Original article

# Effect of grafting on yield of commercial tomato cultivars grown under bacterial wilt (*Ralstonia solanacearum*) infested soil

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## Summary

*Introduction* – **Grafting is a chemical-free intervention and an environmentally friendly method for controlling soil-borne diseases and abiotic stresses such as flooding. Tomato grafting is a well-known practice for bacterial wilt management, but constrained by the presence of multiple strains of its causal agent *Ralstonia solanacearum*. The effect of grafting on susceptible tomato cultivars grown under phylotype I, sequevar 1-31 strain infested soil was assessed to help tomato producers in the long term.** *Materials and methods* – **Tomato cultivars 'Anna F1' and 'Tanya' (susceptible) and 'Tengeru 97' (resistant) were grafted on a resistant rootstock line Hawaii 7996 and evaluated under infested greenhouse soil in Arusha, Tanzania in 2016 and 2017. Wilt score, yield, and other horticultural traits were collected from a randomized complete block design experiment with three replications.** *Results and discussion* – **Grafting delayed flowering, and slowed down plant growth at the initial growth stage as observed from plant height measured at flowering. Grafted 'Anna F1' and 'Tanya' gave significantly higher marketable fruit numbers, size and yields than the corresponding un-grafted controls. Percent wilted plants reached 100, 98 and 12% in un-grafted 'Anna F1', 'Tanya' and 'Tengeru 97', respectively, against 13, 15 and 18% in grafted combination with 'Hawaii 7996', respectively. Advantage of grafting was evident in 'Anna F1' and 'Tanya', but not in 'Tengeru 97'.** *Conclusion* – **Grafting could play a significant role to exploit the potential of bacterial wilt susceptible cultivars that otherwise have desirable traits. Identifying genes controlling resistance in 'Tengeru 97', characterizing the various strains, and search for new sources of resistance are sought. In parallel, farmers' training in bacterial wilt management to suppress the inoculum load and increase the longevity of 'Tengeru 97' remains essential.**

**Keywords**
bacterial wilt, hybrid cultivar, marketable yield, open pollinated cultivars, rootstock, scion

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## Significance of this study

*What is already known on this subject?*
- Grafted susceptible tomato cultivars overcome many abiotic and biotic stresses and increase marketable fruit yield.

*What are the new findings?*
- Two Tanzanian commercial tomato cultivars could be grown and productive in bacterial wilt (phylotype I, sequevar 1-31 strain) infested soils when grafted on a resistant rootstock.
- Under the present conditions, grafting bacterial wilt resistant cultivar had no advantage, and only incurs cost on tomato growers.

*What is the expected impact on horticulture?*
- Grafted bacterial wilt susceptible 'Tanya' and 'Anna F1' are expected to increase the productivity and production of the horticultural sector in Eastern and Southern Africa regions.
- Grafting increases tomato area into bacterial wilt infested soil conditions that in turn increases the production of the horticultural sector.

## Introduction

Tomato is the most popular fruit vegetable cultivated worldwide. Many hot-wet tropical and subtropical climate areas suitable for the crop cultivation have been avoided due to biotic stresses such as bacterial wilt (*Ralstonia solanacearum*), foliar diseases and insect pests, and abiotic stresses (Kissoudis *et al.*, 2015; Bletsos and Olympios, 2008). As a result of the increased use of tomato in various recipes, its production in sub-Saharan Africa (SSA) has been growing and becoming more intensive, including the expansion of greenhouse cultivation (Nordey *et al.*, 2017). Because of repeated cultivation of the crop on the same land, rapid build-up of soil-borne diseases occurs, resulting in yield and quality losses that may lead to 100% income loss (Salau and Shehu, 2015; Gisbert *et al.*, 2012; Srinivasan, 2010). Bacterial wilt (*R. solanacearum*), root-knot nematodes (*Meloidogyne* spp.) and other root diseases are becoming critical tomato production constraints in various areas of Uganda, and coastal regions of Tanzania, and Kenya, Cameroon, and other countries on the continent (Kago *et al.*, 2016; Onduso, 2014; Minja *et al.*, 2011; Mahbou Somo Toukam *et al.*, 2009). Abiotic stresses such as moisture deficit, waterlogging or flooding, and extreme temperatures, also contribute to the extremely low productivity in Tanzania (Kihupi *et al*., 2015).

Many commercial open pollinated and hybrid cultivars are susceptible to one or more soil-borne diseases. Methyl bromide was used to control soil-borne diseases effectively through soil fumigation before its ban in 2005 due to its negative effect on the environment and human health (MBTOC, 2010; Bletsos and Olympios, 2008). Alternative to methyl bromide, other methods such as crop rotation, steaming, radiation, chemical retardants, biological control, resistant cultivars and grafting were adopted in intensive tomato cultivation areas (Bletsos and Olympios, 2008; Maršić and Osvald, 2004). Applying chemical control measures involves complex procedures, cost, time, and human and environmental risks. Grafting susceptible tomato cultivars, that otherwise have good horticultural and consumer quality traits, onto resistant tomato or other rootstock lines offers the possibility of growing them without chemical application (Bletsos and Olympios, 2008). Lines resistant or tolerant to biotic and/or abiotic stresses but lacking desirable horticultural traits to be used as commercial cultivars by themselves are used as rootstock lines of susceptible commercially valuable tomato cultivars.

