INFLUENCE OF TOMATO (*SOLANUM LYCOPERSICUM* L.) SEEDLING GRAFTING ON PLANT GROWTH, FRUIT YIELD AND QUALITY, AND DISEASE TOLERANCE

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Title

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Suman Parajuli

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr Chiwon W. Lee
Chair

Dr Wenhao Dai

Dr Mukhlesur Rahman

Dr Larry Cihacek

Approved:

07/05/2019
Date

Richard D. Horsley
Department Chair

ABSTRACT

Influence of tomato (*Solanum lycopersicum* L.) seedling grafting on the plant growth, fruit yield and quality, and disease tolerance was investigated using 3 cultivars (Big Beef, Celebrity, Cannonball) as scions and two Solanum species (B-blocking, Maxifort) as a rootstock in a randomized complete block design with three replications. The grafted plants were statistically higher in values for stem diameter, leaf chlorophyll and fruit carotenoid contents. Similarly, the scion/rootstock combination 'Big Beef/Maxifort' and 'Big Beef/B-blocking' had prolonged days to maturity and gives a higher yield than the non-grafted 'Big Beef'. Grafting seedling on 'Maxifort' and 'B-blocking' rootstocks improves the fruit quality like titratable acidity (TA), fruit firmness, but didn't alter the pH, total soluble solid (TSS), lycopene and TSS/TA. Also, grafted treatment 'Big Beef/Maxifort' was found to be a highly disease resistant treatment when compared to the 'Big Beef' control with mean relative effect 0.074.

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DEDICATION

This thesis is dedicated to my father, Jaya Hari Parajuli (late) and my mother Yashoda Parajuli for their love and blessings.

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LIST OF ABBREVIATIONS

%	Per cent
^{o}C	Degree Celsius
AES	Agricultural experimental station
ANOVA	Analysis of variance
AVRDC	Asian Vegetable Research and Development Center
BB	Big Beef
BLOC	B-blocking
BB/MAX	Big Beef grafted onto Maxifort rootstock
BB/BLOC	Big Beef grafted into B-blocking rootstock
CAN	Cannonball
CAN/MAX	Cannonball grafted onto Maxifort rootstock
CAN/BLOC	Cannonball grafted onto B-blocking rootstock
CEL	Celebrity
CEL/MAX	Celebrity grafted onto Maxifort rootstock
CEL/BLOC	Celebrity grafted onto B-blocking rootstock
C.D	Critical differences
cm	Centimeter
DAT	Days after transplanting
diam	Diameter
Eq	Equation
ERS	Economic Research Service
et al	co-workers
etc	Etcetera
Fig	Figure

FAO.....Food and Agricultural Organization

GMO .....Genetically modified food

Kg.....Killogram

LSD .....Least significant difference

U.S.A.....United states of America

USDA.....United States Department of Agriculture

m .....meter

MAX .....Maxifort

mg .....milligram

ml .....milliliter

mm .....millimeter

N.....North

NADWN .....North Dakota Agricultural Weather network

NDSU.....North Dakota State University

ND.....North Dakota.

pH.....Negative logarithm of hydrogen ion concentration

RCBD.....Randomly completely block design.

RE .....Relative index

rpm .....rotation per minute

S. Em.....Standard error of mean

S.Ed.....Standard error of difference

Sev.....Severity

TSS.....Total soluble solid

TA .....Titratable acidity

W.....West

viz.....namely

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1. RATIONALE/JUSTIFICATION

Tomato (*(Solanum lycopersicum* L.*)* is one of the most important vegetable crops in the world. It belongs to the family Solanaceae with the chromosome number of 2n=2x=24. Tomato is grown all over the world from temperate to tropical and subtropical regions. The U.S. is the second largest fresh tomato producing country in the world with 1.87 million tons harvested in 2010 (FAO 2012). Florida (6.90 thousand tons), and California (5.82 thousand tons) are the two largest tomato producing states in the U.S. Per capita consumptions of fresh and processed tomatoes in the U.S. are 20.3 lb (9.23 kg) and 73.3 lb (33.3 kg), respectively, in 2017 (USDA ERS, 2018). The tonnage of tomatoes grown in the greenhouse (3.02 thousand tons in 2011) in the U.S. is relatively low (approximately 15%) as compared to field production (USDA-ERS, 2012).

The field production of tomato often encounters various biotic and abiotic stresses that cause a reduction in the fruit yield and quality. The main biotic and abiotic stresses are soil-borne diseases, and fluctuation in light intensity, temperature, relative humidity, soil moisture and mineral nutrition. Plants grown under such stressful conditions frequently suffer from the occurrence of soil-borne diseases, suboptimal temperatures, poor soil nutrition often develop various physiological disorders resulting in the reduction of fruit yield and quality (Lee et al., 2010). Furthermore, breeding work for increasing tomato fruit quality and yield is slow and tedious (Caliman et al., 2010). To increase the quality of tomato, breeders often compromise yield and other production traits. Moreover, the use of the genetic modification technology for tomatoes for fruit yield and quality enhancement has not been accepted, mainly, because of public perception and consumer preference against GMO food. Therefore, grafting techniques are an alternative approach to enhance fruit yield and quality on a tomato plant. It is also a vital

component of low-input sustainable and organic horticulture due to increased plant vigor and disease and abiotic stress resistance.

The practice of seedling grafting techniques for many vegetable crops like watermelon, cucumber, eggplant, pepper, and tomato have been widely used in Asian countries (Lee, 1994; Lee et al., 2010). The use of grafting techniques for vegetable production in the United States is in an infant stage. In our preliminary investigation, the seedling grafted tomato plants provided better growth and fruiting characteristics compared to the non-grafted plants when grown in the field. The purpose of this research was to evaluate the efficacy of using seedling grafted plants on the growth and performance of tomato plants grown in the field. Specific objectives of this research are:

1. To determine if seedling grafted plants perform better than non-grafted plants in terms of growth and yield.
2. To compare the number of days required for flowering and fruiting between seedling grafted and non-grafted plants.
3. To study the influence of seedling grafting on the fruit quality including sweetness, pH, firmness, and pigment content.
4. To study the performance of the grafted plant against viral and fungal diseases.

2. REVIEW OF LITERATURE

Tomato **(***Solanum lycopersicum* L.**)** is a major vegetable crop second in extent after potato and is a reliable source of vitamins and minerals and provides raw materials for a wide range of processing industries. It is also rich in important pigments like lycopene and carotenoids because of which it is known as a poor man's apple. The major adverse biotic factors that impact the production of tomatoes include tomato spotted wilt virus, septoria leaf spot, early blight, and late blight (Turhan et al., 2011). These pest and disease pressures can easily devastate the field production of tomato. Literature on the biology, benefits, techniques, and the extent of using the technology of seedling grafting in tomato and related crops is large. The efficacy of practicing the seedling grafting methods for the culture of tomato and other vegetable crops is briefly reviewed here.

2.1. Growth characters

2.1.1. Plant height

Increase in plant height during heat stressed conditions were noted when heat-susceptible tomato cultivar UC 82-B was grafted onto eggplant cultivar, 'Black Beauty' (Abdelmageed et al., 2004). Similar findings were shown by Vuruskan and Yanmaz (1990), Lee (1994), Rashid et al. (2004), and Leonardi and Giuffrida (2006) who further discovered that grafted plants were taller and more vigorous including larger stem diameter than the non-grafted tomato plants. Moreover, the conclusions by Khah et al. (2006) on growth and yield attributes of grafted tomato plants in the greenhouse and open-field conditions revealed that grafted tomato plants (Big Red/Hemen) indicated a significant difference in plant height (75.3 cm), when compared to the non-grafted tomato plants (70.3 cm). However, this result was reversed when the tomato cultivar, 'Big Red' grafted on 'Primavera rootstock' indicated statistically no significant difference in

plant height between grafted (69.3 cm) and non-grafted tomato plants (70.3 cm). Another report by Mohammed et al. (2009) under protected environment conditions revealed that the grafted tomato (Cecilia F_1/Beaufort) remained the tallest (37.6 cm) in plant height, revealing a significant difference contrasted to the non-grafted tomato plants. Similar work carried out by Rahamatin et al. (2014) on growth, yield, and quality of hydroponic tomatoes, discovered significant increases in plant height (6.8 m) with grafted tomato ('Synda'/ 'Kingkong') in a double stemmed configuration in comparison to non-grafted 'Synda' tomato with a plant height of 5.4 m.

2.1.2. Stem diameter

Mohammed et al. (2009) concluded the effect of tomato cultivar 'Cecilia F_1' onto rootstock 'Beaufort' under the greenhouse condition and discovered that the grafted plants developed a greater stem diameter (4.9 cm) than the control. Another research by Yarsi (2011) on tomato grafted seedlings under greenhouse conditions revealed significant differences in the stem diameter of grafted plants ('Cobra'/ 'Beaufort') (1.69 cm) when compared to non-grafted tomato plants (15.0 mm). Moreover, grafting tomato with hybrid cultivar 'Geronimo' as scions and 'Maxifort F_1' hybrid as a rootstock under greenhouse conditions revealed a significant increase in stem diameter (1.44 cm) as compared to a control (1.29 cm) (Hanna, 2012). Likewise, Al-Harbi et al. (2017) examined the response of 'Faridah' tomato grafted onto the 'Unifort' rootstock under abiotic stresses and attained a significant increase in stem diameter (1.31 cm) in grafted plants as compared to the non-grafted plants (1.26 cm). Comparable results were obtained by Rahamatin et al. (2014) on hydroponic tomato 'Synda' cultivar grafted onto 'Kingkong' rootstock.

2.1.3. Chlorophyll

Under greenhouse conditions, Mohammed et al. (2009) determined that grafting the tomato cultivar 'Cecilia F_1' using 'Beaufort' rootstock significantly increased the chlorophyll content and carotenoid content in the grafted plant. Similarly, Liu et al. (2012) examined the growth and fruit quality aspects of egg plants grafted onto the tomato rootstock 'Lydl' and found that the chlorophyll content in the eggplant was increased by 69.6 percent in comparison with its non-grafted counterparts.

2.1.4. Days to flowering

In the study of eggplant/tomato graft combination, Vuruskan and Yanmaz (1990) noted delayed flowering in 'Prelane' and 'Bauros' tomato cultivars grafted onto eggplant rootstocks when compared to the non-grafted control. Delayed flowering in tomato plants when grafted on different Solanum rootstocks were also reported by Ibrahim et al. (2001) and Rahman et al. (2002). Another experiment carried out by Rashid et al. (2004) revealed that the grafted tomato plants with *Solanum torvum* rootstock took about 10 days more for flowering (66 days) than the non-grafted control (54 days). Furthermore, having studied the effect of tomato plant grafted onto the tobacco rootstock on days of flowering, Yasinok et al. (2009) also found grafting of tomato scions 'Elazig' and 'Cherry' tomatoes onto tobacco rootstock (*Nicotiana tobaccum* L.) delayed 11 days by flowering.

2.1.5. Days to harvesting

Having studied the grafting compatibility between eggplant cultivar and wild *Solanum* species, Rahman et al. (2002) noted that the days for the first harvest of non-grafted 'Sufala' eggplants (65 days) was earlier than the 'Uttara' eggplants grafted on *Solanum torvum* (79.7 days). Similarly, Rashid et al. (2004) who studied grafting of tomato and eggplants, noted that

the grafted tomato plants on *Solanum torvum* rootstock attained fruit maturity in 115 days while the non-grafted tomato plants attained maturity in 98 days.

2.1.6. Number of flowers

Having examined the effect of tomato grafted seedling under the greenhouse condition, Yarsi (2011) reported that there were significant differences in flowers numbers on the 1st and 7th clusters of grafted plants. Grafted plants exhibited a substantially larger number of flowers than the non-grafted tomato plants. However, this result contradicts the findings of Khah et al. (2006) who noted a non-significant difference between the grafted and non-grafted tomato plants with respect to the total number of flowers per plant.

2.2. Yield and yield attributing traits

2.2.1. Fruit index

Hoyos et al. (2010) examined the effect of grafting on the yield and quality of the tomato cultivars grafting tomato cultivars ‘Caramba’ and ‘Tavra’ onto two hybrid rootstocks ‘Heman’ and ‘Multifort’ and noted that fruits from grafted plants were bigger in size than those from non-grafted plants. Having examined the effect of tomato grafting on fruit yield and quality, Turhan et al. (2011) reported that fruit index i.e., a ratio of fruit diameter to the fruit height were higher in grafted plants (Yeni Talya/Beaufort) (1.3) in comparison to the non-grafted counterpart (1.2). Grafting tomato with vigorous rootstock such as ‘Maxifort’ and ‘Brigeror’ resulted into bigger fruit size and yield of tomato fruit under potassium deficiency conditions (Schwarz et al., 2013). Similar results were obtained when two tomato scions ‘Piccolino’ and ‘Classy’ were grafted onto vigorous tomato rootstock such as ‘Maxifort’ (Krumbein and Schwarz, 2013). Further study also revealed that grafting tomato results in significant increase in fruit weight which leads to increment of measure of fruit diameter and size (Riga, 2015) under lower light and temperature

stresses. However, above results contradict the finding of (Mohammed et al., 2009 and Yarsi, 2011).

2.2.2. Fruit weight

Having studied the impact of tomato grafted plant on yield and quality attributes, Turhan et al. (2011) found that 'Yeni Talya'/ 'Beaufort' graft combinations fruits resulted in significantly greater weight (202.1 g) than non-grafted counterpart 'Yeni Talya' (146.6 g). Similar findings were reported by Miller (1990) on cherry tomato F12 grafted on 'Colt' rootstock and Pogonyi et al. (2005) on the grafted tomato 'Lemance F_1'/ 'Beaufort' combination. Another study on the effect of grafted tomato plants under lower light intensity and temperature conditions, overcome the influence of adverse stress conditions with higher fruit weight, diameter and overall qualities (Riga, 2015).

