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RESEARCH ARTICLE

Synergistic role of rootstock and grafting in boosting growth, yield, and quality of cucumber cultivation

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Abstract

Cucumber (*Cucumis sativus* L.) is a widely grown and highly valued cucurbitaceous vegetable crop, commanding premium prices in the vegetable market. However, intensive cultivation and monocropping practices have led to significant challenges in cucumber production, particularly in greenhouses, due to root-knot nematode and soil-borne diseases. Grafting has emerged as an alternative approach to boost abiotic stress tolerance and mitigate root diseases caused by soil-borne pathogens, thereby improving crop productivity. A study was conducted during 2023-2024 on the farmer's field to explore the interactive effects of various grafting techniques by grafting a hybrid cucumber scion onto various local rootstocks. The experiment evaluated the performance of the hybrid cucumber scion Emistar, grafted onto four rootstocks: fig-leaf gourd (*Cucurbita ficifolia*), pumpkin (*Cucurbita pepo*), ash gourd (*Benincasa hispida*), and bottle gourd (*Lagenaria siceraria*). Two grafting techniques-hole insertion and splice grafting, were tested using different scion-rootstock combinations. The study evaluated growth, yield, and fruit quality under controlled environmental conditions. The results indicated that the pumpkin rootstock outperformed the other rootstocks, particularly when grafted using the hole insertion techniques. This combination achieved the earliest flowering (26.33 days), longest plant growth (455.77 cm), and highest fruit yield (8.07 Kg). In contrast, splice grafting on bottle gourd resulted in slower growth and lower yields. Additionally, hole insertion grafting on pumpkin produced superior fruit characteristics, including the longest fruits (16.43 cm), largest diameter (9.1 cm), highest fruit weight (147.24 g), and the highest total soluble solids (TSS) content (2.85°Brix). Correlation and principal component analysis (PCA) highlighted strong positive relationships between yield and growth traits, emphasizing the superiority of the pumpkin rootstock for cucumber grafting. The study showed vigorous rootstocks like pumpkin can significantly enhance cucumber growth and yield through improved nutrient uptake, hormone translocation, and optimized grafting techniques.

Keywords

cucumber; growth; hole insertion grafting; pumpkin rootstock; yield

Introduction

Cucumber is one of India's most economically significant and widely grown crops, with an annual production of 1922.31 tons (India-stat, 2023-24). In recent years, the cultivation of hybrid cucumber varieties has expanded across several country regions. Primarily grown for its immature fruits, commonly used in salads, cucumber is cultivated extensively in tropical and subtropical regions. Vegetable farming practices influence cucumber production, especially in greenhouse environments (1). However, challenges such as pest infestations, soil-borne diseases, and environmental factors negatively impact greenhouse cultivation areas and production levels. Cucumber is increasingly grown under polyhouse conditions, enabling its cultivation as an off-season crop, which provides a high marketable value and profitability. The controlled environment of polyhouses extends the growing seasons, improves fruit quality, and ensures a consistent supply to meet market demand when outdoor cultivation is not feasible. This results in higher returns for growers, especially during off-peak periods when cucumbers are in high demand. Despite these advantages, a major challenge in cucumber production is the reduction in yield due to unfavorable soil conditions, persistent soil-borne diseases, and continuous cropping practices. Approximately 11% of the annual yield loss is attributed to the lack of resistant varieties capable of combating nematodes (2).

Grafting cucumber onto resistant cucurbit rootstocks offers a promising solution to address key challenges, including soil-borne diseases, pest infestations, and resource optimization. This technique involves merging two plant tissues to combine the desirable traits of the rootstock and the scion. Cucumber grafting with robust rootstocks improves yields, fruit quality, and stress resistance by facilitating effective vascular integration between the grafted parts. Soil-borne root-knot nematodes and salinity are among the primary factors limiting cucumber cultivation. Grafting with resistant rootstocks has emerged as an environmentally sustainable approach to mitigate these challenges. This technique addresses pest and disease pressures and improves crop performance under suboptimal soil conditions, making it a valuable tool for sustainable cucumber production (3).