According to King *et al*. (2010) and Edelstein *et al*. (2017), grafting increases tolerance to abiotic stresses and improves water or nutrient uptake that enhance the vigour of scion cultivars. It allows repeated planting of *Solanaceae* crops in protected cultivation where root diseases buildup is expected (Maršić and Osvald, 2004). Grafting improves yield and fruit size of tomato grown under biotic and abiotic stress conditions (Keatinge *et al*., 2014; Genova *et al*., 2013; Rivard, 2006). It reduces growers' financial risk that may come from growing soil-borne disease susceptible tomato cultivars in the disease infested soils. 'Tanya' and 'Tengeru 97' are among the most popular open pollinated tomato cultivars in Tanzania and other countries in Eastern and Southern Africa, although the production of 'Tanya' is limited to soils not infested with bacterial wilt. Grafting has been increasingly used to control soil-borne diseases and improve fruit quality in fruit bearing vegetables in various countries in Asia and Europe (Pradhan *et al*., 2017; Rivard, 2006). For instance, grafted tomato is used in France to prevent problems such as corky root caused by *Pyrenochaeta lycopersici* (Rivard *et al*., 2012; Diánez *et al*., 2007). In Morocco, it is used to control root-knot nematodes (*Meloidogyne* spp.) and other soil-borne diseases in both tomatoes and cucurbits (Oda, 1999). It has also been used in flood-affected countries like Bangladesh and Vietnam in Asia (Keatinge *et al*., 2014; Genova *et al*., 2013). Regardless of its benefits, the application of this technology in tomato and other *Solanaceae* crops in sub-Saharan African countries is minimal. In Tanzania, Kenya, and Uganda, for example, there are commercially viable tomato cultivars with desirable consumer and processing quality traits that cannot be grown in bacterial wilt infested soils. Integrating grafting into the sustainable management of this disease will increase the area under the improved tomato cultivars, and then the productivity and production of the crop.

The World Vegetable Center (WorldVeg) Eastern and Southern Africa started grafting activities in Arusha, Tanzania, in 2014 as an extension to Africa of WorldVeg's experience of the technology in Asia. The activity at the WorldVeg in Arusha was started in 2014/2015 with scion-rootstock compatibility study involving three commercial cultivars, one each of determinate, semi-determinate and indeterminate cultivar, and three tomato rootstock lines (unpublished data). The compatibility study was conducted in bacterial wilt and root-knot nematodes free soils. Little has been known about the performances of Tanzanian bacterial wilt susceptible commercial tomato cultivars when grafted onto resistant rootstocks and grown in the disease infested soils. The current study was conducted with the objective of exploiting the potentials of bacterial wilt susceptible tomato cultivars that otherwise have improved yield, horticultural and processing quality traits. The null hypothesis was no difference between grafted and un-grafted tomato cultivars in yield and other traits when grown in bacterial wilt infested soils.

## Materials and methods

### Experimental location

The study was carried out in bacterial wilt sick plots infested with *R. solanacearum* in greenhouse soil conditions at WorldVeg, Arusha, Tanzania, located 3.2°S, 36.4°E, and 1,235 m above sea level. The bacteria strain in the greenhouse was Phylotype I sequevar 1-31 as identified by ANSES (French Agency for Food, Environmental and Occupational Health and Safety) laboratory (unpublished data, 2014). The pathogen population was maintained by growing a susceptible tomato host cultivar 'Anna F1' in 2015, before the experiment was conducted from June to December in 2016. After growing the susceptible host plants, the soil was thoroughly mixed to uniformly spread the pathogen across the plots in the greenhouse. The experiment was repeated from March to August 2017 on the same sick plot without a break crop. The soil was loamy with pH 6.5 and kept moist to favor the infectious potential of the pathogen. The severe disease incidence on the two susceptible tomato cultivars grown without grafting confirmed the soil infectious potential.

### Plant materials

Three commercial tomato cultivars, 'Tanya' (determinate, open pollinated), and 'Tengeru 97' (indeterminate, open pollinated), both released in Tanzania from WorldVeg lines in 1997, and 'Anna F1' (indeterminate, hybrid) from Monsanto were used as scions. 'Tanya' and 'Tengeru 97', originated from WorldVeg breeding program, are popular open pollinated tomato cultivars in Tanzania and other countries in Eastern and Southern Africa. They accounted for about 50% of regional tomato seed production, and for about 87% of Tanzanian tomato seed production in 2013–2014 (Schreinemachers *et al*., 2017). The seed of 'Anna F1', a cultivar also cropped in many countries in Eastern and Southern Africa, was purchased from Balton Tanzania Ltd., Arusha, Tanzania. Each scion cultivar was grafted on a bacterial wilt-resistant tomato rootstock line called Hawaii 7996. Hawaii 7996 was developed at the University of Hawaii back in the 1970's (Scott *et al*., 2005). The rootstock was reported highly resistant to phylotype I sequevar 1-31 strain collected from Mayotte island (Chesneau *et al*., 2018). Seed of Hawaii 7996 was obtained from the WorldVeg breeding program, Arusha, Tanzania. The scion cultivars 'Tanya', 'Tengeru 97' and 'Anna F1' have improved horticultural and consumer quality traits such as fruit appearance and large fruit size. 'Tanya' and 'Anna F1', however, lack resistance to bacterial wilt (Musebe *et al*., 2014; Onduso, 2014). 'Tengeru 97' was reported to be resistant to many root diseases in Tanzania (Minja *et al*., 2011). The cultivar has also been reported to be tolerant to bacterial wilt in Uganda and preferred for cultivation in soils infested by the disease (Ramathani, 2015, pers. commun.).