2.2.3. Number of fruits per plant

In the study of eggplant/tomato graft combinations, Vuruskan and Yanmaz (1990) observed better growth and number of fruits in the plants of the tomato cultivars 'Prelane' and 'Bauros' grafted onto eggplant rootstock cultivars 'Kyndia' and 'Dario' than the non-grafted controls. Another study by Marsic and Osvald (2004) revealed that the tomato cultivar 'Monroe' when cleft-grafted onto rootstock 'Beaufort' produced higher number of fruits per plant (20 fruits/plant) in comparison to that of the non-grafted tomato plants (14 fruits/plant) in greenhouse. On a further study of grafted tomatoes, Perez et al. (2006) observed that the number of fruits obtained per plant was higher in tomato plants grafted onto 'Beaufort' rootstock (10.4/plant) compared to the number (7.0/plant) of fruits produced by the same scion cultivars grafted on own rootstocks. Comparable results were obtained by Ibrahim et al. (2001) and

Turhan et al. (2011) on tomato/wild *Solanum* species and 'Yeni Talya'/ 'Beaufort' graft combinations, respectively.

2.2.4. Fruit yield

Vegetable grafting was primarily aimed at reducing insect pests and disease problems during its earliest applications. Recently, with the use of suitable rootstock-scion combinations, considerable yield advantage with grafted plants has been found. Watermelon (*Citrullus lanatus*) plants grafted on gourd (*Lagenaria siceraria*) rootstock resulted in substantially higher fruit yield as well as increased harvesting period length resulting from the vigorous, healthy root system compared to own-root, non-grafted plants (Lee, 1994). Comparable results were obtained by Estan et al. (2005) on tomato plants grafted on 'Pera' eggplant rootstock grown in saline soil conditions by increasing the fruit yield by 80%. In addition, 13.4 ton/ha more yield had been obtained in grafted than non-grafted tomato plants in open-field under a hot and humid condition (AVRDC, 2005). Another study by Burleigh et al. (2005) on tomato plants grafted onto heat- and disease-resistant eggplant rootstocks showed a significant increase in marketable fruit yield (13.8 ton/ha) from grafted plants compared to that obtained (5.4 ton/ha) from non-grafted plants. Similar results were obtained by Khah et al. (2006), Perez et al. (2006), Leonardi and Giuffrida (2006), Rivard and Louws (2008), and Al-Harbi et al. (2017) in tomato/eggplant graft combinations. However, under sub-optimal temperature conditions, grafting tomato plants onto heat-tolerant eggplant rootstocks did not provide statistically significant yield advantages over non-grafted plants because of increased vegetative plant growth rather than reproductive growth needed for flowering (Abdelmageed and Gruda, 2009). Under protected environment conditions, Mohammed et al. (2009) determined the effect of grafting tomato cultivar 'Cecilia F_1' onto 'Beaufort' rootstock, showing fruit yield increase of 21% for 'Heman', 15 % for 'Syrian' and 6

% for ‘Beaufort’ tomato cultivars compared to their non-grafted counterparts. Comparable results were also obtained by Turhan et al. (2011) where the highest fruit yield was found in the ‘Yeni Talya’/ ‘Beaufort’ grafted combination (6.8 kg/plant), and the lowest fruit yield recorded in non-grafted ‘Beril’ cultivar (4.5 kg/plant), whereas fruit yield of ‘Swanson’ tomato cultivar was unaffected by grafting onto either ‘Beaufort’ or ‘Arnold rootstock’. Further studies by Rahamtin et al. (2014) also suggest that the seedling grafting substantially increased the fruit weight and yield for hydroponically grown tomatoes. Their research showed that grafting ‘Synda’ tomato onto ‘King Kong’ rootstock for hydroponic culture increased mean fruit weight and total fruit yield by 11% and 27%, respectively, for single-stem training. When plants were double-stem trained, the grafted plants produced higher total fruit yields while reducing the average individual fruit weights by 12%.

2.3. Fruit quality

Fruit quality is the combination of both external appearances like size, shape and color and non-visible quality traits like sweetness, acidity, and aroma (Bai and Lindhout, 2007). The external visual appearance and sizes of fruits and vegetables can greatly influence consumer’s perception and preference in the market (Kays, 1999). Consumer decision and popularity in the market are not only affected by fruit size, shape, and color, but also by freshness, taste, aroma, and nutritional qualities of fruits and vegetables. A few ways of improving the tomato fruit quality include the use of seedling grafting, although there are number of reports that dispute the efficacy of using the grafting method as a means of enhancing the produce quality. The ineffectiveness of applying grafting methods for fruit quality enhancement may have been due to environmental extremes under which research was carried out or improper use of scion/rootstock combinations. The quality traits such as skin color, fruit shape, and soluble solids content of

watermelon were known to be greatly influenced by rootstocks used in grafting under different cultural methods, soil fertility and irrigation practices (Lee, 1994). Similar results were obtained by Davis and Perkins (2005) who showed a significant difference in quality traits such as fruit firmness, brix (% sugar) reading, carotenoid and lycopene content in watermelon (*Citrullus lanatus*). Yetisir (2003) also found that watermelon quality characteristics like sugar content, firmness, rind thickness, and fruit shape were greatly affected by grafting. On the contrary, research carried out by Leoni et al. (1990) and Romano and Paratore (2001) on grafted melons (*Cucumis melo*) under greenhouse conditions showed no change in fruit quality as influenced by grafting. Another study by Mohammed et al. (2009), working on the tomato cultivar 'Cecilia F_1' grafted on 'Beaufort' rootstock under the greenhouse condition, reported that grafted plants produced tomato fruit with higher soluble solids content, but lower lycopene contents compared to non-grafted plants. Similar results were also reported by Turhan et al. (2011) on the yield and quality attributes of grafted tomatoes (Yeni Talya/Beaufort), showing a significant difference in titratable acid content but not pH and lycopene content between grafted and non-grafted plants. Similarly, Riga (2015) found that when the grafted tomato plants were grown under low light and suboptimal temperature conditions produced fruit with higher quality traits like soluble solids contents, firmness, dry weight, and electrical conductivity.

2.4. Disease tolerance and environmental stresses

Tomato plants are grown mainly in the open-field in many countries including the U.S. During field culture, plants are often exposed to various stressful environmental conditions as well as disease and pest pressures that cause the reduction in yield and quality. Most of these diseases were caused by viruses, fungi, bacteria and nematodes (Louws et al., 2010). The application of seedling grafting method as a means of overcoming damage by soil-borne diseases

like *Pythium, Verticillium, and Fusarium* started first with watermelon plants in Japan and Korea where the plants are often grown in the same soil every year without crop rotation (Lee, 1994). Seedlings of watermelon (*Citrullus lanatus*) cultivars were grafted onto the seedlings of the wild gourd (*Momordica charantia*) which confer resistance *Pythium, Verticillium,* and other soil-borne diseases. The interspecific grafting allowed the production of high-quality watermelons from the same field without crop rotation. Almost all watermelons grown in the field and greenhouse in Japan and South Korea are seedling grafted (Lee, 1994). Both interspecific (between different species) as well intraspecific (within the same species) grafting methods are now widely practiced for several vegetable crops including tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum*), watermelon (*Citrullus lanatus*), eggplant (*Solanum melongena*), cucumber (*Cucumis sativus*), and squashes (*Cucurbita maxima*) (Lee, 1994; Lee et al., 2010; Turhan et al., 2011; Choi et al., 2015a; Rivard and Louws, 2008). Grafting seedlings of the same species using disease or other stress-tolerant rootstock cultivars is the most common practice mainly because of the freedom from grafting-incompatibility (Black et al., 2003; Rivard and Louws, 2008). Graft combinations among different species often result in the failure of tissue union leading to mortality of seedling grafts. Cultural procedures required for the producing healthy plants from seedling grafting to transplanting for tomato have been reported by Choi et al. (2012, 2015a, 2015b). The maximum benefit of grafting can be obtained from interspecific grafting practices combining horticulturally desirable scion cultivars with rootstock plants having more vigorous growth habit and disease resistance often found in the native habitats or different gene pool (Bloom et al., 2004; Venema et al., 2008).

Grafting scions of susceptible tomato cultivars onto resistant rootstocks has been successful for managing tomato bacterial wilt and soil-borne diseases for higher yield and quality

(Peregrine and Binahmad, 1982). For instance, an heirloom tomato cultivar ‘German Johnson’ grafted to the resistant ‘CRA 66’ or ‘Hawaii 7996’ tomato rootstock showed no symptom of fusarium wilt, whereas 79% of disease symptom development in the non-grafted control plants (Rivard and Louws, 2008). Improved plant tolerance to such abiotic stresses as sub-optimal temperature, drought and salinity by grafted tomato plants was demonstrated by Schwarz et al. (2010). Liu and Zhou (2009) studied the effect of grafting eggplant seedlings onto tomato rootstock where the grafted eggplants showed resistance against *Verticillium dahalia*. A similar study conducted by Petran (2013) on tomato/eggplant grafting showed an increased tolerance to flooding, drought and heat by grafted plants. Moreover, some interspecific grafted plants between a commercial tomato cultivar and a cold-tolerant wild species (*Solanum habrochaites* cv. LA 1777) exhibited a much higher to low temperatures in comparison to non-grafted plants (Venema et al., 2008).

3. MATERIAL AND METHODS

3.1. Location and climatic condition

This investigation was conducted at the vegetable research field plot on the campus at North Dakota State University. The research work was carried out in the open field condition in 2017-2018. The research plot was situated at 46.897° N latitude and 96.812° W longitude and is 274.93 m above the sea level. Growing period in North Dakota is short (140 days) and characterized by relatively dry weather with day temperature ranging from 10 ^{o}C to 37 ^{o}C. The soil is Fargo silty clay soil having pH of 7.25, calcium carbonate of 2.06%, organic matter content of 4.19%, nitrogen of 27 ppm, phosphorus of 26 ppm and potassium of 413 ppm (Soil Survey Staff, 2016). The weather parameter in the entire period of crop growth as recorded at the North Dakota Agricultural Weather network (NADWN, 2018) is given in Appendix I.

3.2. Plant materials

The determinate, semi-determinate and indeterminate tomato cultivars viz., 'Cannonball' (North Dakota State University), 'Celebrity' (Johny's selected seeds), and 'Big Beef' (Agassiz seed and supply) which were used as scions and were grafted onto two commercially available tomato hybrid rootstocks viz., 'Maxifort' (vegetative rootstock from Johnny's selected seeds) and 'B-blocking' (generative rootstock from Nongwoo Seed Co., Seoul, South Korea). The generative rootstocks direct nutrition into fruit production while the vegetative rootstock directs the energy into growing stems and leaves. The rootstocks used were high resistance to fusarium races, fusarium root rot, nematodes, corky root rot, tobacco mosaic virus, and verticillium wilt. In total, there were 6 different grafting treatments viz., 'Cannonball/Maxifort' (CAN/MAX), 'Cannonball/B-blocking' (CAN/BLOC), 'Big Beef/Maxifort' (BB/MAX), 'Big Beef/B-blocking' (BB/BLOC), 'Celebrity/Maxifort' (CEL/MAX), 'Celebrity/B-blocking'

(CEL/BLOC), and 3 non-grafted control viz., ‘Cannoball’ (CAN), ‘Celebrity’ (CEL) and ‘Big Beef’ (BB).

Table 1. List of plant materials used in grafting studies.

No.	Cultivar	Growth habit	Source
1	Big Beef	Indeterminate	Agassiz Seed and Supply
2	Celebrity	Semi-determinant	Johnny’s Selected Seeds
3	Cannonball	Determinate	NDSU
4	Maxifort	Vegetative rootstock	Johnny’s Selected Seeds
5	B-blocking	Generative rootstock	Nongwoo Seed Co., Seoul, Korea

Table 2. List of grafted and non-grafted treatments used in grafting studies.

No.	Treatments
1	Cannonball
2	Celebrity
3	Big Beef
4	Cannonball/Maxifort
5	Cannonball/B-blocking
6	Celebrity/Maxifort
7	Celebrity/B-blocking
8	Big Beef/Maxifort
9	Big Beef/B-blocking

3.3. Grafting procedure

Seed germination and seedling grafting were carried out at the Agricultural Experimental Station (AES) greenhouse located at North Dakota State University, Fargo, ND. Seeds of the rootstock cultivars were sown 5 days after seeding the scion cultivar seeds to ensure uniformity in the hypocotyl stem diameter because of differences in growth vigor between rootstocks and scions. Forty-six cell pack trays filled with Sungro Mix 1 growing medium was used for the germination of scion and rootstock seeds. Seedlings were grafted after 15 days from sowing, where they achieved the proper stem thickness, height (10-15 cm) and the number of true leaves (4-5). The cleft grafting procedure described by Lee (1994) was followed in this experiment for

grafting. To initiate grafting, rootstock was topped 1 cm above the second node and the remaining leaves were removed from the rootstock. With the help of razor blade, a 1 cm of proximal cut was made about 4-5 cm from the top part of the distal end of the stem. Similarly, in the scions, from the top part of the distal end about 4-5 cm long cut was given toward the proximal end of the stem. The leaves were trimmed for minimizing the transpiration. Now, two opposite slanting cuts of about 1 cm was made given above the basal end of the scion to form a wedge-shaped structure. The edge of scion was inserted onto the rootstock as shown in Figure 1. Para-film and grafting clips were used to wrap and secure the grafted union. To avoid wilting and unnecessary stresses, the grafted plants were watered immediately and were transferred into a humidity chamber with 90-95% relative humidity and temperature of 30 ^{o}C. The seedling grafting took almost 14 days to complete the healing process. After healing, plants were acclimatized in the greenhouse for a week.

3.4. Transplanting and field establishment

After acclimatization in the greenhouse, the grafted and non-grafted seedling were transplanted into the field on June 20th, 2018 as shown in the Figure 1 F. 0.6 meter spacing between plants and 0.9 meter spacing between the rows were used during transplanting in a randomized completely block design containing three replications. Recommended cultural practices such as timely irrigation, tillage, staking, weeding etc. were followed to ensure healthy growth and development of the plants. Plants were fertilized with one table spoon of 20-20-20 commercial analysis N: P: K based fertilizer as well as one tablespoon of calcium sulphate at the interval of 30 days around the base of the plant. Prior to planting, the field plot was fertilized with applied with 90 kg per hectare of nitrogen based on the soil analysis. This made the filed nitrogen level at 157 kg per hectare. Bamboo sticks were used for staking and better upright

growth of the plant. Lateral suckers on the plant were removed every 10 days to develop the plant into a single stem system. Plastic mulch and drip irrigation system were also used for better weed control.

