To Graft or Not to Graft?

When is it worth using grafting for your high tunnel tomatoes? How do you select the right rootstock?

As high tunnel tomato growers are starting to plan and purchase seeds for the next growing season, many may be considering whether it is worth it or not to use grafted plants; and if grafting is considered advantageous, the consequent questions may be: What would be the best rootstock? Should I graft myself, or is it better to purchase grafted plants from a specialized nursery?

The answer to these questions is not simple, and what works in one situation may be different in other cases. To assist growers in making such decisions, we briefly describe the principles of this biotechnology and restate why grafting is used and the criteria that should be used to select suitable rootstocks.

The Principles of Vegetable Grafting

Vegetable grafting is a method applied primarily to fruiting vegetable crops (solanaceous and cucurbits) to create a new plant by physically combining two plants, one providing the shoot (scion) with the desired fruit quality traits, and the other providing the root system (rootstock). If rootstock and scion are compatible, after a relatively short healing phase, the vascular bundles within the stems of the scion and rootstock reconnect in correspondence with the grafting union, and the flow of water, nutrients, and phytoregulators is gradually re-established between the two genotypes (Figure 1).
Why Are Grafted Plants Used?

Grafting allows the combination in a single plant of the traits of the desired cultivar of tomato, which may be selected for the high yield, fruit quality, or resistance/tolerance to foliar pathogens, with those of the rootstock, generally selected to provide resistance or tolerance to soilborne pests and pathogens and/or to provide vigor and in some cases to enhance tolerance to abiotic stress conditions.

Vegetable grafting could be considered a shortcut to obtaining a plant with the desired fruit quality traits and a vigorous and resistant root system simultaneously. For instance, through grafting, it is possible to cultivate high-quality heirloom tomatoes that otherwise would be highly susceptible to soilborne pathogens (Di Gioia et al., 2010). Obtaining a similar plant with good fruit quality traits and resistance/tolerance to biotic and abiotic stress conditions through standard tomato breeding may not always be feasible and certainly would require a long time and a substantial research investment.
Grafting for the Management of Soilborne Pests and Pathogens

Vegetable grafting is primarily considered an Integrated Pest Management (IPM) tool for managing soilborne pests and pathogens and constitutes an environmentally sustainable alternative to the use of chemical fumigation. Grafting can be integrated with other agronomic solutions such as the use of resistant cultivars, crop rotation, cover crop, and other biocontrol approaches such as anaerobic soil disinfestation.

Tomato grafting with resistant or tolerant rootstocks has been successfully used to overcome soilborne pest and pathogen issues that are present in our soils such as Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*), Fusarium crown and root rot (*Fusarium oxysporum* f. sp. *radicis-lycopersici*) (Rivard and Louws, 2008), Verticillium wilt (*Verticillium albo-atrum* and *V. dahliae*), and root-knot nematode (Meloidogyne spp.) (Kokalis-Burelle and Rosskopf, 2011; Barrett et al., 2012). Moreover, grafting may provide resistance to viruses (Spanò et al., 2020) as well as to southern bacterial wilt (*Ralstonia solanacearum*) (Rivard and Louws, 2012) and southern blight (*Athelia rolfsii* anamorph *Sclerotium rolfsii*) (Rivard et al., 2010) a pathogen that is moving north (Figure 2).

In Pennsylvania, the intensification of vegetable production associated with the increased adoption of high tunnels with limited crop rotation opportunities is leading to soil health issues and the emergence of several soilborne pests and pathogens, including Fusarium wilt (Figure 3), Fusarium crown and root rot, Verticillium wilt, and root-knot nematodes. The use of grafted plants with resistant rootstocks is highly recommended in the presence of these specific pest and pathogen issues.

Figure 2. Detail of a tomato plant affected by southern blight (*Athelia rolfsii*) with the typical white mycelium and light-brown reddish sclerotia observed in Pennsylvania. Photo by Francesco Di Gioia, Penn State.
Figure 3. An example of a non-grafted tomato plant affected by Fusarium wilt (caused by *Fusarium oxysporum* f. sp. *lycopersici*) manifested with typical yellowing on one side of the leaf (left), browning of the vascular system and consequent wilting of the plant (right). Photo by Francesco Di Gioia, Penn State.