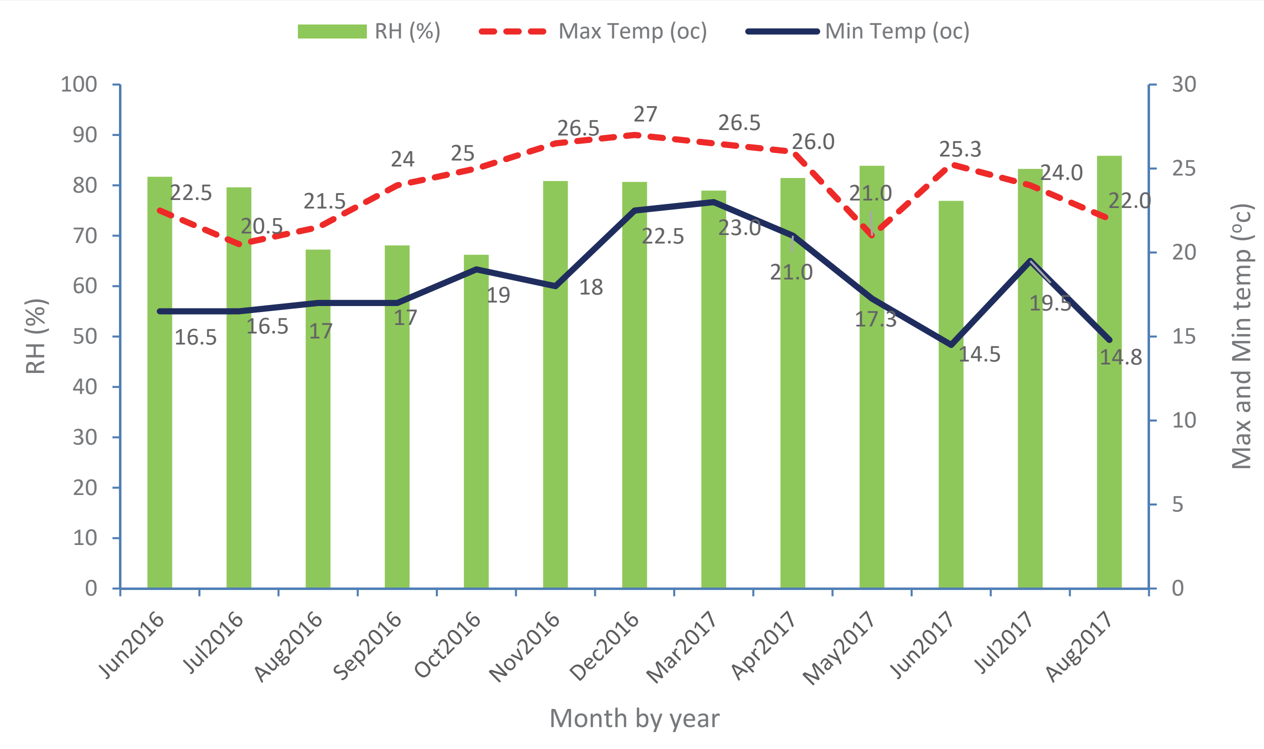


**FIGURE 1.** Outside maximum temperature (Max Temp) and minimum temperature (Min Temp), and mean monthly relative humidity (RH%) at the WorldVeg, Arusha, during the study. (Source: Horti-Tengeru Meteorology Station).

**Scion and rootstock genotype seedlings establishment**

In both the 2016 and 2017 seasons, the rootstock line was sown in polythene tubes of size 8 × 20 cm filled with sterilized soil media containing forest soil, sand, and farmyard manure in the ratio of 3:2:1. Scion cultivars were raised on seedling trays of 70 cells, each using the same sterilized soil media. All the seedlings were raised in screenhouse. Sowing, grafting, and transplanting of the 2016 experiment was done on the 3rd June, 29th June and 15th July 2016, respectively, while the corresponding activity in 2017 was conducted on the 16th March, 6th April and 20th April 2017, respectively.

Temperatures and relative humidity data inside the greenhouse were not recorded in both years due to lack of data loggers. The inside minimum temperature of the same greenhouse in the same seasons but measured in 2018 and 2019, however, ranged from 16.4 °C to 24.6 °C and from 17.2 °C to 23.7 °C, respectively. The corresponding greenhouse maximum temperature ranged from 26.5 °C to 33.1 °C in 2018 and 22.2 °C to 35.0 °C in 2019. The outside weather data in 2016 and 2017 growing seasons are given in Figure 1 and show that the lowest minimum temperature of 14.5 °C was scored in June, followed by 14.8 °C in August 2017. The highest maximum temperature, 27.0 °C, was observed in December 2016.

**Grafting seedlings and healing process**

The scions were grafted at a three-to-four true leaves stage on the rootstocks using latex tube grafting technique to avoid drying of grafted seedlings. The newly grafted seedlings were moved immediately to a healing chamber located near the grafting area. The chamber conditions were maintained whereby direct sunlight intensity reduced by 70% using plastic sheet (0.2 mm thickness), followed by black net and silver net on the outside with average relative humidity of 80% to 86% and an average temperature of 20.8 °C to 25.4 °C. A shallow water layer in the polyethylene floor liner was maintained, and misting was conducted at least three times (morning, noon and evening) per day until the graft union healed. Grafted seedlings were placed on plastic racks placed on bricks to avoid immersing the grafted seedlings in the water layer. Union of scion and rootstock took place 6–8 days in the healing chamber followed by acclimatization for about eight days in shade-house before transplanted to bacterial wilt infested soil in greenhouse. Tomato was the precursor crop of both trials. The trials were irrigated two to three times per week using drip irrigation. The fertilizer NPK (20:10:10) was manually applied as basal application during transplanting at the rate of 120 kg ha$^{-1}$. Urea (46N) at the rate of 100 kg ha$^{-1}$ was split applied, half at transplanting and half at flowering. Abamectin 8 mL (a.i. Avermectin B1a and abamectin) diluted in 20 L water to control spider mites, and Evisect 10 g (a.i. Thiocyclam hydrogen oxalate) in 20 L water to control whiteflies, were applied after every two weeks starting from 21 days after transplanting.