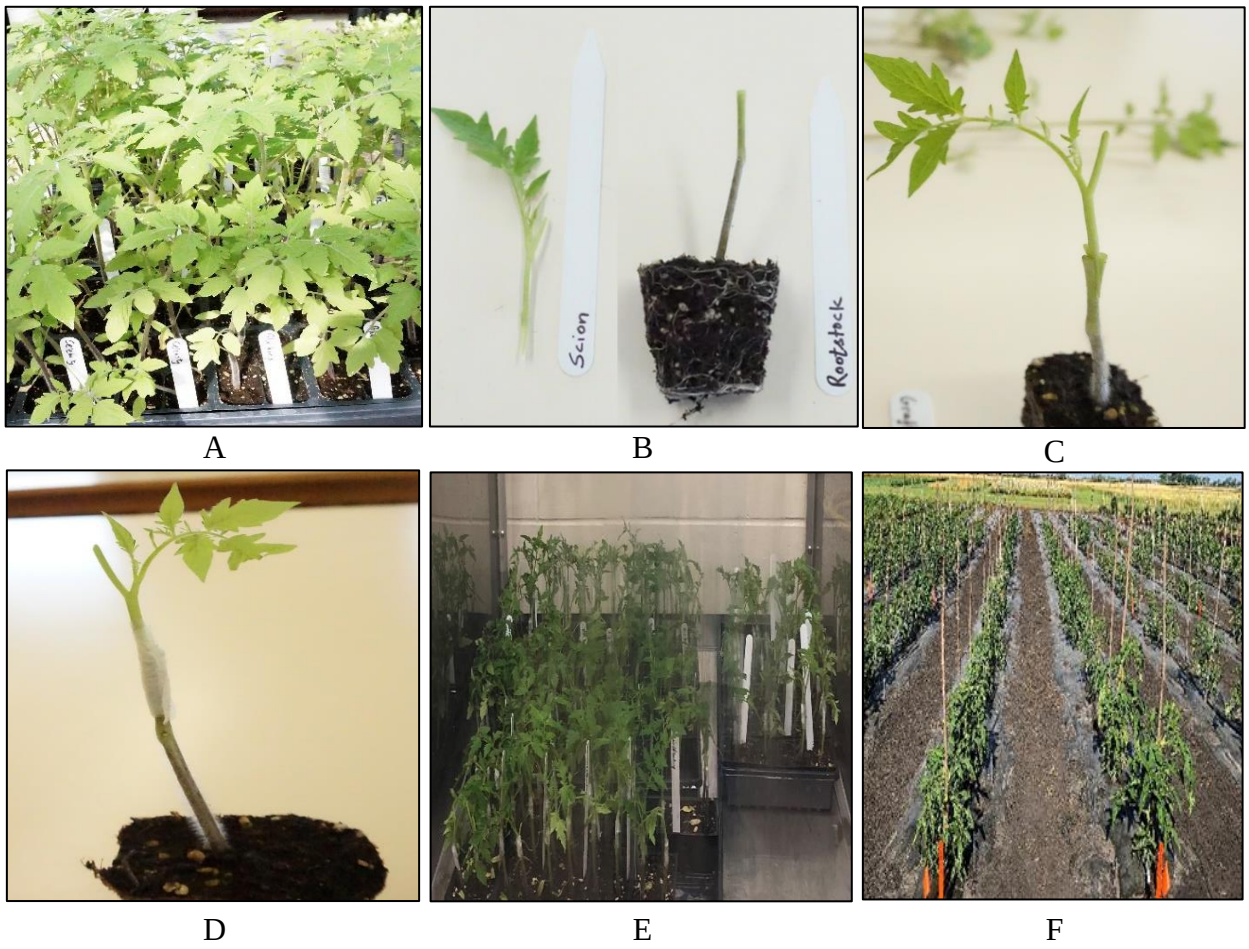


Fig.1. Procedures for tomato seedling grafting, post-grafting care, and field establishment. A-scions and rootstock cultivars, B-scion and rootstock seedlings being prepared for grafting, C-joining the scion and roostock, D-securing the joint with the parafilm, E-grafted tomato seedlings in a humidity chamber for healing, F-grafted tomato after transplanting in the field.

A B

Fig. 2. Field layout and transplantation: A-Field layout containing plastic mulch and drip irrigation hoses. B-Grafted plants transplanted in the field in randomized complete block design.

3.5. Methods of measurements on experimental units

Five plants were selected randomly and tagged from each treatment of the experimental units and measurement were made on these plants for yield and other morphological traits. Measurements were made on the same plants throughout the growing season.

3.5.1. Measurements on growth characteristics

The plant height was measured at 30, 60, and 90 days after transplanting (DAT). Measurements were in centimeters from the ground level to the growing tip of the plant with the help of a two-meter-long metallic ruler. The stem diameter was measured 15 cm above the ground level with help of Vernier calipers at 30, 60, and 90 DAT and were expressed in centimeters. Days to first flowering was measured by counting the days from the date of transplanting to the opening of the first flower and was expressed as a number. Days to 50 percent flowering was measured by counting the number of days after transplanting in which 50

percent of the plants produced flowers and the average was expressed as a number. The number of flowers/clusters was recorded by counting first flush of flowers per cyme of individual plants from the five tagged plants and the average was expressed as a number. Number of flower clusters per plant was measured by counting the number of flowers clusters on the 5 tagged plants and the average was expressed as a number. Days to maturity was measured by counting the number of days after transplanting to the days of the first mature fruit on the five tagged plants and the average was expressed as a number.

The chlorophyll content of leaves was measured at 30, 60, and 90 DAT by collecting the leaf sample taken from the top portion of the plant in all the directions using v-5000 VIS visible spectrophotometer following the procedure suggested by Arnon (1948) with some modification. First, 0.1 g of tomato leaf sample was taken, and the leaf was extracted in 10 ml 80% acetone solution with the help of mortar and pestle. The homogenized mixture was centrifuged at 4000 rpm for 10 minutes. Secondly, the supernatant was collected in a cuvette and the pellet was discarded. Another cuvette two third full of 80% acetone was used as blank to calibrate a spectrophotometer 0% absorbance. Finally, the reading for absorbance was taken at 663 and 645 nm wavelength with the help of following equations, total chlorophyll content was estimated.

$$\text{Ctotal}\left(\frac{\text{mg}}{\text{g}}\right) = \frac{[20.2 \text{ x } A645 + 8.02 \text{ x } A663] \text{x } V}{1000 \text{ x } W} \text{ x } 100 \qquad \text{(Eq.1)}$$

Where, A645 & A663 = absorbance at 645 nm and 663 nm wavelengths.

V = volume of sample.

W= weight of fresh tissue used for extraction.

3.5.2. Yield and yield attributing traits

The polar diameter of the fruit was recorded by measuring five randomly selected fruits from the tagged plants at the maturity stage from the stalk and the tip of the fruit and was expressed in centimeters. Equatorial diameter of the fruit was measured from the five randomly selected fruits at the vegetative maturity stage through the center of the fruit with the help of Vernier calipers with the mean diameter was expressed in centimeters. Number of fruits per plant was recorded by counting the number of fruits at each harvest and the total number of fruits from each harvest was recorded and expressed as a number. Fruit weight was recorded by taking the weight of five fruits from each tagged plant in successive harvests and the mean weight of the fruits was recorded and expressed in kilograms. The fruit yield per plant was measured by taking a weight of tomato fruits from five tagged tomato plants from each plot at each harvest. The total weight of fruit of all harvests was summed up and expressed in kilograms. The fruits were harvested at the fully ripe stage.

3.5.3. Fruit quality attributes

Five representative matured fruit samples from each treatment were used to estimate the pH by using a pH meter (portable pH meter). Around 10 grams of fruit extract was obtained by blending each fruit sample and pH was measured directly with a pH meter. The pH reading from all the samples were then averaged for final measurement. Similarly, a total soluble solid were measured by the help of hand-held digital refractometer and expressed in % soluble solid (Brix). The fruit firmness was measured using hand-held digital fruit firmness tester (DFP001) and expressed in kg/cm^2. For titratable acidity, five grams of tomato pulp was dissolved with 50 ml

of hot distilled water. The solution was then titrated against 0.1 N NaOH solution in a burette at pH 8.1 using phenolphthalein indicator and was expressed as a percentage of citric acid.

$$\text{Titratable acidity} = \frac{\text{titre value x } 0.0064}{\text{weight of fruit (5 g)}} \qquad \text{(Eq.2)}$$

Lycopene extraction was done with hexane:ethanol:acetone (2:1:1) (v/v) mixture by following the procedure suggested by Gordon and Barrett (2007). At first, 0.001 g of fresh fruit sample was dissolved in 1 ml of distilled water and was vortexed at water bath at 30 ^{o}C for one hour in a falcon tube. Then 8 ml of hexane: ethanol: acetone (2:1:1) was added and after 10 minutes, one milliliter of distilled water was added. The mixture was vortexed again and was allowed to stand for 10 minutes for phase separation. The upper yellow liquid layer in falcon tube was collected in a cuvette. Another cuvette filled with two thirds of 80% acetone was used as blank to caliber spectrophotometer to 100% transference or 0% absorbance. For this measurement, the reading for absorbance was taken at 503 nm wavelength in a spectrophotometer and with the help of following equations, lycopene content in the fruits was estimated.

$$\text{Lycopene (mg/kg)} = 171.7 \text{ x A503 x V/W} \qquad \text{(Eq.3)}$$

Where, V = volume of sample.

W = the exact weight of tomato added, in grams.

Carotenoid extraction was done in 80% acetone solution and the equation as suggested by Hendry and Grime (1993) was used. Total leaf carotenoid was determined from the leaf extract that was used for measuring chlorophyll content. Carotenoid extraction requires absorption readings at A663, A645 and A470 nm wavelengths. The concentration of the total carotenoid was measured by subtracting the absorption of chlorophyll a and b and dividing by absorption coefficient of the total carotenoids, i.e. xanthophyll (x) and beta-carotene (c).

$$C\ (x + c) = \frac{(A480\ -\ 0.114\ x\ A663\ -\ 0.638\ x\ A645)x\ V}{112.5\ x\ W} \quad \text{(Eq.4)}$$

Where, A645, A663 & A480 = absorbance at 645, 663 and 480 nm wavelengths.

V = volume of sample.

W = weight of fresh tissue used for extraction.

3.5.4. Disease scoring procedures

Grafted and non-grafted plants were scored against diseases after 75 days of transplanting allowing maximum time for disease exposure in natural conditions. The modified scale of 0-5 given by Saleem et al. (2016) was used as a reference for disease scoring (Table 3). Five plants from each treatment in all replications were scored for disease resistance on the scale of 0-5, where 0 is highly resistant, 2 is resistant, 3 is tolerant, 4 is susceptible and 5 is the highly susceptible disease reaction.

3.6. Statistical analysis

3.6.1. Analysis of variance

All data were subjected to the analysis of variance (ANOVA) using SAS statistical software (Version 9.4). The linear statistical model used for this analysis is as follows:

$$y_{ij}\ =\ \mu\ + r_i +\ t_j + e_{ij} \quad \text{(Eq.5)}$$

Where, y_{ij} = an observation of j_{th} genotype in i_{th} replication

μ = general mean

r_i = the effect of i_{th} replication

t_j = the effect of j_{th} genotype

e_{ij} = uncontrolled variation associated with j_{th} genotype in i_{th} replication

i = number of replication (1, 2…i)

j = number of genotypes (1, 2…j)

Table 3 presents the components of the ANOVA model by providing comparison of variance by partitioning it in various sources.

Table 3. Components of analysis of variance for RCB design.

Source of variation	Degree of freedom	Mean square (MS)	Expected mean square (EMS)
Replications (R)	(r-1)	MS_R	$\sigma_e^2 + g\,\sigma_r^2$
Treatments (T)	(g-1)	MS_G	$\sigma_e^2 + r\,\sigma_g^2$
Error	(r-1) (g-1)	Me	σ_e^2
Total	(rg-1)		

Where, r = number of replications
g = number of genotypes
σ_e^2 = variance due to error
σ_r^2 = variance due to replications
σ_g^2 = variance due to genotypes

The significance of genotype mean squares was tested against error mean squares. The standard error of the mean (SEM) was calculated using the following formula:

$$\text{SEM} = \sqrt{\frac{\text{MSE}}{r}} \qquad \text{(Eq. 6)}$$

Where, MSE= Error mean sum of squares

r = number of replications

The critical difference (C.D.) to compare the mean of any genotype was calculated using following formula.

$$\text{C. D.} = \text{SEM}\; x\; \sqrt{2}\; x\; 't' \qquad \text{(Eq.7)}$$

Where, SEM = standard error of the difference of treatment means to be compared

't'= table value of 't' at 5% level of significance at error degree of freedom.

3.6.2. Mean separation

When the analysis of variance resulted in F significant, we were still not clear which means were significant from each other. Therefore, it was necessary to compare each pairs of treatments. Fisher's LSD test used to compare each pair of treatments.

$$\text{LSD} = t\frac{\alpha}{2} * S\overline{Y1} - S\overline{Y2} \text{ and df for } t = \text{Error df} \quad \text{(Eq. 8)}$$

Where, LSD = least significant difference.

df = degree of freedom.

3.6.3. Disease scoring

The disease score data were subjected to the analysis of variance using PROC GLIMMIX for both normal & non-normal response variables (SAS 9.4, SAS Institute Inc., Cary, NC). Multiple comparisons among treatments were performed using Fisher's LSD test. PROC MEANS of SAS v. 9.4 (SAS Institute Inc., Cary, NC) was used to estimate the median severity for each treatment and then ranked using PROC RANK. Analysis of variance was then executed on the rank value based on PROC MIXED as described by Shah and Madden (2004). In addition, SAS macro LD CI.sas from Brunner et al. (2002) was used to estimate each treatment relative effect and 95% confidence interval.

Table 4. Disease severity index, disease symptoms and host reactions in tomato plants.

Severity index	Disease symptoms	Host reaction
0	No visible disease symptom	HR (Highly resistant)
1	Leaves on about 10% of the total leaf area is affected	Resistant
2	Leaves on about 25% of the total plant area are infected	Tolerant
3	Leaves on about 50% of the total plant area are infected	MS (Moderately susceptible)
4	Leaves on about 75% of the total plant area are infected	S (Susceptible)
5	Leaves on the whole plant are affected and death of a plant	HS (Highly susceptible)

4. RESULTS

The analysis of variance among the treatments revealed significant differences for the characters such as Days to 1st flowering, days to 50% flowering, days to maturity, stem diameter, chlorophyll content, average fruit weight, fruit yield, titratable acidity, TSS/TA, Carotenoid and fruit firmness, but not for plant height, polar diameter, equatorial diameter, pH and Brix.