Figure 4. An example of a tomato root system affected by root-knot nematodes (caused by *Meloidogyne incognita*) manifested with typical root galling. Photo by Francesco Di Gioia, Penn State.

Selecting the Right Rootstock

The rootstock selection should be based primarily on the level of resistance/tolerance provided to specific soilborne pests and pathogens that we have or are likely to have in our soil. A second aspect to consider is the rootstock’s vigor and potential capacity to tolerate abiotic stress conditions.

If you are observing diseased plants, plant wilting, yellowing, or a consistent general decline of your tomato crop and yield, it may be time to check your soil and the health of the plant root system to identify the main cause of the problem. You can submit your diseased plants to the Penn State Plant Disease Clinic. Inspecting the root system during or at the end of the growing season may allow you to identify visible root damage or discoloration, limited root growth, and root galling in the case plants are affected by root-knot nematodes (Figure 4). If the issue is caused by root-knot nematodes, a good option would be to submit soil samples and conduct a nematode assay through the North Carolina Department of Agriculture & Consumer Services Agronomic Division. The nematode assay may allow for determining the level of infestation and the nematode species causing the problem. Once you have identified the main cause of the issue, and there could be several concurring causes, it will be good to check what rootstocks can provide resistance or tolerance to such issues.

As reported in Table 1, several tomato rootstocks available on the market can provide resistance to Corky root rot, Fusarium crown, and root rot, Fusarium wilt, Verticillium wilt, root-knot nematodes, as well as to tomato mosaic virus.

Table 1. Example of commercial tomato rootstocks and their resistance/tolerance or susceptibility to the main pest and pathogen issues affecting tomatoes in Pennsylvania. 1

<table>
<thead>
<tr>
<th>Commercial rootstock</th>
<th>Corky root rot (Pi)</th>
<th>Fusarium Crown Rot (For)</th>
<th>Fusarium wilt (Fol)</th>
<th>Verticillium wilt</th>
<th>Tomato Mosaic Virus</th>
<th>Root-knot Nematodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armstrong</td>
<td>IR</td>
<td>HR</td>
<td>HR (Fol: 1, 2)</td>
<td>HR</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
</tr>
<tr>
<td>Arnold</td>
<td>IR</td>
<td>IR (Fol: 1, 2)</td>
<td>IR (V, Va, Vd)</td>
<td>IR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>Rootstock</td>
<td>Resistance Type</td>
<td>Description</td>
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<tr>
<td>Balance</td>
<td>IR</td>
<td>HR (Fol: 1, 2, 3)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>Beaufort</td>
<td>HR</td>
<td>HR (Fol: 0, 1)</td>
<td>HR (Va: 0, Vd: 0)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>Bowman</td>
<td>IR</td>
<td>HR (Fol: 1, 2, 3)</td>
<td>HR (Va: 1, Vd: 1, 2)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
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<tr>
<td>DRO138TX</td>
<td>HR</td>
<td>HR (Fol: 1, 2)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
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<tr>
<td>DRO141TX</td>
<td>HR</td>
<td>HR (Fol: 1, 2)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>Estamino</td>
<td>HR</td>
<td>HR (Fol: 0, 1, 2)</td>
<td>HR (Va: 0, Vd: 0)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
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<tr>
<td>Fortamino</td>
<td>HR</td>
<td>HR (Fol: 0, 1, 2)</td>
<td>HR (Va: 0, Vd: 0)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
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<tr>
<td>Guardian</td>
<td>R</td>
<td>R (Fol: 3)</td>
<td>R</td>
<td>R Tm</td>
<td>R (N)</td>
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<tr>
<td>Kardia</td>
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<td>HR (Va, Vd)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
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<tr>
<td>Maxifort</td>
<td>HR</td>
<td>HR (Fol: 1, 2)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
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<tr>
<td>Multifort</td>
<td>HR</td>
<td>HR (Fol: 1, 2, 3)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>Protector</td>
<td>IR</td>
<td>HR (Fol: 0, 1, 2)</td>
<td>HR (Va: 0, Vd: 0)</td>
<td>HR/R (Tm) HR (ToMV: 0, 1, 2)</td>
<td>HR/R (Ma, Mi, Mj)</td>
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<tr>
<td>Rootpower</td>
<td>HR</td>
<td>HR (Fol: 0, 1)</td>
<td>HR (Va, Vd)</td>
<td>HR (ToMV)</td>
<td>IR (Ma, Mi, Mj)</td>
<td></td>
</tr>
<tr>
<td>RST-04-105-T</td>
<td>HR</td>
<td>HR (Fol: 1, 2, 3)</td>
<td>HR</td>
<td>S</td>
<td>HR</td>
<td></td>
</tr>
<tr>
<td>RST-04-106-T</td>
<td>CR</td>
<td>Fol: 1, 2, 3</td>
<td>S</td>
<td>MCR (ToMV) Suitable R (Tm)</td>
<td>CR</td>
<td></td>
</tr>
<tr>
<td>RST-04-107-T</td>
<td>CR</td>
<td>CR</td>
<td>CR</td>
<td>MCR (TMV)</td>
<td>CR</td>
<td></td>
</tr>
<tr>
<td>Synergy</td>
<td>IR</td>
<td>HR (Fol: 1, 2, 3)</td>
<td>HR (Va: 1, Vd: 1)</td>
<td>HR (ToMV: 0, 1, 2)</td>
<td>IR (Ma, Mi, Mj)</td>
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</table>