**Experimental design**

In both experiments, a randomized complete block design (RCBD) was used with three replications. Including the non-grafted three scion check cultivars, a total of six treatments were evaluated in both years. Each treatment was evaluated in a net plot size of 6.0 m$^2$ and 5.4 m$^2$ in 2016 and 2017, respectively. Each plot had two rows, 10 and 9 plants per row in 2016 and 2017, respectively. The spacing of 60 cm between rows and 50 cm between plants within row were used.

**Data collection and analysis**

Data collected in the greenhouse both years included: number of wilted plants, days to 50% flowering and fruit maturity from transplanting, plant height (cm) at flowering

**Table 1.** Significance of mean squares from combined analyses of variance of three grafted tomato cultivars and their un-grafted scions evaluated for yield and various horticultural traits under bacterial wilt – Phylotype I sequevar 1-31 strain – infested greenhouse soil in Arusha, Tanzania, in 2016 and 2017.

| Traits | Mean squares | | | |
|---|---|---|---|---|
| | Rep. within season (df = 2) | Season (S, df = 1) | Treatment (T, df = 5) | T × S (df = 5) |
| Total marketable fruit yield (t ha$^{-1}$) | 25 | 1,864** | 3,991** | 95$^{NS}$ |
| Total fruit yield (t ha$^{-1}$) | 25 | 575$^{NS}$ | 4,581** | 151$^{NS}$ |
| Plant height at flowering (cm) | 29 | 11,214** | 1,443** | 61$^{NS}$ |
| Plant height at maturity (cm) | 157 | 11,019** | 20,915** | 266$^{NS}$ |
| Days to flowering | 9 | 117** | 137** | 28* |
| Fruit size (g fruit$^{-1}$) | 11 | 918* | 1,327** | 147$^{NS}$ |
| No. of flowers per truss | 0.16 | 0.12$^{NS}$ | 0.52* | 0.64** |
| No. of fruits per truss | 0.4 | 4** | 3** | 0.11$^{NS}$ |
| No. of truss per plant | 1 | 32** | 14** | 1$^{NS}$ |
| Total no. of marketable fruits per plot | 3,907 | 326,422** | 213,127** | 5,405$^{NS}$ |
| Total no. of plants wilted | 2 | 72** | 408** | 4$^{NS}$ |

*: Significant at $0.01 < P < 0.05$; **: significant at $P < 0.01$; $^{NS}$: non-significant.

and fruit maturity, number of trusses from five plants per plot selected randomly, number of flowers and fruits per truss from five trusses per each of five plants, number of total and marketable fruits per plot, and total and marketable fruit yields (kg plot$^{-1}$), and fruit size (g fruit$^{-1}$). The fruit yields (kg plot$^{-1}$) were later converted to t ha$^{-1}$. All statistical analyses were run in GenStat (release 17.1, release 19.1; VSN International, Hemel Hempstead, U.K.). Data were tested for normal distribution before performing analyses of variances. Individual analysis of variances by season, and combined analyses across the two seasons (treatment × season) were carried out. The number of wilted plants was analyzed using the Generalized Linear Model (GLM) of GenStat with Poisson Distribution.

## Results and discussion

### Analyses of variances

We focused on the results of individual analyses of variances because treatment × season interaction effects were non-significant for almost all traits except in number of flowers per truss and days to flowering (Table 1). Treatment (the three rootstock-scion combinations plus the three un-grafted scion cultivars) and season effects were significant ($0.01 < P < 0.05$) or highly significant ($P < 0.01$) in almost all traits in both individual and combined analyses of variances (Tables 1, 3 and 4).

### Wilted plants

From the GLM analysis, the numbers of wilted plants in grafted 'Anna F1' and 'Tanya' were highly significantly ($P < 0.001$) lower than the number of wilted plants in their un-grafted scion cultivars in both seasons (Table 2, Figure 2). The un-grafted resistant cultivar 'Tengeru 97' was as effective as its grafted scion plants, and as effective as the grafted 'Anna F1' and 'Tanya' in wilt control. In both cropping seasons, the grafted susceptible tomato cultivars had better survival compared to their un-grafted susceptible scion (Table 2). Grafting the resistant cultivar 'Tengeru 97', on the other hand, showed no advantage (Figure 2).

In the 2016 season, the percentage of wilted plants in un-grafted 'Anna F1' and 'Tanya' plots were 100% and 98%, respectively, whereas in grafted plots it was 13% and 15%, respectively. Similarly, in the 2017 season, the percentage of wilted plants in un-grafted 'Anna F1' and 'Tanya' plots was 98% and 76%, respectively, while only about 4% wilted in the grafted plots of each cultivar. The percentages of wilted plants of un-grafted and grafted 'Tengeru 97' were about 12 and 18% in 2016, and 7 and 2% in 2017, respectively.

### Plant heights at flowering and fruit maturity

In both seasons, differences in plant heights among the six treatments (three grafted and three un-grafted genotypes) were highly significant ($P < 0.001$, Table 3). Grafted plants of all genotypes were significantly shorter than their un-grafted scions when measured at 50% flowering in both seasons. Height at 50% fruit maturity of grafted 'Anna F1' was significantly taller than the un-grafted 'Anna F1' in 2016 whereby in 2017 the differences were non-significant (Table 3). Grafted 'Tanya' plants tended to be taller than un-grafted 'Tanya' at maturity stage in both seasons but differences were non-significant. Although the differences were non-significant, the heights at maturity of grafted 'Tengeru 97' plants were shorter than the respective un-grafted plants in both seasons (Table 3). Whether grafted or not, 'Anna F1', indeterminate cultivar, was significantly taller than 'Tanya', a determinate short cultivar.