4.1. Growth characters

4.1.1. Plant height (cm)

The influence of grafting on the plant height at three different stages of plant growth viz., thirty days after transplanting (30 DAT), 60 days after transplanting (60 DAT), and 90 days after transplanting (90 DAT) is shown in the Figure 3. There were non-significant differences between different graft combinations and non-grafted tomato plants for plant height. Among all the graft combinations, Big Beef grafted onto Blocking rootstocks (BB/BLOC) recorded highest plant height across all stages of plant growth viz., 30 DAT (70.82 cm), 60 DAT (129.70 cm) and 90 DAT (151.55 cm) followed by Big Beef grafted onto Maxifort rootstock (BB/MAX) at 30 DAT (69.49 cm), 60 DAT (123.69 cm) and 90 DAT (148.28 cm), respectively. The lowest plant height was found in the Cannonball grafted onto the Blocking rootstocks (CAN/BLOC) at all stages of plant growth. However, among the non-grafted cultivars, Big Beef recorded highest plant height as compared to the Cannonball and Celebrity (Fig. 3) (Table 5).

4.1.2. Stem diameter (cm)

The effect of the grafting on the stem diameter is shown in Figure 4 and Table 5. Significant differences for stem diameter were detected among the grafted and non-grafted plants at various stages of plant growth. ‘Big Beef’ grafted onto ‘Maxifort’ rootstocks recorded highest stem diameter across all the stages of plant growth viz., 30 DAT (1.4 cm), 60 DAT (1.8 cm) and

90 DAT (2.1 cm) followed by ‘Celebrity’ grafted onto ‘Maxifort’ rootstock (CEL/MAX) and ‘Cannonball’ grafted onto ‘Maxifort’ rootstock (CAN/MAX). The smallest diameter was noted in ‘Big Beef’ grafted onto ‘Blocking’ rootstocks at different stage of plant growth. On the other hand, among the non-grafted cultivars, ‘Celebrity’ recorded highest stem diameter when compared to the ‘Cannonball’ and ‘Big Beef’ across all the stages of plant growth (Figure 4) (Table 5).

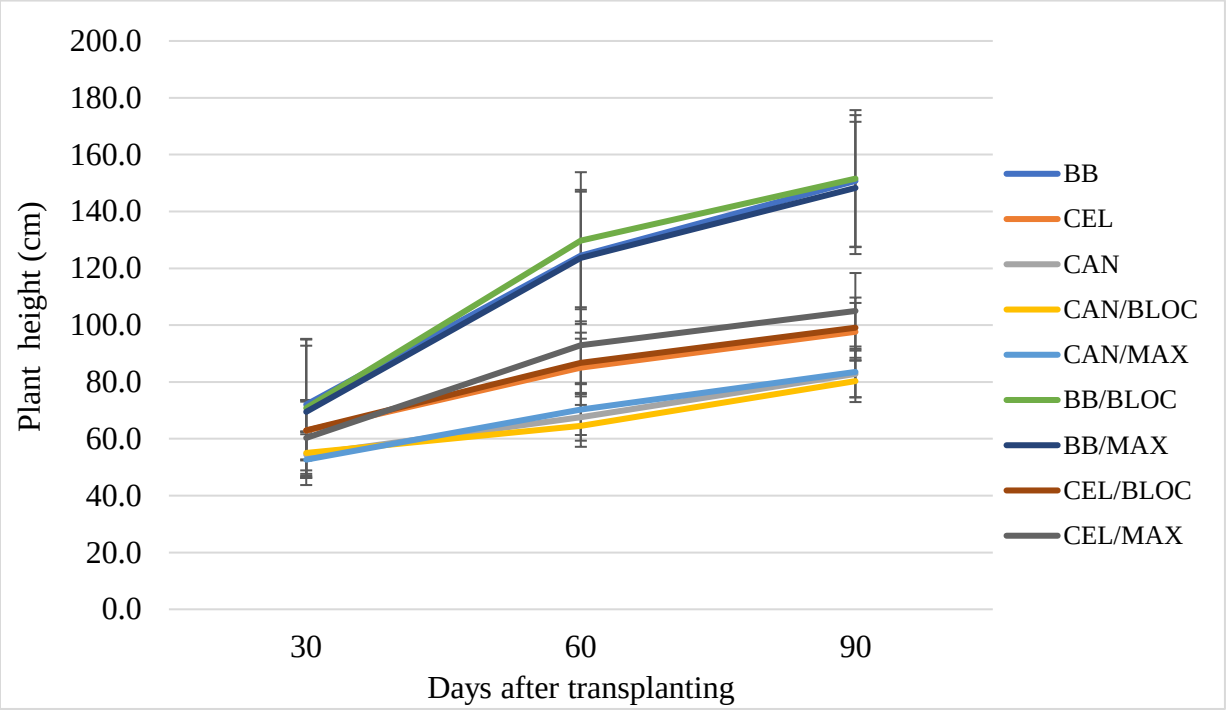


Fig. 3. Influence of grafting on the plant height at 30, 60 and 90 days after transplanting.
[+]Comparison was made between scions of similar graft combinations: ‘Big Beef’ grafted with ‘Maxifort’ rootstock (BB/MAX), ‘Big Beef’ grafted with ‘B-blocking’ rootstock (BB/BLOC) were compared with non-grafted ‘Big Beef’ (BB). Likewise, ‘Celebrity’ grafted with ‘Maxifort’ rootstock (CEL/MAX), along with ‘B-blocking’ rootstock (CEL/BLOC) was compared with non-grafted ‘Celebrity’ (CEL). Also, ‘Cannonball’ grafted with ‘Maxifort’ rootstock (CAN/MAX), along with ‘B-blocking’ rootstock (CAN/BLOC) was compared with non-grafted ‘Cannonball’.

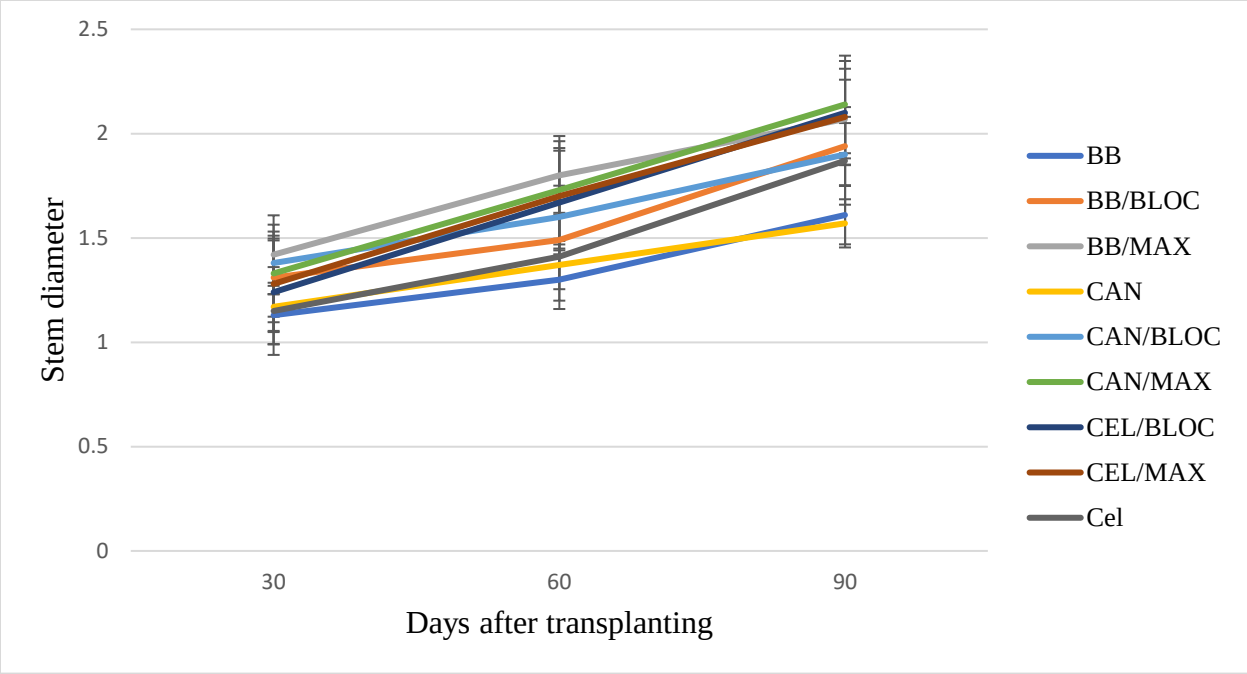


Fig. 4. Influence of grafting on the stem diameter at 30, 60 and 90 days after transplanting. [+]Comparison was made between scions of similar graft combinations: 'Big Beef' grafted with 'Maxifort' rootstock (BB/MAX), 'Big Beef' grafted with 'B-blocking' rootstock (BB/BLOC) were compared with non-grafted 'Big Beef' (BB). Likewise, 'Celebrity' grafted with 'Maxifort' rootstock (CEL/MAX), along with 'B-blocking' rootstock (CEL/BLOC) was compared with non-grafted 'Celebrity' (CEL). Also, 'Cannonball' grafted with 'Maxifort' rootstock (CAN/MAX), along with 'B-blocking' rootstock (CAN/BLOC) was compared with non-grafted 'Cannonball'.

4.1.3. Chlorophyll content (mg/g)

The influence of chlorophyll content of the plant is shown in Figure 5 and Table 6. It was measured at thirty days after transplanting (30 DAT), 60 days after transplanting (60 DAT), and 90 days after transplanting (90 DAT). Significant differences for chlorophyll content were detected between the grafted and non-grafted plants at various stages of plant growth. The 'Celebrity' grafted onto the 'Blocking' rootstock (CEL/BLOC) recorded highest chlorophyll content across all the stages of plant growth 30 DAT (1.7 mg/g), 60 DAT (1.8 mg/g) and 90 DAT (2.4 mg/g) and this was on par with 'Celebrity' grafted onto the 'Maxifort' rootstock (CEL/MAX) at 60 DAT (1.6 mg/g) and 90 DAT (2.5 mg/g). The lowest chlorophyll content was

obtained in Big Beef (non-graft) at all stages of plant growth viz., 30 DAT (0.8 mg/g), 60 DAT (1.1 mg/g) and 90 DAT (1.7 mg/g).

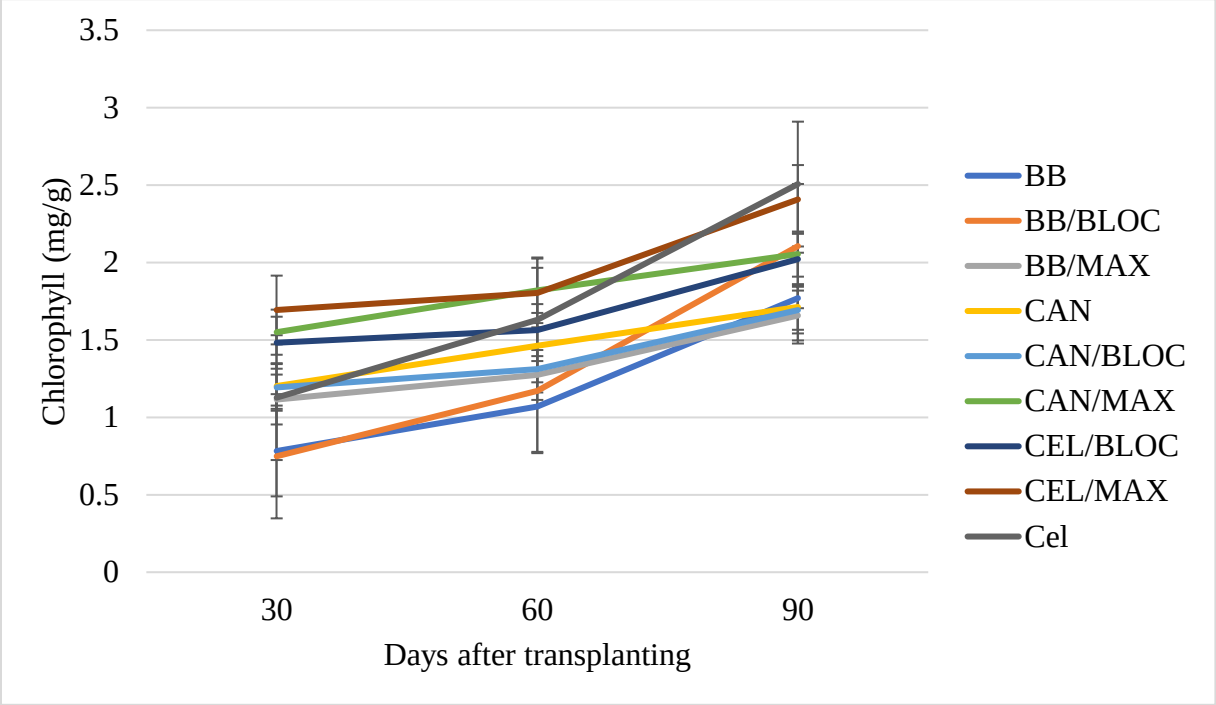


Fig. 5. Influence of grafting on the chlorophyll content at 30, 60 and 90 days after transplanting. [+]Comparison was made between scions of similar graft combinations: 'Big Beef' grafted with 'Maxifort' rootstock (BB/MAX), 'Big Beef' grafted with 'B-blocking' rootstock (BB/BLOC) were compared with non-grafted 'Big Beef' (BB). Likewise, 'Celebrity' grafted with 'Maxifort' rootstock (CEL/MAX), along with 'B-blocking' rootstock (CEL/BLOC) was compared with non-grafted 'Celebrity' (CEL). Also, 'Cannonball' grafted with 'Maxifort' rootstock (CAN/MAX), along with 'B-blocking' rootstock (CAN/BLOC) was compared with non-grafted 'Cannonball'.

