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Inter-specific cucurbitaceous rootstock enhances growth and yield in grafted cucumber (*Cucumis sativus* L.)

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Abstract: In recent years, grafting has emerged as an efficient and alternative tool to the relatively slow conventional breeding methods, aiming to increase tolerance to abiotic stresses and soil pathogens while improving yield and quality attributes in fruit vegetables. In the present investigation, six inter-specific cucurbitaceous rootstocks, viz. sponge gourd (SG), ridge gourd (RG), ash gourd (AG), bottle gourd (BG), and Summerfit (SF), an inter-specific hybrid of snap melon × acidulus melon, were evaluated for cucumber (C) cv. 'Kashi Nutan'. Experimental findings revealed that cucumber grafted onto inter-specific SF exhibited a 14.63%, 57.5%, and 20.05% increase in vine length, number of branches, and dry matter production, respectively, compared to the self-rooted control. Photosynthetic parameters such as photosynthetic rate (P_n), stomatal conductance (g_s), and maximum quantum efficiency of photosystem II (PS II) (Fv/Fm) were also higher in cucumber leaves grafted onto the SF rootstock. Compared to self-rooted plants, cucumber grafted onto SF recorded 72.3% more fruits, a 36.9% increase in fruit weight, and an 80.9% higher fruit yield. The SF rootstock also showed a 44.54% increase in total root length (TRL), a 77.11% increase in root volume, and a 27.25% increase in average root diameter over self-rooted cucumber.

Keywords: cucumber grafting; graft combinations; inter-specific cucurbit rootstocks; net photosynthesis rate; root architecture

Grafting is a special type of plant propagation technique wherein a part of a plant (scion) is joined to another plant (rootstock) to grow as a new plant. The rootstock is generally having better plant vigour and tolerance to various biotic (pathogens) and abiotic (environmental) stresses, whereas the scion has some peculiar qualitative and quantitative horticultural traits. Vegetable grafting was first used in Japan during the late 1920s by grafting watermelon onto pumpkin rootstocks. It is a common practice in Japan, Korea, and several European countries; its main purpose is to control soil-borne diseases and nematodes (Lee, Oda 2003); however, it has now been used for improving yields and tolerance to environmental stresses such as high soil salinity, drought, flooding, high and low temperatures (Bhatt et al. 2015; Li et al. 2015; Bahadur et al. 2015; Ma et al. 2023). Cucumber (*Cucumis sativus* L.) is one of the most cultivated vegetable crops, particularly in polyhouses and greenhouses in the Mediterranean region, because of the short growing cycle and its high economic value in off-season harvest. During the past few years, hybrid cucumber has been intensively grown in different areas of India, but the critical problem is low yield due to unfavourable soil properties, soil-borne diseases, and a successive cropping system. Cucum-

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ber crop productivity mainly depends on the availability of natural resources, including soil, water, nutrients, and climatic elements. Grafting is currently considered a rapid alternative tool to the relatively slow breeding methodology for increasing yields and tolerance to biotic and abiotic stress of fruiting vegetables (Bahadur et al. 2015; Bahadur et al. 2016). Grafting has contributed to sustainable agriculture by reducing the amount of agrochemicals used to disinfect the soil, as it has been used to confer tolerance to soil-borne diseases, improve fruit quality, and increase the absorption of nutrients and yields. Several studies have demonstrated that grafting can enhance plant vigour, harvesting period (Lee et al. 2010), improves yield and fruit quality (Khah et al. 2006; Cansev, Ozgur 2010; Rouphael et al. 2010; Riga et al. 2016; Al-Harbi et al. 2018; Guan et al. 2018; Chawda 2021), tolerates low and high temperatures (Li et al. 2015; Ma et al. 2023), alleviates salinity and heavy metal stress (Huang et al. 2013; Wahb-Allah 2014; Penella et al. 2015; Penella et al. 2016), increases drought and flooding stress tolerance (Bahadur et al. 2015; Bhatt et al. 2015; Bahadur et al. 2016), improves water use efficiency (Cantero-Navarro et al. 2016), nutrient uptake and utilization efficiency (Zhong, Bie 2006; Lee et al. 2010; Huang et al. 2013; Zhang et al. 2014). Generally, the performance of scion cultivar depends on rootstock genotype, which affects plant vigour, yields, and modifies tolerance or susceptibility to biotic and abiotic constraints. It has been observed that grafting of hybrid cucumber on inter-specific cucurbit rootstocks not only enhances plant growth, yields and fruit quality, but also is economically beneficial due to high net returns and benefit-cost ratio as compared to self-rooted cucumber (Noor et al. 2019; Aslam et al. 2020). By improving physiological efficiency, root architecture, and resource utilisation, grafting offers a sustainable solution to challenges such as soil-borne diseases and unfavourable growing conditions, ultimately contributing to higher productivity and economic returns in cucumber cultivation. The present investigation evaluates the performance of various cucurbitaceous rootstocks in cucumber with respect to plant growth, photosynthetic efficiency, root architecture, and yield attributes, as it would highlight the potential of grafting as an effective strategy to enhance cucumber growth, yield, and stress tolerance by utilising inter-specific cucurbitaceous rootstocks.

MATERIAL AND METHODS

Rootstocks and scion materials. Five rootstocks of cucurbits, i.e. sponge gourd (SG) (cv. 'Kashi Shreya'), ridge gourd (RG) (cv. 'Kashi Shivani'), bottle gourd (BG) (cv. 'Kashi Ganga'), ash gourd (AG) (cv. 'Kashi Surabhi'), and Summerfit (SF) (an inter-specific hybrid of snap melon; *Cucumis melo* var. *momordica* × acidulus melon; *Cucumis melo* ssp. *agrestis* var. *acidulus* procured from VNR Seeds Pvt. Ltd., Raipur, India) were used. 'Kashi Nutan', an open-pollinated and improved cucumber variety, was used as a scion. These rootstocks were evaluated during the rainy season (July–September) with self-rooted or self-rooted cucumber ('Kashi Nutan') as a control.

