieties. Grafting ‘Amana’, ‘Black Cherry’, ‘Prudence Purple’, and ‘Cherokee Purple’ scions onto ‘Maxifort’, ‘Multifort’, and ‘TD-2’ rootstocks made the production and sale of these highly sought-after cultivars possible again (Fig. 11; Rosskopf unpublished).

The ability to grow heirloom tomato with high marketable yields has significantly contributed to farm sustainability. While increases in tomato fruit yield resulting from grafting are relatively consistent, the impact of grafting on tomato fruit quality is variable. Soluble solids, sugar content, and flavor components, as well as taste panel preferences appear to be dependent upon which scion and rootstock combinations are used (Di Gioia et al., 2010; Flores et al., 2010; Barrett et al., 2012b).

Grafting is a valuable tool for tomato producers worldwide. As breeding efforts continue and result in desirable rootstocks, more grafting facilities become available in the United States, and growers learn how to successfully graft their own transplants, grafted vegetable plants will continue to gain acceptance as an effective technique and an economically viable tool to reduce disease incidence and increase yields.
References