4.1.4. Days to 1st flowering

The result indicated significant differences between grafted and non-grafted plants in number of days to flowering. When compared to all the grafted plants the non-grafted plants flowered the earliest. Among all the grafted treatment combinations, early flowering was noticed in the Celebrity grafted onto the Blocking rootstock (CEL/BLOC) (55.0 days) followed by Cannonball grafted onto the Blocking rootstock (CAN/BLOC) (58.3 days). However, the graft combination BB/BLOC took the highest number of days for the first flowering (61.0 days). In

the non-graft treatments, the early flowering was recorded in the Cannonball (54.0 days) (Figure 6) (Table 7).

4.1.5. Days to 50% flowering

The data on the number of days taken for 50% flowering are presented in Table 6. The results revealed that compared to grafted plants, non-grafted plants showed earlier in 50% flowering. Among all the grafted treatment combinations, days to 50% flowering was noticed earlier in the Cannonball grafted onto the Blocking rootstock (CAN/BLOC) (62.3 days) followed by Celebrity grafted onto the Blocking rootstock (CEL/BLOC) (63.3 days). However, the graft combination BB/BLOC took the highest number of days to 50% first flowering (67.0 days). In the non-graft treatments, the early days to 50% flowering was recorded in the Cannonball (59.0 days) (Figure 6) (Table 7).

4.1.6. Days to maturity

When compare to the grafted plant, the non-grafted plant matured earlier and exhibited significant differences for days to maturity. The days to maturity ranged from 84 to 97 days. Among all the genotypes, non-grafted CAN (84) was the earliest in maturity and was statistically at par with BB (85). The grafted plant BB/MAX (98) resulted in the maximum days to maturity but it remained statistically at par with BB/BLOC (97) and was followed by CAN/MAX (95) as well as CAN/BLOC (94) (Fig. 7) (Table 7).

4.1.7. Number of flowers per cluster

The results revealed no significant differences for the number of flowers per cluster among grafted and non-grafted tomato plants. The highest number of flowers per cluster was obtained both in the grafted treatments BB/MAX (6.6) as well as BB/BLOC (6.6). However,

among the non-grafted cultivars, ‘Celebrity’ recorded highest number of flowers per cluster (6.3), whereas ‘Cannonball’ recorded the lowest number of flowers per cluster (5.0) (Table 8).

Table 5. Performance of grafted and non-grafted tomato plants for plant height and stem diameter at 30, 60 and 90 days after transplanting.

Treatments	Days after transplanting					
	30	60	90	30	60	90
	Plant height (cm)			Stem diameter (cm)		
BB	72.0a	124.5ab	150.8a	1.1b	1.3c	1.6b
BB/BLOC	70.8ab	129.7a	151.6a	1.3a	1.5b	1.9a
BB/MAX	68.1b	123.7b	148.1a	1.4a	1.8a	2.1a
$LSD_{0.05}$[y]	*3.4*	*5.4*	*11.6*	*0.1*	*0.1*	*0.3*
CEL	62.9a	85.1c	97.7a	1.1a	1.4b	1.8a
CEL/BLOC	62.9a	86.7b	99.1a	1.2a	1.6ab	2.1a
CEL/MAX	60.3a	92.9a	104.9a	1.3a	1.7a	2.1a
$LSD_{0.05}$[y]	*4.5*	*1.6*	*15.2*	*0.1*	*0.3*	*0.3*
CAN	54.4a	67.6a	82.8a	1.2a	1.4c	1.6c
CAN/BLOC	55.0a	64.6a	80.3a	1.4a	1.6b	1.9b
CAN/MAX	52.7a	70.3a	83.5a	1.3a	1.7a	2.1a
$LSD_{0.05}$[y]	*4.3*	*13.4*	*9.1*	*0.3*	*0.1*	*0.1*

[+]Mean values followed by the same letter within columns are not significantly different from their respective control by Fisher’s least significant differences at $p < 0.05$. Data are means of 3 replications. [y]Values for the least significant difference (LSD) at $p < 0.05$ for comparing means in each column. BB= non-grafted Big Beef; BB/BLOC= Big Beef grafted onto B-blocking rootstock; BB/MAX=B-blocking grafted onto Maxifort rootstock; CAN= non-grafted Cannonball; CAN/BLOC= Cannonball grafted onto B-blocking rootstock; CAN/MAX= Cannonball grafted onto B-blocking rootstock; CEL/BLOC= Celebrity grafted onto B-blocking rootstock; CEL/MAX= Celebrity grafted onto Maxifort rootstock; CEL= non-grafted celebrity.

4.1.8. Number of flower cluster per plant

The results indicated non-significant differences for the number of flower clusters per plant between the grafted and non-grafted plants. Among the treatment combinations, the highest flower cluster per plant was obtained in the ‘Cannonball’ grafted onto ‘Maxifort’ rootstock (CAN/MAX) (7.6). However, among the tomato cultivars (non-grafted) the lowest number of flower clusters was observed in ‘Big Beef’ (6) (Table 8).

Table 6. Performance of grafted and non-grafted tomato plants for chlorophyll content at 30, 60 and 90 days after transplanting.

Treatments	Days after transplanting		
	30	60	90
	Chlorophyll content (mg/g)		
BB	0.78c	1.07c	1.77b
BB/BLOC	1.55a	1.82a	2.05a
BB/MAX	1.48b	1.56b	2.02a
$LSD_{0.05}$[y]	*0.01*	*0.03*	*0.05*
CEL	0.75c	1.17b	2.11b
CEL/BLOC	1.69a	1.80a	2.41a
CEL/MAX	1.13b	1.63a	2.51a
$LSD_{0.05}$[y]	*0.02*	*0.20*	*0.20*
CAN	1.12b	1.27c	1.66c
CAN/BLOC	1.20a	1.46a	1.71a
CAN/MAX	1.19a	1.31b	1.69b
$LSD_{0.05}$[y]	*0.01*	*0.03*	*0.01*

[+]Mean values followed by the same letter within columns are not significantly different from their respective control by Fisher's least significant differences at $p < 0.05$. Data are means of 3 replications. [y]Values for the least significant difference (LSD) at $p < 0.05$ for comparing means in each column. BB= non-grafted Big Beef; BB/BLOC= Big Beef grafted onto B-blocking rootstock; BB/MAX=B-blocking grafted onto Maxifort rootstock; CAN= non-grafted Cannonball; CAN/BLOC= Cannonball grafted onto B-blocking rootstock; CAN/MAX= Cannonball grafted onto B-blocking rootstock; CEL/BLOC= Celebrity grafted onto B-blocking rootstock; CEL/MAX= Celebrity grafted onto Maxifort rootstock; CEL= non-grafted celebrity.

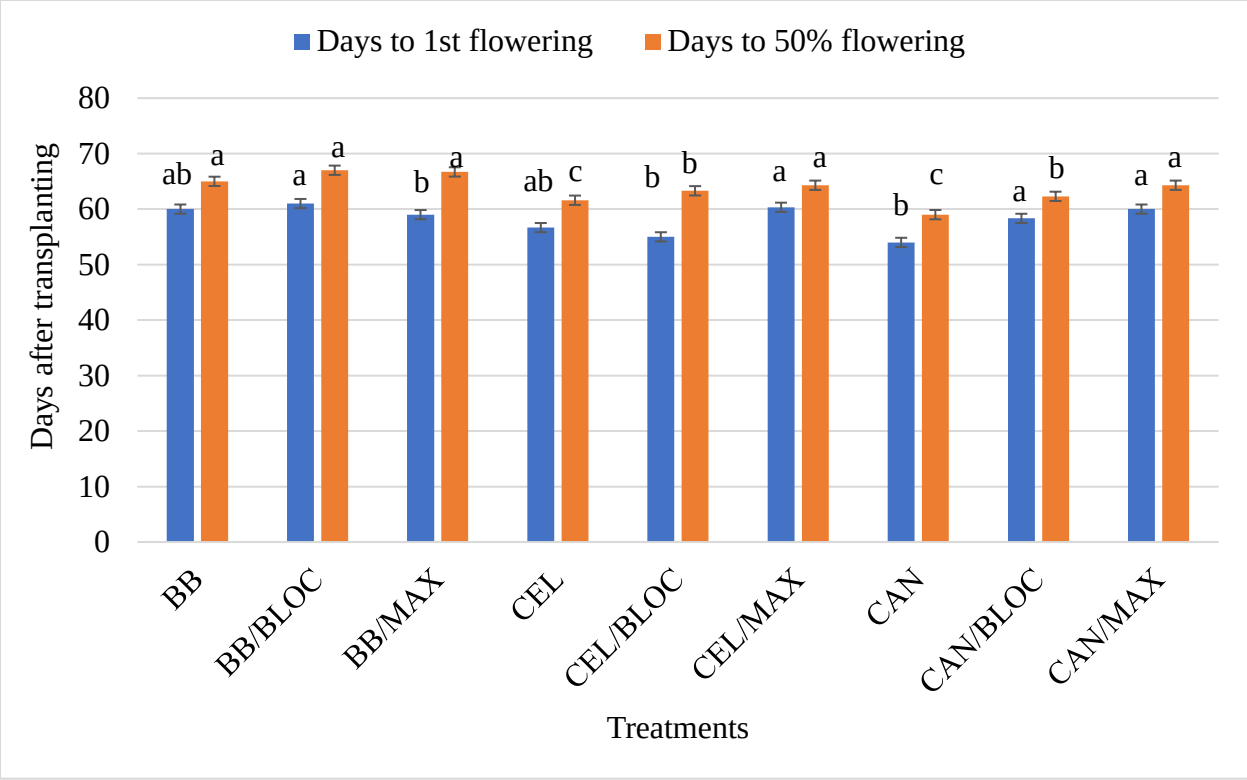


Fig. 6. Influence of grafting on the days to flowering and days to 50% flowering.

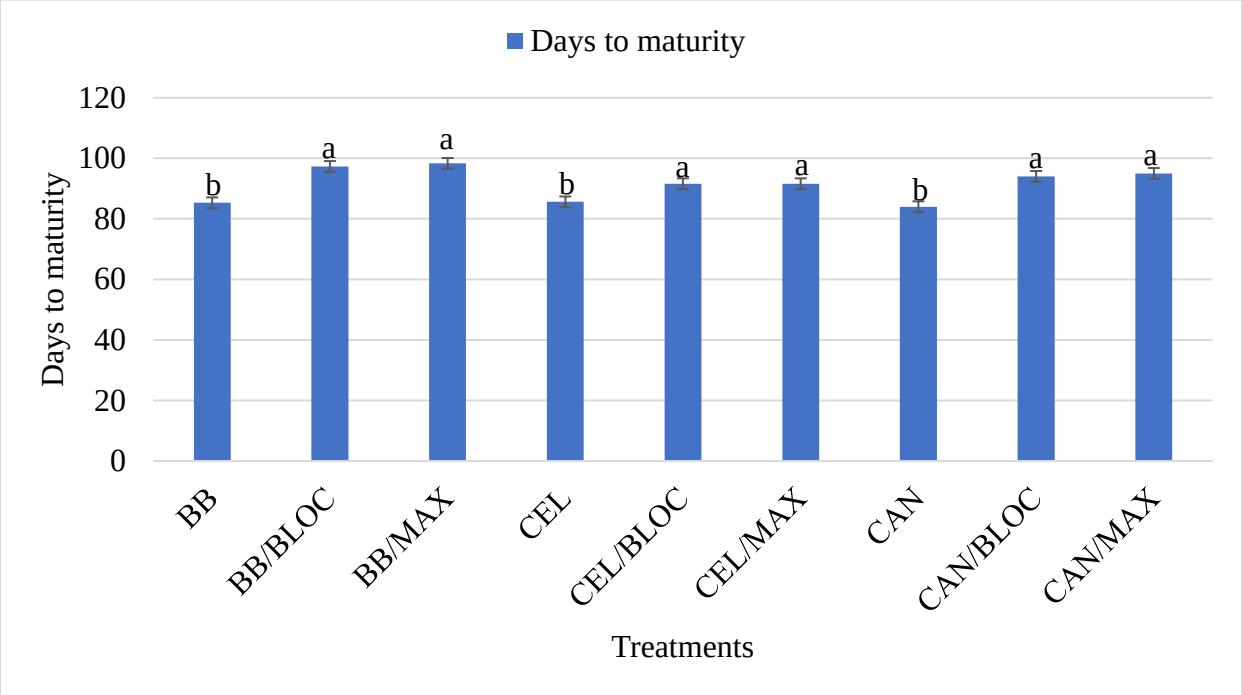


Fig. 7. Influence of grafting on the days to maturity.

Table 7. Performance of grafted and non-grafted tomato plants for days to flowering, days to 50% flowering and days to maturity.

Treatments	Days to		
	1st flowering	50% flowering	maturity
BB	59.7ab	65.3a	85.3b
BB/BLOC	61.0a	67.0a	97.3a
BB/MAX	59.0b	66.7a	98.3a
$LSD_{0.05}$[y]	*1.9*	*3.3*	*4.5*
CEL	56.7ab	61.6c	85.6b
CEL/BLOC	55.0b	63.3b	91.6a
CEL/MAX	60.3a	64.3a	91.6a
$LSD_{0.05}$[y]	*4.1*	*0.8*	*4.1*
CAN	54.0b	59.0c	84.0b
CAN/BLOC	58.3a	62.3b	94.0a
CAN/MAX	60.0a	64.3a	95.0a
$LSD_{0.05}$[y]	*3.5*	*1.5*	*3.0*

[+]Mean values followed by the same letter within columns are not significantly different from their respective control by Fisher's least significant differences at $p < 0.05$. Data are means of 3 replications. [y]Values for the least significant difference (LSD) at $p < 0.05$ for comparing means in each column. BB= non-grafted Big Beef; BB/BLOC= Big Beef grafted onto B-blocking rootstock; BB/MAX=B-blocking grafted onto Maxifort rootstock; CAN= non-grafted Cannonball; CAN/BLOC= Cannonball grafted onto B-blocking rootstock; CAN/MAX= Cannonball grafted onto B-blocking rootstock; CEL/BLOC= Celebrity grafted onto B-blocking rootstock; CEL/MAX= Celebrity grafted onto Maxifort rootstock; CEL= non-grafted celebrity.