Grafts preparation. Seeds of cucurbitaceous rootstocks were sown in small plastic glasses filled with soil, sand, vermicompost and cocopeat (2 : 1 : 1 : 1), 3–4 days before the scion cultivar. Scion cultivar was sown in small pro-trays containing 98 cells, and filled with media comprising a mixture of coco-peat, perlite, vermiculite and sterilised vermicompost in the proportion of 2 : 1 : 1 : 1. Grafts were made when the first true leaves of the scions and rootstocks were fully extended. Rootstocks 25 days old and scions 20 days old from sowing were used for grafting. The thickness of both rootstocks and scions was 2.0–3.0 mm. One cotyledonary splice grafting technique was adopted (Figure 1), wherein a slant cut (45° angle) of 5–7 mm was made both on rootstock and scion using a razor blade with a scoping motion. In rootstocks, one cotyledonary leaf and the growing point were removed, whereas in scions, both cotyledonary leaves and one true leaf were retained.

After placing the scion on the rootstock, a grafting clip was used to fix the grafted position at the union site. Grafted plants were immediately shifted inside the grafting chamber for the next 5 days, wherein the constant temperature between 25 °C and 30 °C and relative humidity of more than 85% were maintained. The light interception in the grafting chamber was not more than 25% of the total incoming radiation. Misting was done 2–3 times daily to maintain appropriate temperatures and humidity. Thereafter, the healed grafted plants were kept in partial shade for 7–10 days with relatively less humidity (65–70%), and higher temperatures (30–35 °C) for acclimatisation. Before transplanting to the field, the grafted plants were exposed to full sunlight for another

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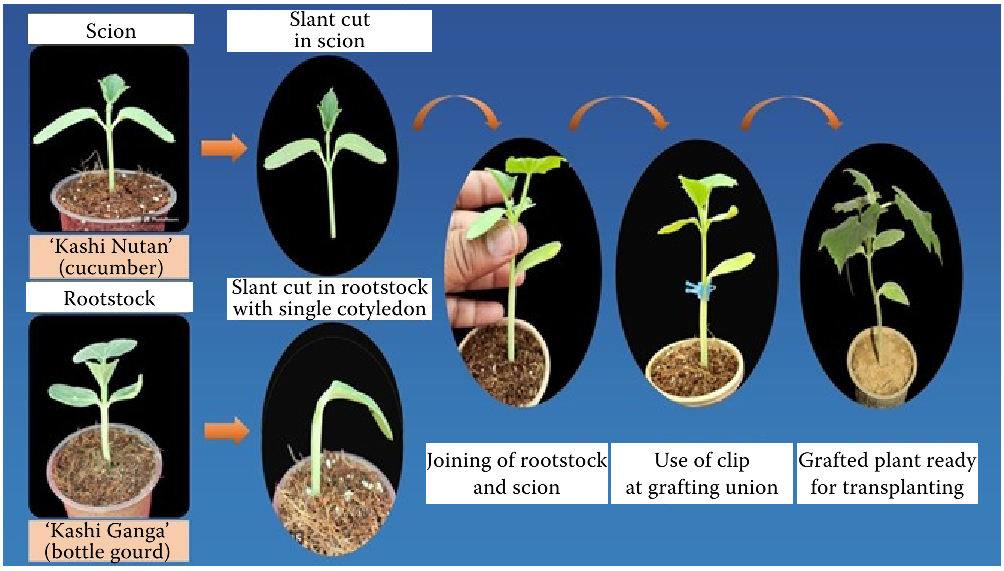

Figure 1. Depiction of single cotyledonary splice grafting of cucumber onto bottle gourd rootstock at 18 days after sowing

5–7 days for hardening. In this way, approximately 20 days are required for transplanting in the field after performing the grafting operation.

Agronomic practices. Grafted plants were transplanted in the field at row-to-row and plant-to-plant distances of 1.25 m × 0.5 m, and soon after planting, light irrigation was given. Before transplanting, farm yard manure (FYM) was applied in the field at the rate of 20 t/ha, whereas NPK was applied at 120 : 60 : 60 kg/ha. Full quantities of P and K, and half quantities of N were applied two days before planting. The rest of N was applied in two split doses equally, i.e. 30 and 50 days after planting. Plants were trained on a vertical trellis system supported with a galvanised iron (GI) pole of 7 feet in height. Two-hand weedings were performed before the split application of N. In the absence of rain, surface irrigation was given at 5–6 day intervals.

Physio-morphological observations. Three plants from each replication (a total of 9 plants from each treatment) were selected, recording observations on plant growth, physiological traits, yields and root parameters. Photosynthetic parameters such as net photosynthesis rate (P_n), stomatal conductance (g_s) and maximum quantum efficiency of photosystem II (PSII) (Fv/Fm) were measured in the top 3rd or 4th fully expanded leaf with the CI-340 Handheld Photosynthesis System (CID Bio-Science Inc., USA). During the observation, the photosynthetically active radiation (PAR) value ranges between 560–1067 μmol/m^2/sec, ambient temperature 35.3–40.1 °C, CO_2 430–487 ppm and relative humidity (RH) 81–87%. Chlorophyl concentration index (CCI) was measured by SPAD 502 chlorophyll meter (Spectrum Technology, Inc., USA). Biomass partitioning in different plant parts, such as stems, leaves, roots and fruits, was recorded at the last harvest. Fruit parameters such as number of fruits per plant, fresh weight (FW), dry weight (DW), length, diameter and yield per plant were recorded during harvest. A total of five harvests were made, usually at 5–7 day intervals.

Root growth parameters such as total root length (TRL), surface area, volume and average diameter were measured after final harvest by using an acquired TIFF-format grey image (400 dpi resolution) with a flatbed scanner (Epson Expression 11000XL, Epson, Suwa, Japan) and the software Win-RHIZO-2013 (Regent Instrument Inc., Quebec, QC, Canada).

Statistical analysis. The experiment was laid out as a randomised complete block design (RCBD) with three replications. A pre-ANOVA test was also carried out, and it was found that the data followed independence and normality. The significant differences (P < 0.05) between treatments were determined by Duncan's multiple range test at a significance level of 0.05 for all growth, yield and physiological parameters. ANOVA and critical difference values were calculated by using SPSS version 27.0 software (SPSS Inc., Chicago, IL, USA) and Microsoft Excel's built-in data analysis options.

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RESULTS

Physio-morphological attributes. Inter-specific grafting significantly affected the plant physio-morphological parameters in cucumber (Table 1). Concerning vine length, SF + cucumber displayed a significantly longer vine (269.00 cm) compared to all other graft combinations, indicating superior overall growth and development. In contrast, RG + cucumber had the shortest vine length (167.00 cm), suggesting that this graft combination may not promote extensive vine growth. SG + cucumber and BG + cucumber combinations were statistically at par with each other, showing intermediate vine lengths. In terms of vine DW, SF + cucumber had the highest value (104.85 g), comparable to SG + cucumber and self-rooted cucumber plants. Conversely, RG + cucumber exhibited the lowest vine DW (54.52 g), indicating a less favourable impact on overall plant biomass.