Grafting has emerged as an effective integrated pest management technique for cucurbitaceous crops, providing significant control over soil-borne pathogens and pests. By grafting susceptible cucumber varieties onto resistant rootstocks, growers can substantially improve plant growth, fruit yield, and overall quality (4). This technique supports sustainable agricultural practices by reducing the reliance on agrochemicals for soil disinfection, enhancing pest and disease tolerance, and improving nutrient absorption. Cucumber, a commercially significant cucurbitaceous vegetable indigenous to India, is highly valued for its nutritional benefits, particularly its rich mineral composition. However, grafting can sometimes lead to undesirable changes in fruit characteristics, such as taste, color, and size. These effects are often mitigated by careful selection of rootstocks. Grafting cucumber scions onto local rootstocks, such as *Cucurbita maxima*, *C. moschata*, *C. ficifolia*, *Lagenaria spp*., and *Luffa spp*., has proven to be an effective strategy to enhance yield and quality while addressing the challenges associated with cucumber production (5).

Grafted vegetable seedlings are increasingly utilized in greenhouses to increase fruit yield and quality in regions where production is hampered by abiotic conditions such as low temperatures, reduced light intensity, high humidity, salinity, and heavy metal contamination. Economic analysis has shown that grafted cucumber cultivation offers a higher benefit-cost ratio and greater net returns than hybrid cucumbers grown on their roots, making grafting a highly favorable practice (2). This research was conducted to evaluate the effect of grafting under polyhouse conditions on plant growth, yield, and quality and to identify the most tolerant scion-rootstock combination for cucumber cultivation.

Materials and Methods

Experimental setup

The research was conducted to investigate the growth, yield, and quality parameters of grafted cucumber under polyhouse conditions during the 2023-2024 period at a farmer's field located at Kelamangalam, Hosur, Krishnagiri The study site was geographically situated at 12.61°N, 77.84° E, at an altitude of 719.41 m above means sea level (MSL). Two grafting methods were assessed, namely hole insertion and splice grafting. The experiment consisted of 9 treatments, with 3 replications each, arranged at 1.5 m × 0.5 m spacing. The treatments included control (non-grafted) (T_1), hole insertion grafting on fig leaf gourd (T_2), hole insertion grafting on Pumpkin (T_3), hole insertion grafting on ash gourd (T_4), hole insertion grafting on bottle gourd (T_5), splice grafting on fig leaf gourd (T_6), splice grafting on pumpkin (T_7), splice grafting on ash gourd (T_8), and splice grafting on bottle gourd (T_9). The scion used for the research was EMIRSTAR, an F1 hybrid developed by Rijk Zwaan India Seeds Pvt. Ltd. Hosur.

Influence of grafting on growth, yield and quality characteristics

Growth parameters included the days to the appearance of the first female flower, the number of primary branches, the node number of the first female flower, and the days to the first harvest. The days to the first female flower were recorded from the sowing date and expressed in days. The node number of the first female flower was noted as a numerical value. The number of primary branches per plant was counted at the final harvest for three plants per replication, with the mean expressed as a number. Vine length (cm) was measured from the first cotyledonary node to the tip of the main stem at the final harvest, using three randomly selected plants, and expressed in meters.

Yield parameters included fruit weight, fruit length, fruit diameter, and fruit yield. The number of fruits per plant was recorded after harvesting, and 10 fruits were randomly selected from each plot to measure fruit diameter (cm), length (cm), and weight per cucumber plant. Quality parameters included total chlorophyll, moisture, and TSS. TSS in the fruit juice was determined using a refractometer, with five fruit samples from each scion-rootstock combination. Chlorophyll content was estimated using the following procedure: a 5 g sample of freshly cut fruits was crushed in 10 ml of 80% acetone using a pestle and mortar, then kept in the dark for 48 hours. The mixture was subsequently filtered through a muslin cloth or tea filter, and absorbance readings were taken at 663 nm and 645 nm using a spectrophotometer. Five randomly selected fruits per replication were weighed using an electronic balance to determine moisture content. A 5 g sample from each fruit was dried in a hot air oven at 60°C for eight hours, and the dry weight was recorded.