4.2. Fruit yield and its components

4.2.1. Polar diameter of the fruit (cm)

The results on the polar diameter of fruit are presented in Table 8. The polar diameter ranged from 7.00 cm to 8.04 cm. The grafted plant BB/BLOC (8.04 cm) had the highest polar diameter and was statistically in similar with BB/MAX (7.9 cm). The lowest polar diameter was found in the grafted combination CAN/MAX (6.9 cm) and followed by CAN/BLOC (7.0 cm) and CEL/BLOC (7.1 cm). Among the tomato seedlings, CAN recorded highest polar (7.5 cm) than the BB (7.2 cm) and CEL (7.4 cm).

4.2.2. Equatorial diameter of fruit (cm)

The results on the equatorial diameter of the fruit are presented in Table 8. Non-significant differences on equatorial diameter were witnessed among the treatments. The grafted tomato plants BB/ BLOC recorded highest equatorial diameter (9.7 cm) compared to the other grafted plants. The equatorial diameter of the fruit was ranged from 8.6 cm -9.7 cm.

4.2.3. Number of fruits per plant

The number of the fruits per plant is related to the higher fruit yield. Significant differences for the number of fruits per plant was noticed among the grafted and non-grafted treatments. The grafted plant BB/MAX (28.0) recorded highest number of fruits per plant and was followed by BB/BLOC (23.2) and CEL/BLOC (23.2). Similarly, in the non-grafted plants, BB (19.0) recorded highest number of fruits per plant flowed by CEL (14.4). The average number of fruits ranged from 11-28 (Table 8).

4.2.4. Weight of fruit (kg)

The results revealed significant differences between grafted and non-grafted plants for the average weight of fruits. Grafted tomato plants confirmed statistically higher fruit weight than the non-grafted plants. Among all the grafted treatments, BB/BLOC (0.5 kg) resulted in the highest fruit weight and was statistically on par with BB/MAX (0. 4 kg). However, tomato seedlings BB (0.3 kg), CEL (0.3 kg) and CAN (0.3 kg) doesn't show any differences for average weight of the fruit. The fruit weights were ranged from 0.5 kg to 0.3 kg (Table 8).

4.2.5. Fruit yield (kg)

The results indicated that fruit yield was greatly influenced by grafting (Figure 9) (Table 8). BB/MAX (8.01 kg), BB/BLOC (6.77 kg), CEL/MAX (5.55 kg), CEL/BLOC (6.05 kg), and CAN/MAX (5.59 kg) as well as CAN/BLOC (6.10 kg) revealed a significant difference in yield

along with its respective non-grafted plants viz., BB, CEL and CAN, respectively. Highest fruit yield was showed in BB/MAX (8.01 kg) followed by BB/BLOC (6.77 kg). Similarly, CEL/MAX (5.55 kg) recorded lowest fruit yield which stood statistically in par with CEL/BLOC (6.06 kg), CAN/MAX (5.59 kg) and CAN/BLOC (6.10 kg).

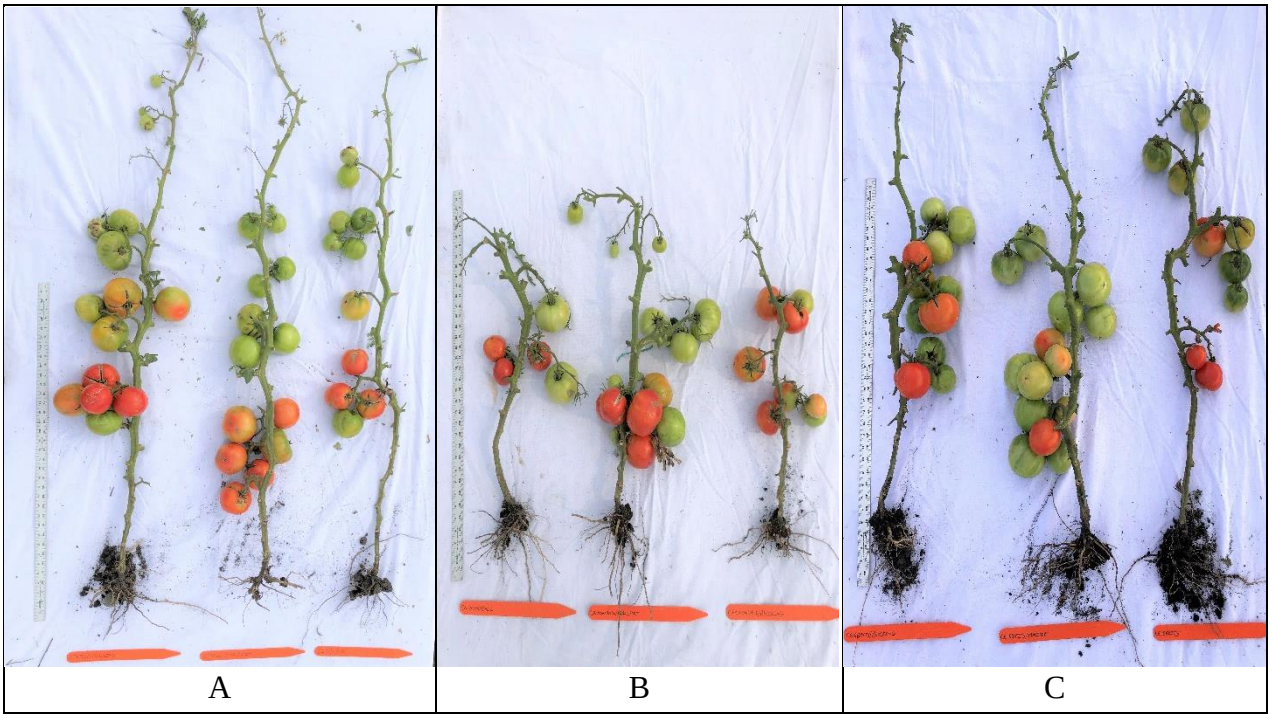
Fig. 8. Grafted and non-grafted tomato fruit showing variations in shape and size. Non-grafted Celebrity, Celebrity/B-blocking, Celebrity/Maxifort; non-grafted Cannonball, Cannonball/B-blocking, and 'Cannonball/Maxifort' and, non-grafted Big Beef, 'Big Beef/B-blocking' and 'Big Beef/Maxifort' (from top to bottom).

4.3. Fruit quality

4.3.1. pH

Grafting effects on fruit pH are shown in the Table 9. The pH was higher in non-grafted plants than in the grafted plants. Among all the grafted combination, significant difference for pH was only found in CAN/MAX (4.27), CAN/BLOC (4.18) when compared along with its respective non-graft CAN (4.55). Moreover, grafted treatments BB/BLOC (4.08), BB/MAX

(4.20) and CEL/BLOC (4.04), CEL/MAX (4.08) remained not statistically different along with its non-grafted counter-parts BB and CEL, respectively. The pH value ranged from 4.04 to 4.55.



A B C

Fig. 9. Grafted tomato plant showing variation in the number of fruit and fruit yield. A- Grafted tomato plants 'Big Beef'/ 'B-blocking', 'Big Beef'/ 'Maxifort' and non-grafted 'Big Beef', B- Grafted tomato plants 'Celebrity'/ 'B-blocking', 'Celebrity'/ 'Maxifort' and non-grafted 'Celebrity', C- Grafted tomato plants 'Cannonball'/ 'B-blocking', 'Cannonball'/ 'Maxifort' and non-grafted 'Cannonball' (from right to left).

4.3.2. Total soluble solids (%)

Total soluble solids were found to be significantly higher in non-grafted BB (5.23 %) and CEL (5.17 %) than their grafted counterparts BB/MAX (4.87 %) and CEL/MAX (4.80 %), respectively. However, being smaller value, grafted tomato plants such as CAN/MAX (4.50 %), BB/BLOC (5.20 %) and CEL/BLOC (5.02 %) did not result into significant differences with their respective control. The total soluble solids ranged from 4.47 % -5.23 % (Table 9).

4.3.3. Titratable acidity (%)

The results revealed significant differences between the grafted and non-grafted plants for the titratable acidity. The grafted treatments BB/BLOC (0.36 %), BB/MAX (0.34 %), CEL/BLOC (0.41 %), CEL/MAX (0.40 %), CAN/BLOC (0.34 %) and CAN/MAX (0.33 %) showed higher in value for titratable acidity when compared with its respective non-graft BB (0.31 %), CEL (0.36 %) and CAN (0.29 %), respectively, indicated higher titratable acidity (Table 9).

4.3.4. TSS/TA

The ratio TSS/TA value varied among treatments. The ratio TSS/TA value was lower in the grafted plants than the non-grafted plants. This ratio stood significantly higher for non-grafted BB (17.12) than grafted BB/BLOC (16.85), BB/MAX (14.48). Similarly, non-grafted CEL (14.53) remained significantly higher with CEL/BLOC (12.44) and CEL/MAX (12.11). Also, non-grafted CAN (15.61) was higher than grafted CAN/BLOC (14.46) and CAN/MAX (13.61), but not significantly different (Table 9).

4.3.5. Lycopene (mg/kg)

Lycopene was significantly higher in non-grafted plants than the grafted plants. The non-grafted plant BB (94.59 mg/kg) resulted in a higher mean value for lycopene content followed by CAN (74.35 mg/kg) and Celebrity (64.47 mg/kg). However, the least lycopene content in CAN/MAX (59.88 mg/kg) was surprisingly similar with other treatment combinations (Table 9).

4.3.6. Carotenoid content (mg/g)

The results of carotene content were statistically higher in the grafted plants than their respective non-graft combinations, and it ranged from 0.79 mg/g to 1.01 mg/g. Above all, the

grafted plant BB/MAX (1.01 mg/g) revealed statistically higher carotene content and was followed by CEL/MAX (0.91 mg/g) and CAN/MAX (0.94 mg/g) as well. Similarly, the lower value for lycopene was declared for CAN/BLOC (0.84 mg/g) followed by CEL/BLOC (0.88 mg/g) and BB/BLOC (0.88 mg/g) (Table 9) as well.

4.3.7. Fruit firmness (kg/cm^2)

The results indicated significantly higher fruit firmness in all the grafted plants than their non-grafted counterparts. Grafted plants BB/MAX (5.96 kg/cm^2) resulted in the highest fruit firmness and was also statistically similar with BB/BLOC (5.91 kg/cm^2), which followed by CEL/BLOC (5.55 kg/cm^2). The least fruit firmness was declared in CAN/BLOC (4.74 kg/cm^2), which was also statically similar with CAN/MAX (5.00 kg/cm^2). Similarly, CEL/BLOC (5.55 kg/cm^2) and CEL/MAX (5.21 kg/cm^2) indicated a statistically significant difference in fruit firmness for non-grafted CEL (4.64 kg/cm^2) (Table 9).

4.4. Disease tolerance

The results of disease ratings for tomato spotted wilt virus is given in Table 10. Both grafted and non-grafted plants were not affected by fungal diseases like early blight and late blight. The visible symptoms on the leaves were leaf deformity and mottling or mosaic. Five plants from each treatment were scored for disease resistance on the scale of 0-5, where 0 is highly resistant, 2 is resistant, 3 is tolerant, 4 is susceptible and 5 is the highly susceptible disease reaction. The median, mean ranks, mean relative effect, and confidence intervals is presented in Table 10. The mean relative effect ranged from 0-1. The relative effect value closer to zero indicated highly resistant reactions and close to one indicated as a susceptible reaction. So, based on mean relative effect, treatment BB/MAX was considered to be highly resistant treatment with mean relative effect 0.074, which was followed by BB/BLOC and CEL/MAX with mean relative

effect 0.198 and 0.259, respectively. On the other hand, non-grafted plants were considered to be highly susceptible to diseases. The non-grafted treatments CAN remained more susceptible to disease with mean relative effect 0.920, which was trailed by CEL and BB with mean relative effect 0.691 and 0.593, respectively.

Table 8. Performance of graft combinations and non-graft in tomato plants for number of flower cluster/plant, number of flower/clusters, fruit polar diameter, fruit equatorial diameter, number of fruits per plant, average weight of fruit and fruit yield.

Treatments	Number of			Diameter (cm)		Average (kg)	
	flower cluster/plant	flower/ cluster	fruits/plant	Polar	Equatorial	Weight /fruit	Yield/plant
BB	5.6b	5.6ba	19.0b	7.2b	9.4a	0.3b	5.3c
BB/BLOC	7.0a	6.6a	23.2ab	8.0a	9.7a	0.5a	6.7b
BB/MAX	7.3a	6.6a	27.6a	7.9a	9.6a	0.4a	8.0a
$LSD_{0.05}$[y]	*1.3*	*0.1*	*4.6*	*0.6*	*0.7*	*0.05*	*0.9*
CEL	8.0a	6.3a	14.4b	7.35a	8.62a	0.3b	4.0b
CEL/BLOC	7.3ab	6.3a	23.2a	7.14a	9.07a	0.4a	6.1a
CEL/MAX	6.6b	6.3a	20.5ab	7.50a	8.66a	0.4a	5.5ab
$LSD_{0.05}$[y]	*0.9*	*2.1*	*7.29*	*0.6*	*0.5*	*0.07*	*1.9*
CAN	7.0a	5.00b	11.2b	7.5a	9.6a	0.3b	4.0b
CAN/BLOC	7.0a	10.00a	18.3a	7.0b	9.4a	0.4a	6.1a
CAN/MAX	7.6a	6.00b	21.5a	6.92b	9.5a	0.4a	5.6ab
$LSD_{0.05}$[y]	*2.0*	*3.1*	*6.0*	*0.5*	*0.4*	*0.15*	*2.0*

[+]Mean values followed by the same letter within columns are not significantly different from their respective control by Fisher's least significant differences at $p < 0.05$. Data are means of 3 replications. [y]Values for the least significant difference (LSD) at $p < 0.05$ for comparing means in each column. BB= non-grafted 'Big Beef'; BB/BLOC= 'Big Beef' grafted onto 'B-blocking' rootstock; BB/MAX= 'B-blocking' grafted onto 'Maxifort' rootstock; CAN= non-grafted 'Cannonball'; CAN/BLOC= 'Cannonball' grafted onto 'B-blocking' rootstock; CAN/MAX= 'Cannonball' grafted onto 'B-blocking' rootstock; CEL/BLOC= 'Celebrity' grafted onto 'B-blocking' rootstock; CEL/MAX= 'Celebrity' grafted onto 'Maxifort' rootstock; CEL= non-grafted 'Celebrity'.