Diverse graft combinations had varying effects on root length. SF + cucumber resulted in the most extended root system (46.77 cm), significantly outperforming over other graft combinations. In contrast, RG + cucumber (28.30 cm) and self-rooted cucumber (29.17 cm) had the shortest roots, suggesting that RG may not be as effective in promoting root elongation. Graft combinations, BG + cucumber and SG + cucumber, displayed comparable, intermediate root lengths. Root DW was highest in SF + cucumber (7.89 g), significantly different from other graft combinations, while RG + cucumber had the lowest root DW (3.16 g). Regarding leaf number per plant, RG + cucumber had the highest value (190.67), not significantly different from SF + cucumber (183.67) and self-rooted cucumber (115.67). AG + cucumber had the lowest leaf number per plant (97.33), suggesting a potential limitation in promoting leaf development. In terms of leaf DW, SF + cucumber resulted in the highest value (63.80 g), indicating better leaf tissue development and potential for higher photosynthetic activity. AG + cucumber had the lowest leaf DW (25.04 g), suggesting that AG may not contribute as much to leaf biomass. Branch number per plant was highest in SF + cucumber (6.3), significantly different from other graft combinations, indicating enhanced branching and potential for increased fruit production. However, RG + cucumber and SG + cucumber were not significantly different but lower than SF + cucumber. The best-performing graft combination, SF + cucumber, showed a 14.6% increase in vine length, 10.1% increase in vine DW, 60.4% increase in root length, and 91.6% increase in root DW compared to the self-rooted cucumber. Additionally, it exhibited a 33.8% increase in leaf DW and a 57.5% increase in the number of branches per plant, indicating superior vegetative growth and potential for higher productivity.

Among different graft combinations, SF + cucumber exhibits the highest photosynthetic activity (Figure 2). The significantly high P_n suggests that the SF rootstock positively influences the cucumber plant's ability to photosynthesise efficiently. Following closely, the RG + cucumber combination also demonstrates noteworthy photosynthetic activity, indicating that the rootstock positively impacts the overall photosynthesis process. AG + cucumber and self-rooted cucumber plants display the least photosynthetic activity. It suggests that grafting with AG rootstock or having self-rooted plants may negative-

Table 1. Physio-morphological attributes in grafted cucumber affected by various rootstocks

Graft combination	Vine length (cm)	Vine DW (g)	Root length (cm)	Root DW (g)	Leaves/ plant	Leaf DW (g)	Branches/ plant
SG + C	208.0 ± 5.51^{bc}	95.48 ± 4.62^{a}	36.93 ± 1.88^{c}	6.37 ± 0.63^{b}	179.67 ± 4.1^{ab}	75.03 ± 4.93^{a}	5.0 ± 0.58^{ab}
RG + C	167.0 ± 8.08^{d}	54.52 ± 4.29^{c}	28.3 ± 1.58^{d}	3.16 ± 0.12^{c}	190.67 ± 5.49^{a}	56.39 ± 2.25^{bc}	4.6 ± 0.33^{ab}
BG + C	213.67 ± 5.46^{bc}	73.14 ± 5.06^{b}	39.73 ± 1.66^{bc}	3.41 ± 0.23^{c}	144.67 ± 36.22^{ab}	26.10 ± 0.93^{d}	5.0 ± 0.58^{ab}
AG + C	194.33 ± 8.11^{cd}	50.69 ± 1.67^{c}	44.97 ± 1.73^{ab}	3.34 ± 0.6^{c}	97.33 ± 41.88^{b}	25.04 ± 1.13^{d}	4.0 ± 0.58^{b}
SF + C	269.0 ± 14.74^{a}	104.85 ± 7.84^{a}	46.77 ± 3.29^{a}	7.89 ± 0.4^{a}	183.67 ± 31.75^{ab}	63.80 ± 3.22^{b}	6.3 ± 0.88^{a}
C_{SR}	234.67 ± 9.7^{b}	95.24 ± 3.43^{a}	29.17 ± 2.07^{d}	4.12 ± 0.21^{c}	115.67 ± 4.33^{ab}	47.69 ± 2.79^{c}	4.0 ± 0.0^{b}

SG – sponge gourd; RG – ridge gourd; BG – bottle gourd; AG – ash gourd; SF – Summerfit; C – cucumber; C_{SR} – cucumber self-rooted; DW – dry weight

$^{a–d}$mean values followed by the same letter are not significantly different (P < 0.05) as established by Duncan's multiple range test