### Days to flowering

Grafting 'Anna F1' delayed their flowering significantly ($P = 0.001$ in 2016 and $P = 0.003$ in 2017), whereas grafting 'Tanya' did not significantly delay its flowering in 2016 but in 2017 (Table 3). In the 2016 season, grafted 'Tengeru 97' flowered significantly later than its un-grafted counterpart, while in 2017 the difference was non-significant although the grafted plants were to the later side. 'Tengeru 97' was the latest flowering when compared to the other two cultivars under both grafted and un-grafted treatments in both seasons.

### Flower, truss and fruit characteristics

Grafted 'Anna F1' and 'Tanya' did not significantly differ from their corresponding un-grafted scions in number of flowers and fruits per truss in both seasons (Table 3).

**TABLE 3.** Days to 50% flowering, plant height and other horticultural traits measured on rootstock-scion combinations and their scion cultivars evaluated in bacterial wilt infested soil at WorldVeg, Arusha, Tanzania, 2016 and 2017.

| Treatments | 2016 | | | | | | | 2017 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF | PHF (cm) | PHM (cm) | NoTP | NoFIT | NoFrT | FW (g) | DF | PHF (cm) | PHM (cm) | NoTP | NoFIT | NoFrT | FW (g) |
| Anna F1 | 24 | 88.1 | 183.3 | 4.8 | 7.1 | 5.6 | 55.4 | 20.7 | 129.0 | 243.4 | 4.0 | 6.4 | 4.9 | 54.5 |
| Hawaii 7996^Anna F1 | 31 | 67.9 | 238.5 | 4.5 | 6.7 | 5.1 | 100.3 | 27.0 | 110.0 | 273.9 | 3.0 | 7.1 | 4.7 | 74.6 |
| Tanya | 25 | 60.2 | 88.4 | 8.2 | 6.8 | 4.3 | 59.7 | 20.7 | 93.0 | 116.5 | 6.6 | 6.2 | 3.4 | 53.3 |
| Hawaii 7996^Tanya | 27 | 53.8 | 101.1 | 7.6 | 6.2 | 4.2 | 80.1 | 31.7 | 79.0 | 124.4 | 4.8 | 6.4 | 3.6 | 62.2 |
| Tengeru 97 | 33 | 77.2 | 170.6 | 5.7 | 5.7 | 4.1 | 87.5 | 26.7 | 115.0 | 207.2 | 3.8 | 6.7 | 3.7 | 86.6 |
| Hawaii 7996^Tengeru 97 | 39 | 59.6 | 167.1 | 4.9 | 5.9 | 3.8 | 87.3 | 30.7 | 92.0 | 193.6 | 1.9 | 6.4 | 2.7 | 78.6 |
| Mean | 30 | 67.8 | 158.2 | 6.0 | 6.4 | 4.5 | 78.4 | 26.2 | 103.0 | 193.2 | 4.0 | 6.5 | 3.8 | 68.3 |
| F-test (*P*) | < 0.001 | < 0.001 | < 0.001 | 0.008 | 0.012 | 0.019 | 0.007 | 0.003 | < 0.001 | < 0.001 | < 0.001 | 0.216 | < 0.001 | 0.01 |
| LSD (5%) | 5 | 4.9 | 25.2 | 2.0 | 0.7 | 1 | 22.1 | 5.4 | 14.0 | 38.4 | 1.3 | 0.8 | 0.6 | 18.1 |

DF: Days to 50% flowering from transplanting; PHF: Plant height at flowering (cm); PHM: Plant height at maturity (cm); NoTP: Number of truss per plant; NoFIT: Number of flowers per truss; NoFrT: Number of fruits per truss; FW: Fruit weight (g fruit$^{-1}$); ^: The symbol indicates the scion cultivar on the right side of the symbol was grafted on the rootstock line Hawaii 7996.

**TABLE 4.** Fruit yield, fruit number and size measured on rootstock-scion combinations and their scion cultivars evaluated in bacterial wilt infested soil at WorldVeg, Arusha, Tanzania, 2016 and 2017.

| Treatments | 2016 | | | | | | 2017 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NoMFrP | NoNMFrP | MFrYDP (kg plant$^{-1}$) | NMFrYDP (kg plant$^{-1}$) | MFrYD (t ha$^{-1}$) | Total yield (t ha$^{-1}$) | NoMFrP | NoNMFrP | MFrYDP (kg plant$^{-1}$) | NMFrYDP (kg plant$^{-1}$) | MFrYDha (t ha$^{-1}$) | Total yield (t ha$^{-1}$) |
| Anna F1 | 22.9 | 4.8 | 1.1 | 0.1 | 21.0 | 22.6 | 4.6 | 5.5 | 0.3 | 0.2 | 5.9 | 7.8 |
| Hawaii 7996^Anna F1 | 45.0 | 5.0 | 3.3 | 0.2 | 88.0 | 92.6 | 30.0 | 11.2 | 2.3 | 0.3 | 67.9 | 77.2 |
| Tanya | 20.8 | 11.7 | 1.1 | 0.3 | 21.5 | 23.4 | 15.4 | 18.8 | 0.9 | 1.1 | 7.7 | 15.6 |
| Hawaii 7996^Tanya | 35.3 | 4.0 | 2.3 | 0.1 | 58.2 | 59.6 | 28.2 | 15.8 | 1.8 | 0.5 | 46.8 | 56.2 |
| Tengeru 97 | 34.9 | 3.9 | 2.2 | 0.1 | 61.7 | 65.2 | 24.1 | 11.6 | 2.1 | 0.5 | 60.4 | 74.8 |
| Hawaii 7996^Tengeru 97 | 28.7 | 6.8 | 1.8 | 0.2 | 52.5 | 57.3 | 12.1 | 11.8 | 1.0 | 0.4 | 28.0 | 41.1 |
| Mean | 31.3 | 6.1 | 2.0 | 0.3 | 50.5 | 53.5 | 19.1 | 12.4 | 1.4 | 0.5 | 36.1 | 45.5 |
| F-test (*P*) | 0.027 | 0.043 | 0.002 | 0.149 | < 0.001 | < 0.001 | 0.002 | 0.195 | < 0.001 | 0.196 | < 0.001 | < 0.001 |
| LSD (5%) | 13.9 | 4.9 | 0.9 | NS | 23.2 | 23.4 | 10.4 | NS | 0.7 | 0.7 | 16.7 | 18.9 |