$$Moisture\ content\ (\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Fresh weight}} \times 100$$

(Eqn. 1)

Statistical analysis

The experiment was conducted using a completely randomized design (CRD) with a significance level of 5% ($p < 0.05$) to identify significant differences among the scion-rootstock combinations. Principal component analysis and correlation analysis were performed to analyze the relationships between various indicators. The corresponding coefficient for each index in the two principal components was calculated by dividing the component matrix values by the square root of the corresponding eigenvalue. Specifically, the coefficient was determined using the formula:

Coefficient = Component matrix value/sqrt (eigenvalue).

(Eqn. 2)

Results and Discussion

Performance of grafted cucumber plants on growth characters

The results presented in Table 1 indicate significant variations in vegetative growth parameters among the grafted cucumber treatments. The shortest time to the appearance of the first female flower was observed in cucumbers grafted onto bottle gourd using the hole insertion technique (26.60 days), demonstrating earlier flowering compared to other treatments. Conversely, cucumbers grafted onto ash gourd using the splice grafting method exhibited the longest time to the first female flower (40.67 days). These results align with previous findings, which reported earlier flowering in greenhouse-grown cucumbers grafted onto various cucurbitaceous rootstocks compared to non-grafted plants (2). The observed differences in performance among treatments may be attributed to factors such as graft compatibility and the influence of rootstocks and scion varieties (6).

The number of primary branches was highest in cucumbers grafted onto pumpkins using the hole insertion method (3.56), indicating that this combination may enhance vegetative growth. The non-grafted control had fewer primary branches (2.94) than most grafted treatments. Regarding the number of nodes from the first female flower to the apex, the highest value was observed in cucumbers grafted onto bottle gourd using the splice grafting technique (6.90). In contrast, the lowest value was recorded for those grafted onto pumpkins using the hole insertion method (4.63). Plant length (Fig. 1a) was significantly greater in cucumbers grafted onto pumpkins using hole insertion (455.77 cm), likely due to improved graft compatibility and resource uptake.

In contrast, the splice grafting method on bottle gourd resulted in shorter plants (319.24 cm). Similar findings have been reported in other studies, documenting increased plant height with grafting (2, 7). However, another study also noted intermediate plant heights in cucumbers grafted onto bur cucumbers compared to those grafted onto pumpkins or left non-grafted (8).

The days to the first harvest were the shortest for cucumbers grafted onto pumpkins using the hole insertion method (37.03 days), indicating earlier maturity. These variations can be attributed to the differential compatibility of rootstocks with cucumber, which affects nutrient uptake, plant vigor, and stress tolerance. The enhanced growth and yield observed in some treatments, particularly those involving grafting onto pumpkin and bottle gourd, likely result from these rootstocks' superior vigor and ability to optimize resource utilization. Conversely, the delayed

Table 1. Assessment of growth parameters in grafted cucumber under polyhouse conditions

Treatments	DFFF (Days)	NPB	NNFFFA	PL (cm)	DFH (Days)
T_1: Control (non-grafted)	32.07	2.94	5.57	427.10	38.63
T_2: Hole insertion grafting on fig leaf gourd	29.83	3.10	5.27	435.10	38.07
T_3: Hole insertion grafting on pumpkin	31.03	3.56	4.63	455.77	37.03
T_4: Hole insertion grafting on ash gourd	33.77	2.37	5.63	391.30	42.17
T_5: Hole insertion grafting on bottle gourd	26.60	3.18	5.30	436.96	40.90
T_6: Splice grafting on fig leaf gourd	33.67	3.18	5.73	367.68	41.33
T_7: Splice grafting on pumpkin	36.57	3.17	6.70	409.49	41.83
T_8: Splice grafting on ash gourd	40.67	3.11	6.50	388.64	42.97
T_9: Splice grafting on bottle gourd	33.53	2.80	6.90	319.24	44.00
SE	1.24	0.23	0.63	3.72	1.31
C.D. ($p \leq 0.05$)	2.60	0.48	1.33	7.81	2.76