The present table is not exhaustive of all the rootstocks commercially available, and a more complete list is available through the Vegetable Grafting website.

In selecting the rootstock, it should be considered that sometimes the rootstock provides resistance only to specific races of pathogens, such as Fusarium wilt and Verticillium wilt. Diseases like Fusarium root and crown rot (For) caused by *Fusarium oxysporum* f.sp. *radicis-lycopersici* (Figure 5) can also be transmitted through the seeds, and the use of resistant rootstocks may avoid the manifestation of the disease.
In selecting the rootstock, particular attention should be given to the compatibility between rootstock and scion. If there are well-known incompatibility issues, the rootstock seed company should report those. A possible incompatibility issue between rootstock and scion may be associated with the tomato mosaic virus (ToMV) susceptibility/resistance. Most rootstocks provide high resistance to ToMV. However, grafting a susceptible heirloom tomato variety affected by ToMV onto a highly resistant rootstock may cause incompatibility issues (Figure 6). Therefore, selecting rootstock compatible with heirloom varieties susceptible to ToMV should be done carefully, considering that these plants may be compatible only with rootstocks that are susceptible to ToMV.

**Grafting for Plant Vigor and Tolerance to Abiotic Stress Conditions**

Grafted plants are also used for their enhanced plant vigor, which can benefit high tunnel production systems given the longer crop cycle and harvesting season. The vigor of grafted plants is defined by the vigor of the rootstock selected and is modulated by the rootstock-scion interaction; therefore, selecting both rootstock and scion is critical to have a good synergy. Vigorous rootstocks may also be beneficial to face some abiotic stress conditions that may occur during the crop cycle. In Pennsylvania, tomato plants may be exposed to several abiotic stress conditions associated with relatively low and high temperatures, drought, salinity, and/or excess of nutrients (Figure 7). Using grafted plants with a vigorous rootstock may provide more tolerance in facing lower temperatures in an early planting (Venema et al., 2008) and relatively high temperatures over the summer (Schwarz et al., 2010). Yet, the capacity of a larger root system to uptake more water and nutrients (Djidonou et al., 2013) and explore a larger volume of soil may help face drought stress and/or salinity stress (Di Gioia et al., 2013), nutrient excess (Di Gioia et al., 2017), and even lower levels of nutrients.
Most seed companies indicate whether their rootstock is vigorous or not, but there is no standard metric to define the vigor of a rootstock, and the claim of the rootstock seed companies should be verified.