NoMFrP: Number of marketable fruits per plant; NoNMFrP: Number of non-marketable fruits per plant; MFrYDP: Marketable fruit yield per plant; NMFrYDP: Non-marketable fruit yield per plant; MFrYD: Marketable fruit yield; ^: The symbol indicates that the scion cultivar on the right side of the symbol was grafted on the rootstock line Hawaii 7996; NS: Not significant.

**Table 2.** Mean numbers and percentages of plants wilted due to bacterial wilt, and statistical levels of significance (*P*) of differences in this trait among the six treatments (three rootstock-scion combinations plus three un-grafted cultivars), in 2016 and 2017, Arusha, Tanzania. The symbol ^ indicates that the scion cultivar on the right side of the symbol was grafted on the rootstock line Hawaii 7996.

| Treatments | Means | Wilted plants (%) | *P* | | | | |
|---|---|---|---|---|---|---|---|
| | | | Anna F1 | Hawaii 7996^ Anna F1 | Hawaii 7996^ Tanya | Hawaii 7996^ Tengeru 97 | Tanya |
| *2016 season* | | | | | | | |
| Anna F1 | 20.0 | 100.0 | | | | | |
| Hawaii 7996^Anna F1 | 2.7 | 13.3 | < 0.001 | | | | |
| Hawaii 7996^Tanya | 3.0 | 15.0 | < 0.001 | 0.808 | | | |
| Hawaii 7996^Tengeru 97 | 3.7 | 18.3 | < 0.001 | 0.493 | 0.655 | | |
| Tanya | 19.7 | 98.3 | 0.927 | < 0.001 | < 0.001 | < 0.001 | |
| Tengeru 97 | 2.3 | 11.7 | < 0.001 | 0.796 | 0.618 | 0.350 | < 0.001 |
| *2017 season* | | | | | | | |
| Anna F1 | 17.7 | 98.1 | | | | | |
| Hawaii7996^Anna F1 | 0.7 | 3.7 | < 0.001 | | | | |
| Hawaii7996^Tanya | 0.7 | 3.7 | < 0.001 | 1.000 | | | |
| Hawaii7996^Tengeru 97 | 0.3 | 1.9 | < 0.001 | 0.571 | 0.571 | | |
| Tanya | 13.7 | 75.9 | 0.217 | < 0.001 | < 0.001 | < 0.001 | |
| Tengeru 97 | 1.3 | 7.4 | < 0.001 | 0.423 | 0.423 | 0.214 | < 0.001 |

'Tengeru 97' was exceptional in 2017 as its un-grafted plants produced significantly higher fruit number per truss than its grafted plants. In both seasons, grafted 'Anna F1' did not significantly differ from its un-grafted plants in number of truss per plant. Similarly, grafted 'Tanya' and grafted 'Tengeru 97' did not significantly differ from their un-grafted plants in this trait in the 2016 season, but they gave significantly a smaller number than their un-grafted plants in the 2017 season. In both 2016 and 2017 seasons, grafted 'Anna F1' produced significantly bigger fruits compared to un-grafted 'Anna F1'scion (Table 3). However, differences in fruit size between grafted and un-grafted 'Tanya', and similarly between grafted and un-grafted 'Tengeru 97', were non-significant in both seasons.

**Number of marketable fruits and fruit yield**

In 2016 season, both grafted 'Anna F1' and 'Tanya' produced a significantly higher number of marketable fruits per plant than their respective un-grafted scion plants, while the difference in this trait between un-grafted and grafted 'Tengeru 97' did not reach a significant level (Table 4). Similar results were obtained in 2017 season where grafted 'Anna F1' and 'Tanya' gave a significantly higher number of marketable fruits as compared to their corresponding un-grafted scion plants. However, un-grafted 'Tengeru 97' gave a significantly higher number of marketable fruits than grafted 'Tengeru 97' in this season. Non-marketable fruit number per plant was significantly the highest in un-grafted 'Tanya' in 2016. Differences among the treatments were non-significant in this trait in the 2017 season.

In both seasons, both grafted 'Anna F1' and 'Tanya' gave significantly higher marketable fruit yield per plant and hectare, and total fruit yield per hectare than their corresponding un-grafted scions (Table 4). Grafted and un-grafted 'Tengeru 97' did not significantly differ in marketable and total fruit yields in 2016 season, whereas grafting 'Tengeru 97' in the 2017 season significantly reduced both marketable and total fruit yields compared to the un-grafted scion. From all the six treatments, three grafted plus three un-grafted scion cultivars, grafted 'Anna F1' gave significantly the highest total and marketable fruit yields except in 2017 in which its yield difference with un-grafted 'Tengeru 97' was non-significant (Table 4). 'Anna F1' and 'Tengeru 97' are indeterminate type cultivars, whereas 'Tanya' is a determinate cultivar.