DFFF: Days to first female flower appearance, NPB: Number of primary branches, NNFFFA: Number of nodes to first female flower appearance, PL: Vine length, DFH: Days to first harvest

Fig. 1. (a) Evaluation of grafted cucumber plants under polyhouse conditions, (b) Hole insertion grafting on pumpkin rootstock (T_3), (c) Hole insertion grafting on bottle gourd rootstock (T_5), (d) Non-grafted cucumber plants (Control) (T_1).

flowering and reduced growth in other combinations, such as splice grafting on ash gourd, may reflect less favorable graft compatibility. This finding aligns with previous research, which reported that grafting significantly improved vegetative growth parameters, including plant height, the number of branches, and leaf development, compared to non-grafted plants (5).

Rootstocks such as pumpkin and fig leaf gourd, especially when combined with hole insertion grafting, significantly enhanced the growth parameters of grafted cucumbers. These rootstocks likely improve water and nutrient absorption, providing the scion with enhanced vegetative and reproductive growth resources. Hole insertion grafting consistently produced better results than splice grafting, likely due to the formation of stronger graft unions that ensure more efficient resource flow between the scion and rootstock. In contrast, splice grafting delays plant development, possibly due to weaker graft unions or slower recovery post-grafting.

Rootstock-specific responses in the bottle gourd rootstock varied depending on the grafting technique. Hole insertion grafting on bottle gourd promoted early flowering, while splice grafting on bottle gourd resulted in delayed growth. This indicates the importance of optimizing rootstock-scion compatibility and grafting techniques for each combination. Rootstocks like pumpkin likely enhance hormone translocation, particularly cytokinin, and auxins, which regulate vegetative growth and flowering. Efficient hormone movement through the graft union may explain the earlier flowering, increased branching, and overall growth vigor observed in these treatments. Similar results have been reported for vegetative growth characteristics in grafted cucumbers (9-11).

Performance of grafted cucumber plants on yield and quality characters

The analysis revealed significant differences in yield and quality parameters among the treatments. Cucumbers grafted onto pumpkin rootstocks exhibited the highest performance, showing maximum fruit length (16.43 cm), fruit diameter (91.41 mm), fruit weight (147.24 g), and fruit yield (8.07 Kg), indicating superior growth and productivity [Fig. 1 (b), (c), and (d)]. Conversely, splice grafting on ash gourd resulted in the lowest values for these parameters, including fruit length (13.30 cm), fruit diameter (82.53 mm), fruit weight (112.37 g), and fruit yield (5.67 Kg) (Table 2). A similar finding was noted in another study, which noted that self-grafted cucumbers outperformed other varieties in yield-related characteristics (12).

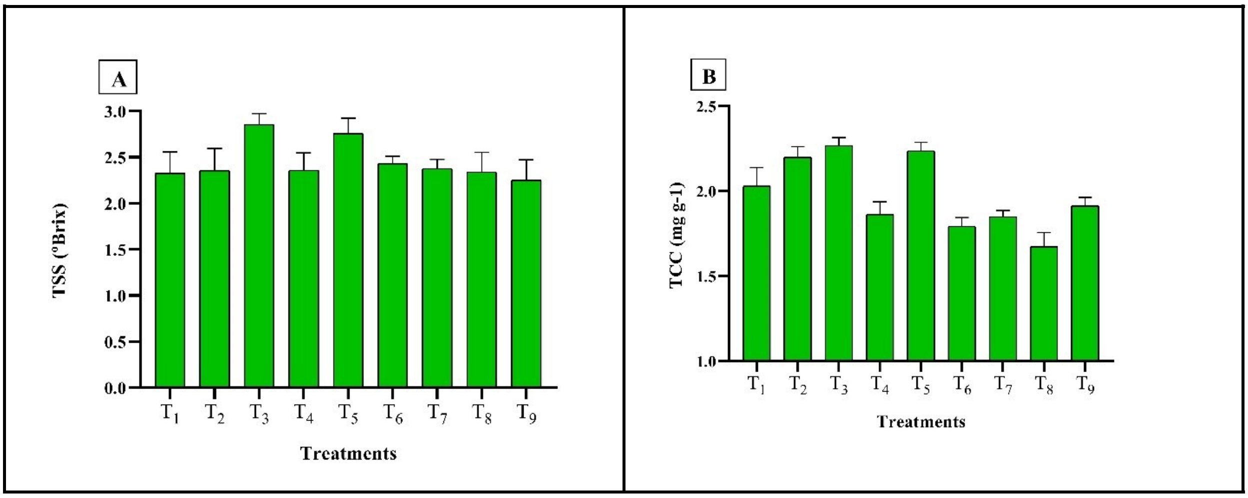
Furthermore, significant variations were observed in all yield characteristics between grafting treatments. Similarly, cucumber grafted onto fig leaf gourd rootstocks yielded significantly less than non-grafted cucumbers (13). Similar findings were reported in another investigation, which found that grafted cucumber fruit with higher fresh weight and dry matter had a higher concentration of nutrients than fruit with lower fresh weight (14).