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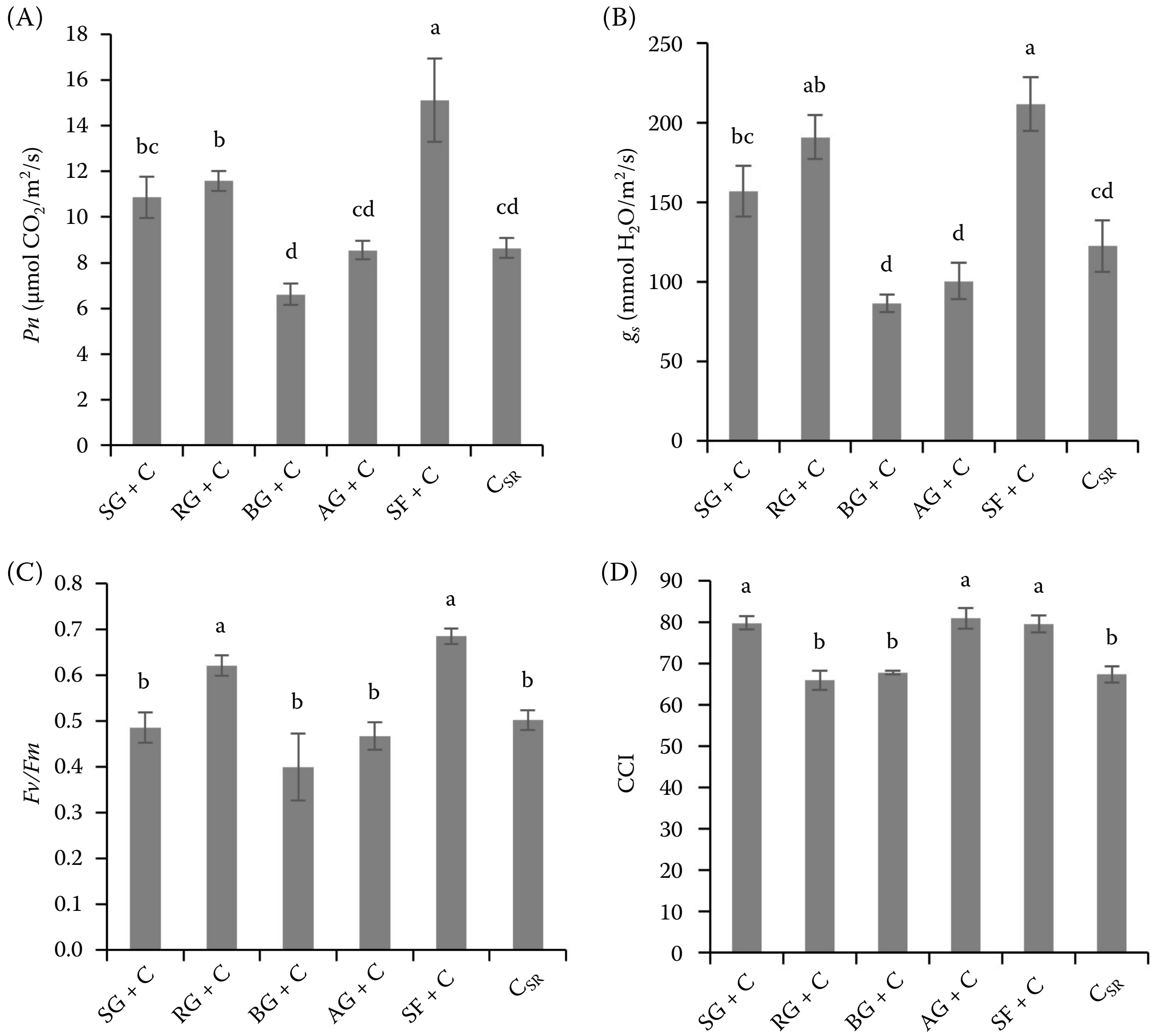

Figure 2. Effect of different inter-specific cucurbits rootstocks on (A) photosynthetic rate (P_n) (µmol $CO_2/m^2/s$), (B) stomatal conductance (g_s) (mmol $H_2O/m^2/s$), (C) maximum quantum efficiency of PSII (*Fv*/*Fm*), and (D) chlorophyll concentration index (CCI)

SG – sponge gourd; RG – ridge gourd; BG– bottle gourd; AG – ash gourd; SF – Summerfit; C – cucumber; C_{SR} – cucumber self-rooted

[a–d]mean values followed by the same letter are not significantly different ($P < 0.05$) as established by Duncan's multiple range test at a particular time of measurement

ly affect photosynthetic efficiency. Furthermore, SF + cucumber graft combination excels in stomatal conductance (g_s), indicating efficient uptake of CO_2 and release of oxygen during photosynthesis. RG + cucumber and SG + cucumber combinations also show notable stomatal conductance, suggesting that the rootstocks contribute positively to the plant's photosynthetic processes. While BG + cucumber registers the lowest value for gaseous exchange, indicating potential limitations in photosynthetic activity in this graft combination. The maximum quantum efficiency of PSII (*Fv*/*Fm*) was noted to be the highest in SF + cucumber combination (0.684), suggesting optimal efficiency in light energy conversion during photosynthesis. Although comparable to SF + cucumber, RG + cucumber still demonstrates a high *Fv*/*Fm* ratio, indicating a healthy and well-functioning photosynthetic system. Other graft combinations do not show statistically significant differences with each other and express similar *Fv*/*Fm* values. Regarding CCI, grafting cucumber onto SG, SF and AG rootstocks results in the maximum CCI, indicating high-

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er chlorophyll content. These findings suggest that rootstocks positively influence the chlorophyll levels in cucumber leaves. Self-rooted control, RG + cucumber and BG + cucumber were statistically comparable, and showed lower CCI compared to SG, SF, and AG combinations. The results regarding physiological traits indicate that the SF + cucumber graft combination consistently performs exceptionally well across all measured parameters, including photosynthetic activity, gaseous exchange, maximum quantum efficiency of PSII, and chlorophyll concentration. RG + cucumber also demonstrates positive effects on these parameters. On the other hand, AG + cucumber and self-rooted plants show comparatively lower values, suggesting potential limitations in physiological processes. Additionally, the choice of rootstock (SG, SF, or AG) appears to have a notable impact on chlorophyll concentration, with SG being particularly effective. Further statistical analysis can help confirm the significance of these findings and guide the selection of optimal graft combinations for cucumber cultivation.

Fruit yield attributes. Grafting had a varying impact on fruit yields under different graft combinations as indicated in Table 2. Among all interspecific rootstocks, SF displayed a remarkable superiority in cucumber fruit production, with the highest number of fruits per plant (15.11). This suggests that the rootstock SF helped in the promotion of fruit set and fruit development in cucumber. BG + cucumber, on the other hand, exhibited the lowest number of fruits per plant (4.11). This considerable difference indicates that the choice of BG as a rootstock may have limitations in supporting optimal fruit production. Concerning fruit weight, RG + cucumber and BG + cucumber showcased the heaviest fruits, weighing 231.97 g and 230.23 g, respectively. This finding suggests that RG and BG as rootstocks contributed positively to fruit weight. In contrast, SG + cucumber had the lightest fruits (180.84 g), indicating that while SG may promote other aspects of plant growth, it has substantially less impact on individual fruit weight. For individual fruit DW, self-rooted plants had the highest value (8.47 g), significantly different from other graft combinations, suggesting that in this study, grafting might not have significantly contributed to dry matter production of fruits compared to self-rooted plants. Conversely, RG + cucumber had the lowest fruit DW (4.81 g). Regarding fruit length, SF + cucumber yielded significantly longer fruits (20.78 cm), followed by RG + cucumber (19.24 cm), which shows the positive influence of SF as a rootstock in fruit elongation. SG rootstock produced the shorter fruits (16.22 cm) and was comparable to the self-rooted control, indicating that SG did not affect the length of individual fruits. In terms of fruit diameter, the graft combination BG + cucumber demonstrated the largest fruit diameter (4.58 cm), but was on par with SF + cucumber (4.44 cm), emphasising the positive impact of BG and SF as rootstocks on the overall girth of the fruits. In this study, self-rooted cucumber had the smallest fruit diameter (3.44 cm), signifying that grafting in cucumber may contribute to enhancing the width of individual fruits. Fruit yield is the most important and economical parameter, and maximum fruit yield was registered under SF + cucumber (2.83 kg/plant and 16.87 t/ha). This graft combination, noticed 62.7%, 56.6%, 314.9%, 89.3% and 80.9% higher fruit yields (individual plant basis),