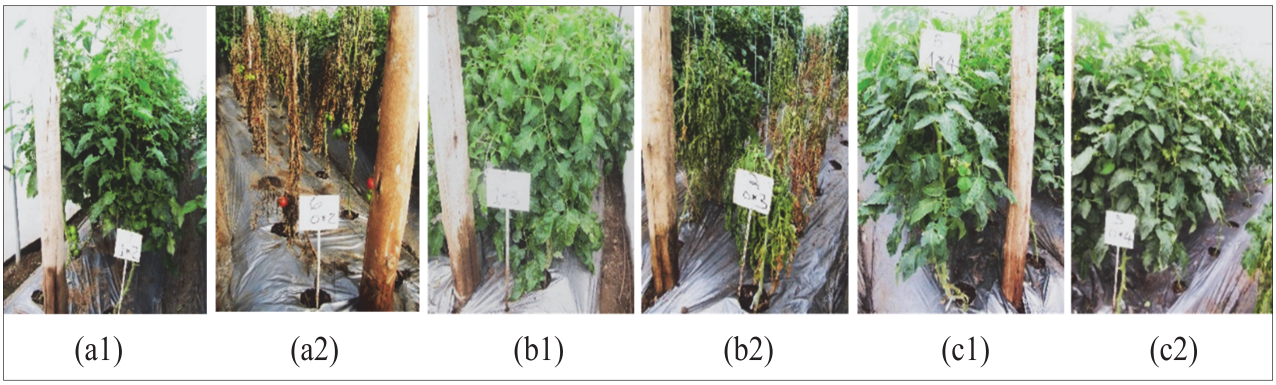


**Figure 2.** Grafted (on 'Hawaii 7996') and un-grafted tomato scion cultivars as affected by bacterial wilt. (a1) Grafted 'Anna F1'; (a2) Un-grafted 'Anna F1'; (b1) Grafted 'Tanya'; (b2) Un-grafted 'Tanya'; (c1) Grafted 'Tengeru 97'; and (c2) Un-grafted 'Tengeru 97'.

**Effect of resistant cultivar and grafting on wilt incidence**

The uniform spread of the pathogen across the experimental plots and its infectious potential was apparent from the 98% and 100% wilted plants in the susceptible un-grafted 'Anna F1' in 2017 and 2016, respectively. Results obtained from 'Tanya' plots, the other susceptible cultivar, are leading to a similar interpretation. The grafted susceptible plants of 'Anna F1' and 'Tanya' showed high levels of resistance with less wilting compared to their un-grafted plants, and on par with the un-grafted plants of 'Tengeru 97'. The relatively smaller number of plants wilted in 2017 than in 2016 indicates less inoculum load in 2017. The reason could be 'Anna F1', the susceptible tomato cultivar, was the sole precursor crop of the 2016 experiment, while a mixture of susceptible cultivars ('Tanya' and 'Anna F1') and resistant cultivar ('Tengeru 97') was the precursor crop of the 2017 trial. Whereas the cultivar 'Tanya' showed 98% wilt during the 2016 season, it showed only 76% in 2017, indicating that 'Tanya' may exhibit some level of tolerance with a reduced pathogen inoculum.

**Effect of grafting on plant height**

The shorter plant height we obtained at the 50% flowering in the grafted plants than un-grafted plants was in agreement with observation by Rivard (2006). There is grafting-shock due to wounding and need for a healing period during much of the early growth stage. The taller plant height in the grafted plants than un-grafted plants at the fruit maturity, on the other hand, might be explained to the stabilization of water and nutrients uptake to the scions by the vigorous or resistant rootstock on which the impact of wilt was neutralized. The taller the plants, the more numbers of nodes and internodes, and then the more crop productivity in protected cultivation where nutrient and water resources are relatively kept at an optimum level. Turhan *et al.* (2011) reported similar results and concluded that grafting significantly improves tomato growth and productivity depending on rootstock scion combination. The significant difference in plant height at fruit maturity between grafted and un-grafted 'Anna F1' in 2016, but not in 2017, could be related to less inoculum load in 2017 to significantly affect the height of the un-grafted plants.

**Days to flowering, and number of flowers and fruits per truss**

The delay in flowering in grafted plants could be due to grafting-shock. Khah *et al.* (2006) reported delayed flowering due to stress caused by grafting. Un-grafted 'Tengeru 97' gave a higher number of flowers and fruits per truss as compared to the grafted 'Tengeru 97'. Generally, grafting in this cultivar caused a decrease in number of flowers and fruits per truss. This implies that the grafting in this cultivar only caused shock that retarded its growth such as plant height, and resulted in lower fruit set, and then lower yield per plant and hectare. Minja *et al.* (2011) reported that 'Tengeru 97' is resistant to many soil-borne diseases. The cultivar is grown in Uganda in bacterial wilt hotspot areas (Dr. Idd Ramathani, pathologist, National Crop Resource Research Institute (NaCRRI), Namalonge, Uganda, 2015, pers. commun.). It is apparent from the current study and previous experiences that 'Tengeru 97' could be used without grafting in phylotype I sequevar 1-31 strain infested soils, instead of using grafted susceptible cultivars. Proper bacterial wilt management practices such as the inclusion of non-host plant species in crop rotation, however, need to be applied to increase the life span of 'Tengeru 97'. Training farmers in the pathogen management is essential. The response of 'Tengeru 97' to other strains of the pathogen needs to be studied. Search for other sources of resistance is vital to diversify cultivars grown in bacterial wilt hotspot areas. A cost-benefit analysis needs to be conducted to justify whether growing a grafted susceptible cultivar is profitable than using un-grafted 'Tengeru 97'. A recent visit to seedling growers in Tanzania by WorldVeg staff members observed that the price of grafted hybrid cultivar seedlings is about three times that of the corresponding un-grafted seedlings.