Table 9. Performance of grafted and non-grafted tomato plants for pH, Brix, titratable acidity, TSS/TA, carotene, lycopene and fruit firmness.

Treatments	pH	Brix (%)	Titratable acidity (%)	TSS/TA	Carotenoid (mg/g)	Lycopene (mg/kg)	Fruit Firmness (kg/cm^2)
BB	4.24a	5.23a	0.30c	17.12a	0.82c	94.59a	5.43b
BB/BLOC	4.08a	5.20a	0.36a	14.51b	0.88b	60.73b	5.91a
BB/MAX	4.20a	4.87b	0.33b	14.48b	1.01a	60.29b	5.96a
$LSD_{0.05}$[y]	*0.15*	*0.26*	*0.01*	*0.96*	*0.01*	*12.01*	*0.36*
CEL	4.14a	5.16a	0.36b	14.53a	0.86b	64.5a	4.64b
CEL/BLOC	4.04a	5.01a	0.41a	12.44b	0.88d	62.5b	5.55a
CEL/MAX	4.08a	4.80b	0.40a	12.11b	0.94a	60.1c	5.21a
$LSD_{0.05}$[y]	*0.22*	*0.18*	*0.01*	*0.50*	*0.03*	*1.66*	*0.35*
CAN	4.54a	4.46a	0.29b	15.61a	0.79c	74.35a	4.39a
CAN/BLOC	4.17b	4.93a	0.34a	14.46a	0.84b	62.74b	4.73ab
CAN/MAX	4.27b	4.50a	0.33a	13.61a	0.91a	59.88b	4.99b
$LSD_{0.05}$[y]	*0.27*	*0.75*	*0.01*	*2.63*	*0.01*	*4.31*	*0.50*

[+]Mean values followed by the same letter within columns are not significantly different from their respective control by Fisher's least significant differences at $p < 0.05$. Data are means of 3 replications. [y]Values for the least significant difference (LSD) at $p < 0.05$. BB= non-grafted Big Beef; BB/BLOC= Big Beef grafted onto B-blocking rootstock; BB/MAX=B-blocking grafted onto Maxifort rootstock; CAN= non-grafted Cannonball; CAN/BLOC= Cannonball grafted onto B-blocking rootstock; CAN/MAX= Cannonball grafted onto B-blocking rootstock; CEL/BLOC= Celebrity grafted onto B-blocking rootstock; CEL/MAX= Celebrity grafted onto Maxifort rootstock; CEL= non-grafted celebrity.

Table 10. Response of grafted and non-grafted tomato plants to a tomato spotted wilt virus evaluated in field experiment at agricultural research station of North Dakota State University.

Treatments	Median[a]	Mean ranks	Treatment relative effect[b]	
			Mean	95% Confidence interval
BB	3	5.83	0.593	0.528-0.653
BB/BLOC	2	2.16	0.198	0.130-0.308
BB/MAX	1	1.16	0.074	0.058-0.176
CAN	5	8.66	0.920	0.819-0.940
CAN/BLOC	3	6.83	0.691	0.504-0.821
CAN/MAX	3	5.83	0.593	0.528-0.653
CEL/BLOC	2	4.83	0.481	0.309-0.659
CEL/MAX	2	2.83	0.259	0.212-0.315
CEL	4	6.83	0.691	0.504-0.821

[a]Medians based on the disease score according to the 0-5 scale of Saleem et al. [b]Mean relative effect closer to zero are considered as more resistant. BB= non-grafted 'Big Beef'; BB/BLOC= 'Big Beef' grafted onto 'B-blocking' rootstock; BB/MAX= 'B-blocking' grafted onto 'Maxifort' rootstock; CAN= non-grafted 'Cannonball'; CAN/BLOC= 'Cannonball' grafted onto 'B-blocking' rootstock; CAN/MAX= 'Cannonball' grafted onto 'B-blocking' rootstock; CEL/BLOC= 'Celebrity' grafted onto 'B-blocking' rootstock; CEL/MAX= 'Celebrity' grafted onto 'Maxifort' rootstock; CEL= non-grafted 'Celebrity'.

Non-grafted Cannonball

Grafted Cannonball

Non-grafted celebrity

Grafted Celebrity

Non-grafted Big Beef

Grafted Big Beef

Fig. 10. Disease reactions in grafted and non-grafted tomato plant at 75 days after transplanting.

5. DISCUSSION

5.1. Plant growth characters

5.1.1. Plant height (cm) and stem diameter (cm)

All the grafted plants were shortest in plant height at 30 days after transplanting (DAT), and eventually grew taller by 90 DAT, however, there was no any statistical differences between grafted and non-grafted tomato plants in all three stages of plant growth viz., 30, 60, and 90 DAT. The smallest plant height in the grafted plant at 30 DAT might be due to the limited vascular tissue connection, and limited absorption of minerals, water and photosynthetic from the ground to the plant (Ives et al., 2012) which might have a negative impact on plant growth. This result agreed the finding of Khah et al. (2006) who showed non-significant differences between grafted and non-grafted plants of tomato cultivar Big Red grafted onto Primavera rootstock and contradicts the findings of Abdelmageed et al. (2007), Khah et al. (2006), Mohammed et al. (2009), and Rahamatin et al. (2014) as well.

Grafted tomato plants BB/BLOC, BB/MAX, and CAN/MAX remained significantly larger in stem diameter than the non-grafted BB, and CAN at all three stages (30, 60 and 90 DAT) of the plant growth. This might be because grafted plants were more vigorous than the non-grafted tomato plants (Lee, 1994). However, at 30 DAT grafted tomato plants CEL/BLOC (1.24 cm) and CEL/MAX (1.28) didn't show any statistical difference when compared with its non-grafted counterpart CEL (1.15 cm). Also, grafted tomato plant CAN/BLOC (1.6 cm) was not a significantly different from the non-grafted CAN (1.37 cm) at 60 DAT. The smallest stem diameter might be due to the limited translocation of minerals, water and photosynthetic from the ground to the plant (Ives et al., 2012). These findings neither support nor dispute the findings of Mohammed et al. (2009), Yarsi (2011) and Hanna (2012).

5.1.2. Chlorophyll content (mg/g)

Chlorophyll content in the grafted tomato plants remained statistically higher than the non-grafted tomato plants in all three stages (30, 60 and 90 DAT) of plant growth. It might be due to the higher accumulation of minerals, photosynthate, and water from the ground to the plant. Similar findings were obtained by Lee et al. (1994), Khah et al. (2006), Mohammed et al. (2009), and Liu et al. (2012) as well.

5.1.3. Days to flowering and maturity

There was a significant difference between grafted and non-grafted tomato plant for days to first flowering, days to 50% flowering, and days to maturity. When compared to the grafted plants, all the non-grafted plants flowered earlier and reached 50% of flowering at the earliest date. Delayed flowering in tomato plants when grafted on different *Solanum* rootstocks was also reported by Ibrahim et al. (2001) and Rahman et al. (2002) as well. Similar findings were also obtained by Rashid et al. (2004) on the grafted tomato plants with *Solanum torvum* rootstock resulting in about 10 days more time for flowering (66 days) than the non-grafted plants (54 days). The delayed in flowering might be due to the stress faced by the plant in the time of grafting (Ibrahim et al., 2001) (Khah et al., 2006). Statistical differences between the grafted and non-grafted tomato plants was also observed for days to maturity. Among all the treatments, the non-grafted CAN (84 days) matured earliest which was followed by BB (85 days) and CEL (86 days), and significantly differed with its grafted counterparts CAN/BLOC (94 days), CAN/MAX (95 days), CEL/BLOC (92 days), CEL/MAX (92 days), BB/BLOC (97 days) and BB/MAX (98 days), respectively. Similar findings were reported by Rahman et al. (2002) in non-grafted ‘Sufala’ eggplants (65 days) that was 15 days earlier than the ‘Uttara’ eggplants grafted on *Solanum torvum* (80 days). Rashid et al. (2004) also reported grafted tomato plants on *Solanum*

torvum rootstock took more days for fruit maturity (115 days) than the non-grafted tomato plants (98 days). The delayed in maturity might be due to the stress faced by the plant in the grafting operation (Ibrahim et al., 2001) and (Khah et al., 2006).

5.1.4. Number of flowers

The results of experiment didn't reveal any significant difference for the number of flowers per cluster and the number of flower clusters per plant between the grafted and non-grafted plants. However, grafting significantly increases the number of flowers per cluster in CAN/BLOC (10) when compared to non-grafted CAN (5). Similar findings were obtained by Yarsi (2011) in flowers numbers on the 1st and 7th clusters of grafted tomato plants grown in greenhouse conditions. However, the result contradicts the findings of Khah et al. (2006) who found a non-significant difference between the grafted and non-grafted tomato plants with respect to the total number of flowers per plant.

5.2. Fruit yield and its components

5.2.1. Polar diameter (cm) and equatorial diameter (cm)

Regardless of higher polar diameter, the findings did not reveal significant differences among CAN/BLOC, CAN/MAX and CAN. On the other hand, both grafted plant BB/BLOC (8.04) and BB/MAX (7.95) revealed significant differences when compared with the non-grafted BB (7.27) for polar diameter. Similarly, non-significant differences were found in between CEL/BLOC, CEL/MAX and CEL (7.35). Also, for equatorial diameter, no significant differences were detected among the grafted and non-grafted tomato plants. This result also contradicts the finding of Riga (2015) who reported that grafting tomato causes into significant increase in fruit weight which results into increased fruit diameter and size under lower light and temperature stresses. However, the above results are similar with the finding of Mohammed et al.

(2009) and Yarsi (2011) who reported that the fruit size of grafted tomato plant does not statically differ from the fruit size of the control plants.

5.2.2. Number of fruits per plant, average weight of fruits and fruit yield

The number of fruits per plant related to the higher fruit yield revealed significant differences among the treatments CAN/BLOC (18), CAN/MAX (22) and non-graft CAN (11). Similarly, CEL/BLOC (23) also exhibited significant differences in the respective non-grafted CEL (14). Despite the higher fruit number, BB/BLOC (23), BB/MAX (28) and CAN/MAX (22) did not reveal any significant differences from non-grafted BB (19) and CEL (14), respectively. The findings revealed significant differences between grafted and non-grafted plants for the weight and yield of fruit. BB/BLOC (0.45 kg), BB/MAX (0.44 kg), CEL/BLOC (0.39 kg), CEL/MAX (0.38 kg), CAN/MAX (0.40 kg) and CAN/BLOC (0.37 kg) detected the highest fruit weight from the non-grafted counterpart BB (0.33 kg), CEL (0.30 kg) and CAN (0.27 kg), respectively. Similarly, for fruit yield, BB/MAX (8.01 kg), BB/BLOC (6.77 kg), CEL/MAX (5.55 kg), CEL/BLOC (6.05 kg), CAN/MAX (5.59 kg) and CAN/BLOC (6.10 kg) revealed a significant difference in yield when compared with non-grafted BB, CEL and CAN, respectively. These increases in weight and yield of fruit of grafted tomato plants might be due to the increased water and mineral uptake and increased reaping period ensuing from a vigorous, healthy root system compared to the non-grafted plants (Lee, 1994). This finding also confirms the conclusion of Estan (2005), Burleigh et al. (2005), Khah et al. (2006), Perez et al. (2006), Leonardi and Giuffrida (2006), Rivard and Louws (2008), and Al-Harbi et al. (2017).

5.3. Fruit quality

5.3.1. pH

The findings of pH in fruit revealed non-significant differences between grafted plants and a non-grafted tomato plants. However, grafted treatments CAN/MAX (4.27), CAN/BLOC (4.18) resulted in a significant difference for pH along with its respective non-grafted CAN (4.55). This result confirms the findings of Khah et al. (2006) and disagrees with the findings of Turhan et al. (2011).

5.3.2. Total soluble solids, titratable acidity and TSS/TA

Total soluble solid were significantly higher in non-grafted BB (5.23) and CEL (5.17) than their grafted counterparts BB/MAX (4.87) and CEL/MAX (4.80), respectively. Despite being the smaller in magnitude with other grafted tomato plants, the other cultivars and graft combinations tomato plants didn't reveal significant differences for total soluble solids. This result supports the findings of Khah et al. (2006) and contradicts the findings of Ibrahim et al. (2001) and Mohammed et al. (2009) who reported increased total solid content in the grafted tomato.

Similarly, titratable acidity was detected significantly higher in value for grafted treatment combinations BB/BLOC (0.36), BB/MAX (0.34), CEL/BLOC (0.41), CEL/MAX (0.40), CAN/BLOC (0.34) and CAN/MAX (0.33) than its non-grafted counterpart's BB (0.31), CEL (0.36) and CAN (0.29), respectively. The results contradict with the findings of Ibrahim et al. (2001), Turhan et al. (2011), and Mohammed et al. (2009).

Further, the ratio (TSS/TA) which is an important parameter for flavor and nutritional quality of the tomato was shown to be lowered in the grafted plant than in the non-grafted plant. The results also conflict with the findings of Ibrahim et al. (2001), Turhan et al. (2011), and

Mohammed et al. (2009) as well. The overall findings suggested that there was inconsistency of the results among the treatments for fruit pH, total soluble solids, titratable acidity, and TSS/TA. This might be because of tomato rootstocks grown under different cultural methods, soil fertility and irrigation practices.

5.3.3. Lycopene and carotene and fruit firmness

Lycopene content was observed to be significantly lower in grafted tomato plants than the non-grafted counterparts. The low lycopene content might be due to the increased in water content of the tomato fruits. This result agrees with the findings of Turhan et al. (2011) Mohammed et al. (2009) and Khah et al. (2006) as well. On the other hand, carotene content and fruit firmness were found to be statistically higher in the grafted plant than their respective non-graft combinations. Similar findings were obtained by Davis and Perkins (2005) who reported a significant difference in fruit firmness, Brix (% sugar) content, carotenoid and lycopene content in watermelon. Yetisir (2003) also suggested that watermelon quality characteristics like sugar content, firmness, rind thickness, and fruit shape were greatly affected by grafting. On the contrary, the findings of Leoni et al. (1990) and Romano and Paratore (2001) on grafted melons in greenhouse experiments suggested no change in fruit quality as influenced by grafting.