Table 2. Yield and yield attributes of cucumber as influenced by different rootstock combinations

Graft combination	Fruits/ plant	Fruit FW (g)	Fruit DW (g)	Fruit length (cm)	Fruit diameter (cm)	Yield/plant (g)	Yield (t/ha)
SG + C	7.77 ± 0.77^{c}	180.84 ± 16.85^{c}	3.35 ± 0.38^{c}	16.22 ± 0.5^{c}	3.72 ± 0.06^{cd}	1 742.39 ± 154.41^{b}	9.61 ± 0.63^{b}
RG + C	9.77 ± 0.39^{b}	231.97 ± 21.98^{ab}	4.81 ± 0.37^{bc}	19.24 ± 0.94^{ab}	4.13 ± 0.32^{abc}	1 810.94 ± 79.52^{b}	10.43 ± 0.41^{b}
BG + C	4.11 ± 0.22^{d}	230.23 ± 12.3^{ab}	6.47 ± 0.49^{ab}	17.91 ± 0.97^{bc}	4.58 ± 0.18^{a}	683.2 ± 43.82^{c}	3.59 ± 0.36^{c}
AG + C	8.0 ± 0.19^{bc}	191.56 ± 6.54^{bc}	7.34 ± 1.60^{ab}	17.75 ± 0.16^{bc}	3.93 ± 0.1^{bcd}	1 497.08 ± 69.56^{b}	9.60 ± 0.73^{b}
SF + C	15.11 ± 0.98^{a}	250.08 ± 15.34^{a}	7.37 ± 0.6^{ab}	20.78 ± 0.31^{a}	4.44 ± 0.24^{ab}	2 835.03 ± 102.67^{a}	16.88 ± 0.38^{a}
C_{SR}	8.77 ± 0.39^{bc}	182.67 ± 4.62^{c}	8.47 ± 0.56^{a}	16.43 ± 0.37^{c}	3.44 ± 0.14^{d}	1 566.89 ± 97.99^{b}	9.60 ± 0.40^{b}

SG – sponge gourd; RG – ridge gourd; BG – bottle gourd; AG – ash gourd; SF – Summerfit; C – cucumber; C_{SR} – cucumber self-rooted; FW – fresh weight; DW – dry weight

$^{a-d}$mean values followed by the same letter are not significantly different ($P < 0.05$) as established by Duncan's multiple range test

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respectively, over SG, RG, BG, AG and self-rooted control. This suggests that inter-specific SF rootstock is highly effective in promoting the overall fruit production of cucumber. In contrast, BG + cucumber had the lowest fruit yield (0.683 kg/plant and 3.58 t/ha), which was 56.4% less in comparison to self-rooted cucumber. It suggests that BG as rootstock can reduce cucumber production significantly. The best-performing graft combination, SF + cucumber, exhibited a 72.3% increase in the number of fruits per plant, 36.9% increase in fruit FW, 32.8% increase in fruit length, 29.1% increase in fruit diameter, 80.9% increase in yield per plant, and a 75.8% increase in yield (t/ha) compared to the self-rooted cucumber, demonstrating its significant advantage in enhancing productivity and fruit quality. It is revealed that the choice of rootstock in cucumber grafting significantly influences various yield attributes. SF + cucumber consistently performed exceptionally well for most of the yield parameters, indicating its overall positive influence on fruit quantity, size, and yield. Conversely, BG + cucumber consistently showed relatively lower performance across these attributes. These findings underscore the importance of selecting an appropriate rootstock for cucumber grafting to optimise yield and fruit quality.

Root architecture. Root is an important trait for the mining of water and minerals from the soil. The TRL varies significantly across different graft combinations. Among graft combinations, RG + cucumber combination demonstrates a maximum TRL of 2 250 cm, followed by BG + cucumber (2 100 cm). On the other hand, the SG self-rooted and cucumber self-rooted combinations have comparatively shorter root lengths at 1 474 ± 46.6 cm and 1 286 ± 41.5 cm, respectively. Likewise, surface measurements also display variations among graft combinations (Table 3 and Figure 3). BG self-rooted combination stands out with the largest surface area of 686.15 ± 36.86 cm^2, while SF self-rooted has the smallest surface area at 247.16 ± 11.94 cm^2. This parameter highlights the influence of grafting on the extent of root spread. The volume of the root system is another crucial parameter. BG self-rooted has the highest volume at 14.65 ± 0.34 cm^3, indicating a voluminous root structure. Conversely, SF self-rooted exhibits a smaller volume of 6.74 ± 0.18 cm^3. Graft combinations like SG self-rooted and cucumber self-rooted fall in between, showcasing moderate volumes. Further, the average diameter of roots varies noticeably across graft combinations, reflecting differences in root thickness. BG self-rooted has the thickest roots with an average diameter of 1.16 ± 0.03 mm, while RG self-rooted has the thinnest roots at 0.93 ± 0.03 mm. The average diameter provides insights into the robustness of the root system. The best-performing graft combination, SF + cucumber, exhibited a 44.5% increase in TRL a 16.6% increase in root volume, and a 27.1% increase in average root diameter compared to the self-rooted cucumber. However, it had a 16.8% lower root surface area than the self-rooted counterpart. These results highlight the enhanced root development and potential for better nutrient uptake in the