**Fruit number, size and yield**

Grafted 'Anna F1' and 'Tanya' performed well in marketable fruit numbers, because many plants survived to maturity stage, and each survived plant produced a high number of fruits per plant and larger fruit size. Most of the un-grafted plants wilted or died starting from the second week of transplanting, and very few plants that reached maturity produced inferior fruits that are unmarketable. Onduso (2014) and Musebe *et al.* (2014) reported that these cultivars are susceptible to bacterial wilt, hence grafting them to resistant rootstocks may increase their productivity under disease pressure. The yield decrease in grafted 'Tengeru 97', the resistant cultivar, in 2017 but not in 2016 season is attributed to the adverse effects of grafting that may differ with seasons. The large fruit size (g fruit$^{-1}$) of the grafted 'Anna F1' over the fruit size of the un-grafted scion cultivar may indicate the hybrid vigor nature of the scion cultivar that responds well to grafting. Maršić and Osvald (2004) and Pogonyi *et al.* (2005) reported fruit size increase when hybrid cultivars 'Monroe' and 'Lemance F1' were used as scions.

The lack of significant treatment × season interaction effects in all measured traits (Table 4) indicates that the performances of the six treatments were consistent across the two cropping seasons. Although further study is warranted involving additional environmental conditions, it appears that results obtained in one of the seasons could apply to the other.

The advantage of grafting on yield in the disease infested soil environments was evident in 'Anna F1' and 'Tanya' cultivars in both seasons. The marketable yield in grafted 'Anna F1' was 88.0 t ha$^{-1}$ in 2016 and 67.9 t ha$^{-1}$ in 2017. The corresponding yields in the un-grafted 'Anna F1' were 21.0 t ha$^{-1}$ and 5.9 t ha$^{-1}$ in 2016 and 2017, respectively. A similar trend was observed between grafted *vs.* ungrafted 'Tanya'. There was a severe wilt incidence in un-grafted 'Anna F1' (98% in 2017 and 100% in 2016) and un-grafted 'Tanya' (76% in 2017 and 98% in 2016). Onduso (2014) reported a 95% reduction of bacterial wilt incidence when 'Anna F1' was grafted to bacterial wilt resistant rootstock. High fruit yield of grafted tomato plants is partly attributed to the effect of grafting on increasing fruit size and number of fruits per plant as reported by Yassin and Hussen (2015) and Pogonyi *et al.* (2005). On the other hand, grafting added no positive effect on yield and horticultural traits of 'Tengeru 97', the resistant cultivar, in both seasons. The high yields observed in 'Anna F1' and 'Tengeru 97' indicate their suitability for protected cultivation because of their indeterminate growth habit. 'Tanya' is a determinate tomato type that completes flowering and fruit setting within a short period during a growing season. The two indeterminate cultivars, 'Anna F1' and 'Tengeru 97', give fruits over a long period as far as water and nutrients are available. The general low yields in 2017 could be attributed to the relatively low minimum temperature from May to August (Figure 1). Moreover, the fluctuations of both minimum and maximum temperatures were higher during the 2017 season than during the 2016 season.

**Price of grafted *vs.* ungrafted seedlings**

In the current study, the yield of grafted seedlings was about six times that of un-grafted seedlings when grown in bacterial wilt-infested soils. A recent visit to seedling growers in Tanzania by WorldVeg staff members observed that the price of a grafted hybrid cultivar seedling is about three times the price of an un-grafted seedling (Elias Shem, 2020, pers. commun.). Cost-benefit analysis to determine the profit margin of growing grafted seedlings in bacterial wilt infested soils, therefore, should be one of the future research areas. The marketable fruit yield of un-grafted 'Tengeru 97' (61 t $ha^{-1}$) was comparable to the yield (78 t $ha^{-1}$) of grafted 'Anna F1'. Unless otherwise the profit margin of growing grafted 'Anna F1' attracts growers, 'Tengeru 97' without grafting may serve in bacterial wilt-infested soils in its adaptation areas.

## Conclusion

The current study demonstrated the advantage of grafting Tanzanian susceptible tomato cultivars on resistant rootstocks for production in bacterial wilt-infested soils. The low yields observed in un-grafted 'Anna F1' and 'Tanya' indicate that growing these cultivars in bacterial wilt hotspot areas without grafting onto resistant rootstocks incurs high yield reduction and up to 100% income loss. Grafting, therefore, can be an essential tool to exploit tomato cultivars with desirable horticulture traits but susceptible to bacterial wilt. It might be possible to extend the benefit to other soil-borne diseases such as root-knot nematode and fusarium wilt. It could be highly beneficial in coastal regions of Tanzania and Kenya, and in Uganda where bacterial wilt and other soil-borne diseases are significant production constraints. It should also be integrated to the sustainable management practices in protected tomato cultivation that is expected to increase in peri-urban areas, where soil-borne diseases build-up become a looming problem.

Growing resistant cultivars, whenever available, is the most straightforward, cheapest, and safest approach. 'Tengeru 97' is an interesting cultivar for the majority of farmers that depend on un-grafted tomato cultivars in Eastern and Southern Africa. The mean yield of un-grafted 'Tengeru 97' under bacterial wilt infested soil conditions was comparable with that of the grafted hybrid cultivar, 'Anna F1'. Future studies may focus on characterizing bacterial strains, identifying genes controlling resistance in 'Tengeru 97', managing the resistance sustainability of this open pollinated cultivar, and searching for new sources of resistance. A detailed cost-benefit analysis of grafting should also be established. Capacitating farmers in bacterial wilt management such as the use of cultivar resistance, proper crop rotation, and field sanitation to reduce the bacterial density in the soil is essential.

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