5.4. Disease tolerance

The grafted and non-grafted tomato plants were only affected by tomato spotted wilt virus and were not affected by other fungal diseases like early and late blight. The visible symptoms in the leaves were leaf deformity and mottling or mosaic. Based on mean relative effect, treatment BB/MAX was a highly resistant treatment with mean relative effect 0.074, which was followed by BB/BLOC and CEL/MAX with mean relative effect 0.198 and 0.259, respectively. On the other hand, non-grafted plants were found to be highly susceptible to

diseases. The non-grafted treatment, CAN was more susceptible to disease with mean relative effect 0.920, which was followed by CEL and BB with mean relative effects of 0.691 and 0.593, respectively. This confirms the findings in which grafting scions of susceptible tomato cultivars onto resistant rootstocks has been successful for managing tomato bacterial wilt and soil-borne diseases for higher yield and quality (Peregrine and Ahmad, 1982). This also confirms the finding of Lee, 1994; Lee et al., 2010; Turhan et al., 2011; Choi et al., 2015; Rivard and Louws, 2008 who reported that grafted tomato plants were more vigorous and tolerant to different fungal, bacterial, viral and nematodes.

6. SUMMARY AND CONCLUSION

6.1. Summary

The findings of my experiment revealed that grafted plants resulted in higher values for stem diameter and chlorophyll content. The combinations of scion/rootstock that had a positive impact on these characters are BB/BLOC, BB/MAX and CAN/MAX. Similarly, the scion/rootstock like BB/MAX and BB/BLOC prolonged days of maturity and contributes a higher yield than the non-grated BB. The results further suggested that grafting seedling on 'Maxifort' and 'B-blocking' rootstocks improves the fruit quality based on the titratable acidity, but didn't improve the parameters like pH, TSS, lycopene and TSS/TA. The findings of this research also suggested that the scion/rootstock combination have a positive impact on improving fruit quality parameters like leaf carotenoid and fruit firmness and this increased in fruit firmness in the grafted plant will in turn increased the shelf life of the fruits. The grafted tomato plants had higher resistance to the viral and fungal diseases especially in the BB/MAX and BB/BLOC treatment combinations.

6.2. Conclusion

The use of rootstock 'B-blocking' and 'Maxifort' considerably increased the yield and disease tolerance in Big Beef, Celebrity, and Cannonball cultivars, so it is highly recommended to use the grafted combinations viz., CAN/MAX, CAN/BLOC, CEL/MAX, CEL/BLOC, BB/MAX and BB/BLOC for exploiting the yield potential.

The use of B-blocking and Maxifort rootstock increased the titratable acidity, leaf chlorophyll, leaf carotenoid and fruit firmness in scion cultivars like 'Big Beef', 'Celebrity', and 'Cannonball'. Therefore, these treatment combinations may be considered for increasing the flavor and shelf life in the tomatoes.

Since there was a negative impact of the rootstocks, ‘B-blocking’ and ‘Maxifort’ for improving quality parameters like TSS, pH, and lycopene, it is proposed to perform additional research to discover the best rootstock and scion combination for improving these quality parameters in the tomato fruit.

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APPENDIX

Table A1. Monthly meteorological data from North Dakota Agricultural Weather Network of the year 2018.

Year	Months	Avg. wind speed (mph)	Total rainfall (inch)	Total solar rad (Lys)	Temperature (°F)		
					Max	Min	Avg.
2018	April	8.57	0.23	479.80	45.00	24.98	34.99
2018	May	7.27	1.71	500.33	77.76	50.89	64.3
2018	June	7.6	4.85	551.94	80.92	59.99	70.46
2018	July	5.89	3.18	555.04	82.08	60.78	71.43
2018	August	6.22	3.97	440.17	80.67	58.23	69.45
2018	September	7.44	2.53	329.48	69.59	48.23	58.91

Table A2. Analysis of variance for days to 1st flowering, days to 50 % flowering, days to maturity, number of flower cluster, number of flower per cluster, number of fruit per plant, polar diameter, equatorial diameter, average fruit weight, fruit yield, pH, Brix, titratable acidity, TSS/TA, carotenoid, lycopene, fruit firmness in between Big Beef (control), Big Beef/ Maxifort, and Big Beef/Blocking treatments.

		Days to 1st flowering		Days to 50 % flowering		Days to maturity	
Source	df	MSE	F	MSE	F	MSE	F
Replication	2	0.77	1.00ns	1.33	0.62ns	3.00	0.75ns
Treatment	2	3.11	4.00ns	2.33	1.08ns	157.00	39.25***
Error	4	0.77		2.16		4.00	
		No. of flower cluster		No. of flower per cluster		Number of fruits per plant	
Replication	2	0.01	0.28ns	0.90	7.95***	2.10	0.50**
Treatment	2	2.33	7.00*	0.82	7.18***	56.34	13.51ns
Error	4	0.33		0.11		4.17	
		Polar diameter.		Equatorial diam.		Average wt. of fruit	
Replication	2	0.07	0.71ns	0.07230	0.71ns	0.0034	0.61ns
Treatment	2	0.05	0.46*	0.04543	0.46ns	0.0136	24.32**
Error	4	0.10		0.10173		0.0056	
		Fruit yield		pH		Brix	
Replication	2	0.05	0.26ns	0.00164	0.34ns	0.090	6.75ns
Treatment	2	4.23	23.10**	0.20144	4.14ns	0.123	9.25*
Error	4	0.18		0.0048		0.013	
		Titratable acidity		TSS/TA		Carotenoid	
Replication	2	0.00010	0.40ns	0.83	4.92ns	0.00001	0.18ns
Treatment	2	0.00214	77.20***	6.88	37.65***	0.02807	459.45***
Error	4	0.00003		0.18		0.00006	
		Lycopene		Firmness			
Replication	2	32.94	1.17ns	0.0189	0.74ns		
Treatment	2	1161.70	41.36***	0.2569	10.04**		
Error	4	28.09		0.0256			

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square; TSS/TA= total soluble solid / titratable acidity

Table A3. Analysis of variance for plant height, stem diameter and chlorophyll content at 30, 60 and 90 days after transplanting (DAT) in between Big Beef (control), Big Beef/Maxifort, and Big Beef/Blocking treatments.

Source	df	Plant height (30 DAT)		Plant height (60 DAT)		Plant height (90 DAT)	
		MSE	F	MSE	F	MSE	F
Replication	2	8.25	3.63ns	6.15	1.08ns	25.16	0.95ns
Treatment	2	12.10	5.32ns	32.10	5.66ns	8.71	0.33ns
Error	4	2.27		5.67		26.38	
		Stem diameter (30 DAT)		Stem diameter (60 DAT)		Stem diameter (90 DAT)	
Replication	2	0.0023	0.062ns	0.0205	17.98**	0.0272	1.32ns
Treatment	2	0.0627	16.54ns	0.1888	164.98***	0.1661	8.04*
Error	4	0.0037		0.0002			
		Chlorophyll (30 DAT)		Chlorophyll (60 DAT)		Chlorophyll (90 DAT)	
Replication	2	0.5390	3.25ns	0.0007	2.77ns	0.0727	0.97
Treatment	2	0.0001	12127.30***	0.4317	1766.23***	0.0058	122.60***
Error	4	0.0001		0.0002		0.0006	

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square; DAT= Days after transplanting.

Table A4. Analysis of variance for days to 1st flowering, days to 50 % flowering, days to maturity, number of flower cluster, number of flower per cluster, number of fruit per plant, polar diameter, equatorial diameter, average fruit weight, fruit yield, pH, Brix, titratable acidity, TSS/TA, carotenoid, lycopene, fruit firmness in between Celebrity (control), Celebrity/ Maxifort, and Celebrity/Blocking treatments.

		Days to 1st flowering		Days to 50 % flowering		Days to maturity	
Source	df	MSE	F	MSE	F	MSE	F
Replication	2	0.00	0.00ns	0.777	7.00*	0.33	0.10ns
Treatment	8	22.33	6.70*	5.444	49.00***	36.00	10.80**
Error	16	3.33		0.111		3.33	
		No. of flower cluster		No. of flower per cluster		Number of fruits per plant	
Replication	2	1.33	8.00*	0.333	0.40ns	0.00003	0.03ns
Treatment	8	1.33	8.00*	0.00	0.00ns	0.00823	7.06ns
Error	16	0.166		0.833		0.00116	
		Polar diameter.		Equatorial diam.		Average wt. of fruit	
Replication	2	0.2793	4.01ns	1.06	20.97ns	0.00003	0.03ns
Treatment	8	0.0981	1.41ns	0.19	3.72ns	0.00821	7.06*
Error	16	0.0697		0.05		0.00111	
		Fruit yield		pH		Brix	
Replication	2	0.49	0.68ns	0.0070	0.73ns	0.0100	1.48ns
Treatment	8	3.42	4.70ns	0.0081	0.85ns	0.1019	14.68**
Error	48	0.73		0.0096		0.0069	
		Titratable acidity		TSS/TA		Carotenoid	
Replication		0.00001	0.40ns	0.06	1.25ns	0.00021	1.00***
Treatment		0.00221	79.60***	5.16	102.65***	0.00474	22.47ns
Error		0.00002		0.05		0.00021	
		Lycopene		Firmness			
Replication		0.52	0.97ns	0.09	3.98ns		
Treatment		14.26	26.50***	0.64	26.61***		
Error		0.54		0.02			

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square; TSS/TA= total soluble solid / titratable acidity.

Table A5. Analysis of variance for plant height, stem diameter and chlorophyll content at 30, 60 and 90 days after transplanting (DAT) in between Celebrity (control), Celebrity/ Maxifort, and Celebrity/Blocking treatments.

Source	df	Plant height (30 DAT)		Plant height (60 DAT)		Plant height (90 DAT)	
		MSE	F	MSE	F	MSE	F
Replication	2	1.79	0.45ns	14.24	29.44*	103.47	2.15ns
Treatment	2	6.95	1.74ns	51.61	106.70*	45.29	0.94ns
Error	4	3.99		0.48		48.03	
		Stem diameter (30 DAT)		Stem diameter (60 DAT)		Stem diameter (90 DAT)	
Replication	2	0.0037	1.04ns	0.0024	0.14ns	0.0011	0.06ns
Treatment	2	0.0125	3.48ns	0.0784	4.63ns	0.0480	2.54ns
Error	4	0.0036		0.0169		0.0189	
		Chlorophyll (30 DAT)		Chlorophyll (60 DAT)		Chlorophyll (90 DAT)	
Replication	2	0.00007	1.0ns	0.0093	1.45ns	0.0121	1.48ns
Treatment	2	0.67581	8689.0***	0.3204	49.81*	0.1300	15.89**
Error	4	0.00007		0.0064		0.0081	

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square. DAT= Days after transplanting.

Table A6. Analysis of variance for days to 1st flowering, days to 50 % flowering, days to maturity, number of flower cluster, number of flower per cluster, number of fruit per plant, polar diameter, equatorial diameter, average fruit weight, fruit yield, pH, Brix, titratable acidity, TSS/TA, carotenoid, lycopene, fruit firmness in between Cannonball (control), Cannonball/Maxifort, and Cannonball/Blocking treatments.

		Days to 1st flowering		Days to 50 % flowering		Days to maturity	
Source	df	MSE	F	MSE	F	MSE	F
Replication	2	1.44	0.59ns	0.77	1.75ns	0.77	0.44*
Treatment	2	28.77	11.77*	21.77	49.00***	104.11	58.56***
Error	4	2.44		0.44		1.77	
		No. of flower cluster		No. of flower per cluster		Number of fruits per plant	
Replication	2	0.78	1.00ns	2.11	1.00ns	12.71	1.84ns
Treatment	2	0.44	0.57ns	20.11	9.53*	84.11	12.20**
Error	4	0.78		2.11		6.89	
		Polar diameter.		Equatorial diam.		Average wt. of fruit	
Replication	2	0.18	3.17ns	0.25	0.31ns	0.0005	0.50ns
Treatment	2	0.38	6.64*	0.01	7.49ns	0.0133	12.22**
Error	4	0.05		0.03		0.0010	
		Fruit yield		pH		Brix	
Replication	2	0.82	1.06ns	0.0070	0.50ns	0.091	0.82ns
Treatment	2	3.47	4.43ns	0.1105	7.66*	0.203	1.82ns
Error	4	0.78		0.01442		0.111	
		Titratable acidity		TSS/TA		Carotenoid	
Replication	2	0.00004	1.00ns	0.7310	0.54ns	0.00007	7.0*
Treatment	2	0.00241	54.25***	3.0022	2.24ns	0.00981	883.0***
Error	4	0.00004		1.3467		0.00001	
		Lycopene		Firmness			
Replication	2	8.00	2.21ns	0.0154	0.31ns		
Treatment	2	176.35	48.77***	0.2779	5.56ns		
Error	4	3.61		0.0499			

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square; TSS/TA= total soluble solid / titratable acidity

Table A7. Analysis of variance for plant height, stem diameter and chlorophyll content at 30, 60 and 90 days after transplanting (DAT) in between Cannonball (control), Cannonball/Maxifort, and Cannonball/Blocking treatments.

Source	df	Plant height (30 DAT)		Plant height (60 DAT)		Plant height (90 DAT)	
		MSE	F	MSE	F	MSE	F
Replication	2	0.10	0.02ns	0.87	0.02ns	8.78	0.55ns
Treatment	2	4.51	1.24ns	24.56	0.70ns	8.66	0.54ns
Error	4	3.63		34.93		16.01	
		Stem diameter (30 DAT)		Stem diameter (60 DAT)		Stem diameter (90 DAT)	
Replication	2	0.008	0.37ns	0.0091	9.04*	0.0057	6.11ns
Treatment	2	0.0348	1.47ns	0.1013	100.23***	0.2400	257.18***
Error	4	0.0236		0.0010		0.0009	
		Chlorophyll (30 DAT)		Chlorophyll (60 DAT)		Chlorophyll (90 DAT)	
Replication	2	0.00003	1.0ns	0.00001	0.05ns	0.00007	1.75ns
Treatment	2	0.00730	219.0***	0.02934	139.00***	0.00221	49.00***
Error	4	0.00003		0.00020		0.00004	

*, **, *** Indicates significant at p=0.05, p=0.01, and p=0.001 levels, respectively; ns=non-significant; df =degree of freedom; MSE= mean sum of square; DAT= Days after transplanting.