Table 3. Root morphology under different graft combinations

Graft combination	Total root length (cm)	Surface area (cm^2)	Volume (cm^3)	Average diameter (mm)
SG + cucumber	1 661± 67.71^{ef}	448.82 ± 41.78^{cd}	10.05 ± 0.30^{c}	0.78 ± 0.01^{cde}
SG self-rooted	1 474± 46.6^{g}	413.78 ± 28.82^{d}	8.97 ± 0.18^{c}	0.84 ± 0.01^{bcd}
RG + cucumber	2 250 ± 37.8^{b}	439.62 ± 43.66^{cd}	10.16 ± 0.30^{c}	0.69 ± 0.02^{ef}
RG self-rooted	1 550 ± 93.7^{fg}	404.94 ± 34.05^{d}	9.35 ± 0.43^{c}	0.93 ± 0.03^{b}
BG + cucumber	2 100 ± 62.1^{bc}	517.05 ± 13.44^{bc}	10.14 ± 0.23^{c}	0.77 ± 0.01^{de}
BG self-rooted	1 936 ± 85.3^{cd}	686.15 ± 36.86^{a}	14.65 ± 0.34^{a}	1.16 ± 0.03^{a}
AG + cucumber	1 775 ± 39.9^{de}	481.27 ± 34.87^{cd}	11.96 ± 1.06^{b}	0.84 ± 0.02^{bcd}
AG self-rooted	2 592 ± 73.7^{a}	592.22 ± 25.95^{b}	10.63 ± 0.46^{bc}	0.66 ± 0.01^{f}
SF + cucumber	1 858 ± 33.0^{d}	249.52 ± 4.65^{e}	11.91 ±0.81^{b}	0.89 ± 0.09^{bc}
SF self-rooted	1 392 ± 16.4^{gh}	247.16 ±11.94^{e}	6.74 ± 0.18^{d}	0.85 ± 0.01^{bcd}
Cucumber self-rooted	1 286 ± 41.5^{h}	299.72 ± 31.98^{e}	6.73 ± 0.64^{d}	0.7 ± 0.03^{ef}

SG – sponge gourd; RG – ridge gourd; BG – bottle gourd; AG – ash gourd; SF – Summerfit

$^{a–h}$mean values followed by the same letter are not significantly different (P < 0.05) as established by Duncan's multiple range test

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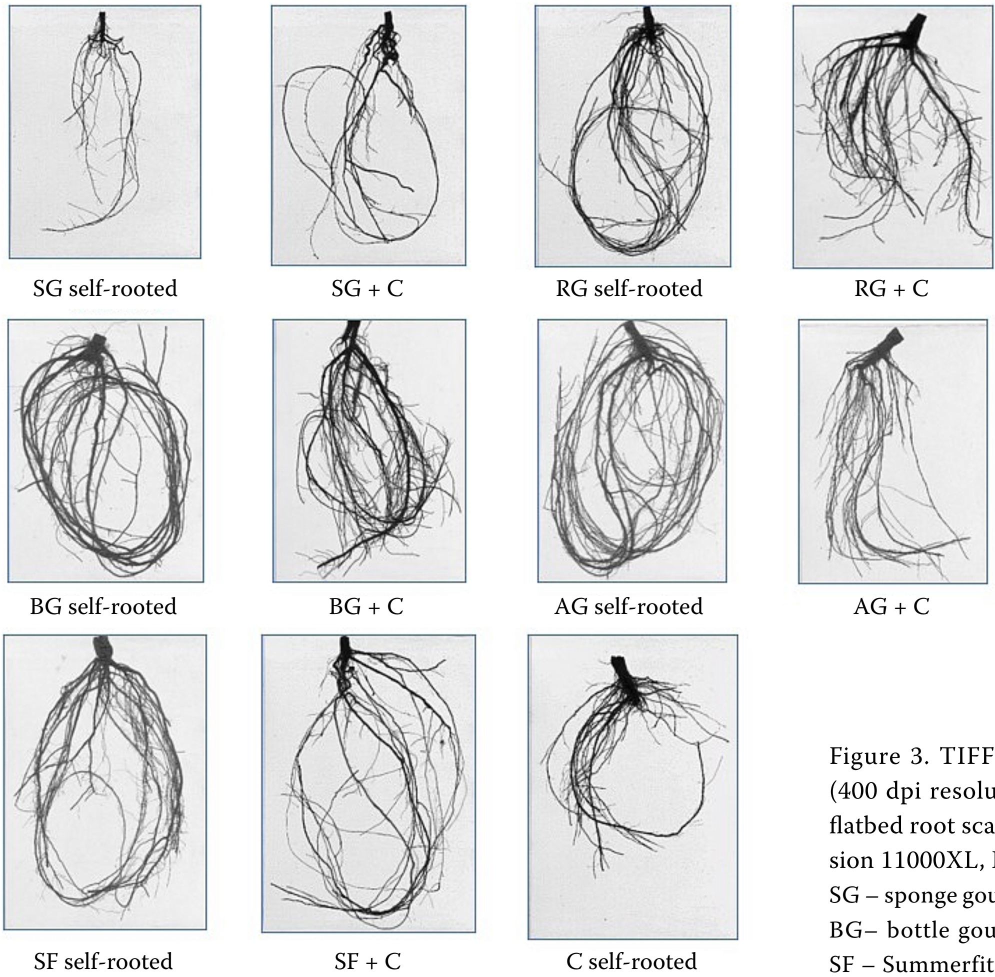

Figure 3. TIFF-format grey image (400 dpi resolution) captured with flatbed root scanner (Epson Expression 11000XL, Epson, Suwa, Japan)
SG – sponge gourd; RG – ridge gourd; BG– bottle gourd; AG – ash gourd; SF – Summerfit; C – cucumber

SF + cucumber combination. These findings underscore the impact of grafting on root morphology, with each combination exhibiting unique characteristics. The variations observed in TRL, surface area, volume, and average diameter emphasise the importance of graft selection in influencing the overall development of the root system. Further statistical analysis would be beneficial to determine the significance of these differences among graft combinations.

DISCUSSION

Physio-morphological attributes. The utilisation of inter-specific grafting through splice grafting had a notable impact on both plant physio-morphological parameters in cucumber, as evidenced by the results presented in Table 1. Cucurbitaceous crops are known for their viny growth habit, which is an important indicator of plant vigour (Anand et al. 2021). Vine length varied significantly with respect to rootstocks and scions used in the present investigation. The maximum vine length (269.0 cm) in cucumber was recorded with SF rootstocks. Cucumber grafted over SF rootstocks showed 14.6% higher vine length than an un-grafted plant. This is in line with the observations made by Bikdeloo et al. (2021), in grafted watermelons, wherein they reported that the grafting positively impacted plant growth, especially on vine length, internodal length and shoot FW and DW. In contrast, vine length was significantly reduced on RG (28.8%) and AG (17.2%) rootstocks. The differences in plant vigour due to grafting on various rootstocks could be attributed to the fact that cytokinin concentration in xylem sap of grafted and un-grafted plants differ significantly in various cucurbits. The higher cytokinin concentration in the ascending xylem sap adequately contributes to the high vigour of the plant (Pradhan et al. 2017). Cucumber on SF also recorded the maximum number of leaves (183.67/plant) and branches (6.3/plant).