Some growers may be concerned about an excess vigor of grafted plants and a potential delay in fruit ripening or a negative impact on the fruit quality. For this reason, some seed companies are breeding rootstocks that they claim to be more regenerative, but this should also be verified.

Our research conducted at the Penn State High Tunnel Research Facilities shows that in a high tunnel, the use of grafted tomato plants with a vigorous rootstock may improve the nitrogen use efficiency and provide higher marketable yield and extra-large fruit compared to non-grafted plants even in the absence of soilborne pests and pathogens or abiotic stress conditions (Blunk, 2022). We
observed a slight delay in fruit ripening only for a week or two at the beginning of the season and no consistent negative or positive effects on the fruit quality. Due to the higher plant vigor and biomass produced, grafted plants need additional trellising compared to non-grafted plants, and a hanging trellising system rather than stakes may be beneficial if grafted plants are used (Figure 8).

Besides the trellising, a simple but very important recommendation, often forgotten or given for granted, is that grafted plants should be transplanted, maintaining the grafting point well above the soil surface (Figure 9). This is critical because if the scion is covered or comes in close contact with the soil, it may easily develop adventitious roots and bypass the rootstock. When this happens, the resistance or tolerance to soilborne pests and pathogens and all the potential advantages provided by the rootstock may be lost.

Figure 8. Example of hanging trellising systems used for grafted tomato plants in a high tunnel. Photo by Francesco Di Gioia, Penn State.

Figure 9. Example of grafted tomato plant correctly planted with the grafting point above the ground surface. The silicon grafting clips should be left on the grafting point, and they will come off by themselves as the stem is growing. Photo by Francesco Di Gioia,
Economic Considerations

From an economic point of view, it is important to consider that the cost of production of grafted plants is usually higher than non-grafted plants. However, under the conditions of our study, the economic analysis revealed that despite the higher cost, grafted tomato plants were more profitable due to the higher yield, even in the absence of biotic and abiotic soil-level stressors (Blunk, 2022). Figure 10 shows the estimated cumulative income derived from Red Deuce tomato plants non-grafted or grafted onto DRO141TX for a 30’ × 96’ high tunnel calculated by multiplying the marketable yield provided by the grafted and non-grafted plants throughout the growing season by the weekly red fresh-market tomato prices recorded at the Leola Produce Auction during the 2021 growing season. Similar results were obtained during the 2020 growing season. Based on the results of our two-year study and previous studies, our experience suggests that in a high tunnel or greenhouse production system, the longer the crop cycle, the higher the potential benefits and return of investment on using grafted tomato plants.

Figure 10. Cumulative income estimated over the 2021 trial season for a 30’ × 96’ high tunnel. Income was calculated using weekly marketable yield multiplied by the corresponding weekly red fresh-market tomato prices recorded at the Leola Produce Auction (Blunk, 2022).

The choice of grafting tomato plants on your own farm versus purchasing grafted plants from a specialized nursery is primarily a personal choice. Even though in some cases grafting on your own may be more cost-effective than purchasing grafted plants, the actual prospect of grafting plants on your own farm is dependent on the availability of time, specialized labor, proper greenhouse facilities, and adequate understanding and experience of the grafting process. Not always doing your own graft is the cheaper option. The costs of these two strategies must be carefully weighed against each other.

Grafting tomato plants require some planning, experience, and a particular set-up for the healing process, as described in the following Vegetable Grafting Manual (Rosskopf et al., 2018). Therefore, more and more growers prefer to rely on nurseries specializing in the production of grafted plants. In Pennsylvania, it is possible to purchase grafted plants from local nurseries, or plants can be shipped from a long distance as long as the order is placed on time. Specialized nurseries can produce plants with the rootstock-scion combination of your choice right on time for your defined planting date. Having experience with different grafting combinations may provide suggestions on alternative rootstocks and rootstock-scion combinations. Of course, the quality of grafted plants may determine the success of your crop, so the choice of grafting on your own or the selection of the nursery that will produce your plants are important choices.

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