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An increased number of leaves in grafted plants may be owed to improved water and nutrient uptake (Khah et al. 2006). Plant dry matter production and its distribution in different plant parts were also influenced significantly using different cucurbitaceous rootstocks. The maximum dry matter production (183.91 g/plant) was noticed over SF rootstocks, followed by SG (180.23 g/plant). Cucumber on AG registered the least dry matter production (86.41 g/plant). Cucumber on SF had an appropriate distribution of dry matter in stem (57.0%), leaf (34.7%), root (4.3%) and fruits (4.0%). Total dry matter content of the cucumber-SF combination may have contributed predominantly to the highest vine length and fruit yield, which is in accordance with the findings of Tamilselvi and Pugalendhi (2018) when bitter gourd grafted onto pumpkin rootstocks. Leaf number was significantly higher on SG, RG and SF rootstocks as compared to the un-grafted control, whereas the number of branches was significantly higher on SF (6.3 ± 0.88/plant). Similar to our findings, Guan et al. (2018) also reported that irrespective of rootstock and scion cultivars, grafting improved plant growth, earliness and overall yield in seedless cucumber. Yetisir and Sari (2003) reported 42–180% higher DW and 58–100% larger leaf area in grafted watermelon plants than self-rooted ones. Improved growth of grafted cucumber plants could be ascribed to the interaction of phenomena such as enhanced water and nutrient uptake, robust root system, increased endogenous growth regulators production and better scion vigour (Tamilselvi, Pugalendhi 2018).

Photosynthetic traits such as CCI, P_n, g_s and *Fv*/*Fm* were also influenced significantly with the use of inter-specific cucurbitaceous rootstocks (Figure 2). The maximum quantum yield of PSII efficiency (*Fv*/*Fm*) was affected by the combination of scion/rootstock. The *Fv*/*Fm* ratio represents the maximum efficiency of excitation capture in dark-adapted plants and is correlated with the number of functional PSII reaction centres (Goto et al. 2013). Graft combinations such as SF + cucumber and RG + cucumber significantly increased *Fv*/*Fm* values compared to the self-rooted control, indicating improved maximum quantum efficiency of PSII. These higher *Fv*/*Fm* values suggest that grafting onto these rootstocks enhances the scion's ability to convert light energy into chemical energy. Similarly, Kappel et al. (2024) reported that rootstocks such as 'Hikyaku' (*Solanum melongena* × *Solanum integrifolium*), 'Taibyou' (*Solanum grandiflorum* × *Solanum melongena*), and 'Emparador' (*Solanum lycopersicum*) significantly increased *Fv*/*Fm* values compared to the self-rooted control eggplant (*Solanum melongena* cv. 'Madonna'). Maximum P_n (15.23 μmol/m^2/s), g_s (211.89 mmol/m^2/s) and maximum quantum efficiency of PSII (*Fv*/*Fm*) (0.684) in cucumber were noticed on SF rootstock. In contrast, significantly higher CCI values were observed on SG (79.89), AG (88.97) and SF rootstocks (79.66) (Figure 2). Higher CCI values indicate more chlorophyll formation in graft combinations. Higher chlorophyll contents improve photosynthesis, cucumber fruit appearance, and nutritive value (Anand et al. 2021). Grafting enhances the CCI in vegetables by improving nutrient uptake, water use efficiency, and photosynthetic activity while increasing tolerance to abiotic stresses. Vigorous rootstocks enhance root development, leading to better absorption of essential nutrients like nitrogen (N), magnesium (Mg), and iron (Fe), which are crucial for chlorophyll synthesis (Rouphael et al. 2018). Further, the grafted plants exhibit higher activity of enzymes involved in chlorophyll biosynthesis (Kyriacou et al. 2017). Rootstocks also influence hormonal transport, particularly cytokinins, which delay leaf senescence and sustain chlorophyll levels (Gálvez et al. 2021). Thus, grafting serves as an effective strategy to maintain higher chlorophyll content and enhance overall plant performance. Stomata are the main gate for water and carbon exchanges between plant leaves and the environment. The maximum opening of stomata can be characterised by maximum g_s, which is determined by stomatal area and stomatal density. Stomatal area and density are affected by genotypes and environment interaction through stomatal development and adaptation (Lawson, Matthews 2020). The gas exchange in grafted plants is directly related to the rootstock used, as it can change the vigour and productivity of the scion (Colla et al. 2012). Due to sufficient vascular connection between the rootstock and scion, and vigorous root system, the flow of nutrients and water in the scion increases, resulting in an increase of photosynthesis (Salehi et al. 2010). Earlier, He et al. (2009), Liu et al. (2011) and Amaro et al. (2014) also reported that the grafting improved CO_2 assimilation rate, g_s and transpiration rate with higher growth and yield. Furthermore, Martínez-Ballesta et al. (2010) suggested that changes in the scion are controlled by the rootstock through controlled uptake, synthesis, and translocation of water, minerals,

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and plant hormones. Grafting in cucumber is also known to change the microbial community, increase the number of beneficial microflora, and enhance soil enzyme activities (polyphenol oxidase, catalase, urease and saccharase) in plant rhizome, and decrease the number of harmful soil fungi (Dong et al. 2010). Such favourable soil microbial and enzymatic activities and better gas exchange might have been the reason for improved plant growth in cucumber. Furthermore, it has been reported that inter-specific cucurbit rootstocks, such as *Cucurbita ficifolia*, *Cucurbita maxima*, *Cucumis melo* subsp., enhanced growth parameters in cucumber on different rootstocks, particularly on inter-specific hybrid SF, is more related to the intrinsic ability of the hybrid rootstock to confer vigour driven by better nutrient uptake, as suggested by Zhong and Bie (2006) and Zhang et al. (2014). In a study on cucumber, Zhang et al. (2014) reported that grafting improved plant growth, and N, P and K uptake by 49.6–53.3%, 16.7–29.0% and 32.2–40.5%, respectively. The total plant biomass and fruit yield were significantly higher under different-root-grafting than under self-root-grafting.

Fruit yield attributes. Fruit yield parameters such as number, weight, size and yield were significantly higher when cucumber was grafted over SF rootstock (Table 2). Compared to an un-grafted plant, cucumber on SF rootstock registered 72.3%, 36.9%, 26.5% and 29.1% higher numbers of fruits, fruit weight, fruit length and fruit diameter, respectively. It has been reported that the maximum fruit yields (2.83 kg/plant or 16.87 t/ha) were obtained on SF rootstock, thereby an increase of 80.9% in yield was registered with SF rootstock. Cucumber yield was reduced by 56.4% when grafted on bottle gourd rootstock. Increase in yield over SF could be ascribed to larger fruit size, weight and more fruit numbers per plant, as Salam et al. (2002) also noted a more than threefold higher yield in watermelon grafted over BG owing to larger fruit size and more fruits per plant. The impact of grafting on fruit size and weight depends on grafting combinations. Vigorous rootstocks result in the production of large-sized fruits (Kyriacou et al. 2017). In corroboration of our findings, Aslam et al. (2020) also observed that inter-specific cucurbitaceous rootstocks showed better compatibility with hybrid cucumber scion, and registered comparable performance in terms of vegetative growth, yield and storage. Furthermore, they concluded that grafting hybrid cucumber on different cucurbitaceous rootstocks is a profitable practice, as the grafted cucumber showed higher net return and benefit-cost ratio in comparison with the own-rooted hybrid. Similarly, Chawda (2021) also noticed significant improvement in the growth and yield of muskmelon and cucumber with the use of SF as a rootstock. Grafting in cucumber with different rootstocks induces earliness and total yields as reported by Cansev and Ozgur (2010). They observed that grafting of hybrid cucumber on 'P360' (*Cucurbita maxima* × *Cucurbita moschata*) and 'Arican-97' (*Cucurbita maxima* Duch.) rootstocks induced earliness and total yield by 53–120% and 87-209%, respectively, in cv. 'Marathon F1' and by 20–100% and 54–154%, respectively, in cv. 'Assos F1', compared with control plants. Zhong and Bie (2006) also found that cucumber grafted on fig-leaf (*Cucurbita ficifolia*) rootstock increased the fruit FW by 36–38% compared with non-grafted cucumber plants. Fruit K and Mg concentrations in grafted plants were also significantly higher than those of non-grafted controls. Further, Zhang et al. (2014) also noticed significantly improved plant growth, total plant biomass, nutrient uptake and fruit yield in cucumber under different rootstock grafting than that under self-root-grafting. Enhancement in cucumber yield (27%), and fruit quality such as total soluble solid contents (13%), titratable acidity (39%) and vitamin C (33%) was also noticed by Al-Harbi et al. (2018) by grafting onto an inter-specific hybrid of *C. maxima* × *C. moschata* rootstock. In watermelon, an increase in fruit size by 52% and fruit weight by 22% was reported using inter-specific cucurbitaceous hybrid rootstocks (Alan et al. 2007). In support to our findings, Noor et al. (2019) also reported that grafting hybrid cucumber onto local cucurbits rootstocks improved the growth (CCI and plant vigour), yield (fruit size and weight) and quality of fruit (N, P, K, Ca and Mg content) as well as the development of immunity to disease than those of non-grafted plants.

Root architecture. Root architecture, such as TRL, surface area, volume and average diameter, varied significantly in various cucurbits rootstocks (Table 3 and Figure 3). Maximum TRL was observed in un-grafted AG (2 591.9 cm), followed by cucumber grafted on RG rootstock (2 249.9 cm). Surface area of root was maximum in un-grafted BG (686.15 cm^2), followed by un-grafted AG (592.22 cm^2). Un-grafted BG also registered the highest root volume (14.65 cm^3) and average root

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diameter (1.16 mm). Root morphology and physiology are associated with the growth and development of the aboveground plant parts. Several findings demonstrate that root architectural traits such as diameter, length, volume and spatial distribution significantly affect the water and nutrient uptake (Ho et al. 2005; Hill et al. 2006; Comas et al. 2013), and tolerance to abiotic stresses (Schwarz et al. 2010; Al-Harbi et al. 2018). Bertucci et al. (2018) notice significant variation in root morphology, such as TRL, average root diameter, surface area and root-shoot DW ratio among various cucurbits rootstocks, including inter-specific hybrids. In our study, AG, BG and RG have shown higher TRL and surface area as compared to the maximum productive SF rootstock. This may be due to the fact that the root is the organ for the uptake of water and nutrients, but it is also consuming assimilates produced by the aboveground portion. The energy used to produce root biomass is as 2-folds as that used to produce aboveground biomass (Passioura 1983). Study in rice indicated that root biomass, root/shoot ratio and root oxidation activities were not significantly correlated with tiller and panicle number, and negatively correlated with grain yield (Cai et al. 2003). Similar to our findings, Ma et al. (2010) and Aziz et al. (2017) also reported that higher root length, biomass or area did not affect the plant growth and grain yield in wheat, particularly under non-stressful conditions. In our study, grafted SF rootstock, however, showed less TRL, surface area and volume in comparison to AG, BG and RG, but an increase of 44.54% in TRL, 77.11% in root volume and 27.25% in average diameter were observed over self-rooted cucumber.

The dramatic impact of any particular rootstock on scion performance may be owed to the anatomical and physiological compatibility of the graft combinations, which enables the rootstock to influence plant performance considerably. The genetic mechanism of graft compatibility and its role in improving the physiological functioning of scion cultivars has largely been unexplored. There is a need to identify systemic phloem signals, such as non-coding microRNAs and proteins, for their roles in post-grafting physiological changes. Likewise, identifying inheritable locus-specific alterations in scion DNA methylation patterns will help develop epi-molecular markers for selection of superior quality grafted vegetables (Kyriacou et al. 2017).

CONCLUSION

Among the five different rootstocks evaluated, SF (an inter-specific hybrid of snap melon *Cucumis melo* var. *momordica* × acidulous melon) demonstrated superior performance in improving growth, physiological attributes related to photosynthesis, and yield of cucumber scion. The enhanced vigour imparted by SF resulted in significantly higher yield, highlighting its potential as a promising rootstock for cucumber cultivation. The findings confirm the critical role of rootstock-scion compatibility in optimising plant performance and productivity.

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