The highest TSS (2.85°Brix) were found in cucumbers grafted onto the pumpkin, reflecting better fruit sweetness. In contrast, the lowest TSS were observed in the non-grafted control (2.32°Brix) (Fig. 2A). Moisture content was highest in cucumbers grafted onto bottle gourd (96.49%). The lowest was recorded in splice grafting on bottle gourd (91.00%). The highest total chlorophyll content (TCC) was observed in cucumbers grafted onto pumpkin (2.27 mg g^{-1}). In contrast, the lowest was found in splice grafting on fig leaf gourd (1.79 mg g^{-1}) (Fig. 2B). The variability in yield and quality parameters underscores the significant impact of grafting

Table 2. Assessment of yield and quality parameters in grafted cucumber under polyhouse conditions

Treatments	FL (cm)	FD (mm)	FW (g)	FY (Kg)	MC (%)
T_1: Control (non-grafted)	14.77	86.85	129.78	7.20	94.08
T_2: Hole insertion grafting on fig leaf gourd	14.97	87.72	133.04	7.30	95.09
T_3: Hole insertion grafting on pumpkin	16.43	91.41	147.24	8.07	94.84
T_4: Hole insertion grafting on ash gourd	14.33	81.60	123.93	6.47	92.45
T_5: Hole insertion grafting on bottle gourd	15.37	88.05	138.79	7.40	96.49
T_6: Splice grafting on fig leaf gourd	12.83	77.40	123.26	6.33	91.86
T_7: Splice grafting on pumpkin	13.20	85.16	119.94	6.60	91.43
T_8: Splice grafting on ash gourd	13.30	82.53	112.37	5.67	92.04
T_9: Splice grafting on bottle gourd	14.20	70.11	111.54	6.17	91.00
C.D. ($p \leq 0.05$)	1.28	1.87	7.23	0.30	1.52
SE	0.61	0.89	3.44	0.14	0.72

FL-Fruit length, FD-Fruit diameter, FW-Fruit weight, FY-Fruit yield, MC-Moisture content



fruit

Fig. 2. Quality parameters (A) TSS-Total soluble solids, (B)TCC-Total chlorophyll content.

methods and rootstock selection on cucumber performance. Among the grafting techniques, hole insertion generally yielded better outcomes than splice grafting. For instance, hole insertion grafting on pumpkin resulted in higher fruit yield, larger fruit size, and better overall quality than other combinations. These results indicate that grafting cucumber onto specific rootstocks and using particular grafting techniques can significantly influence fruit characteristics and yield. Pumpkin rootstock consistently demonstrated superior performance in fruit length, diameter, weight, and yield, suggesting that it provides enhanced support for cucumber plants, leading to better fruit development and overall productivity.

Pumpkin rootstock, particularly with hole insertion grafting, improved fruit quality and plant health by increasing TSS and chlorophyll content. In contrast, splice grafting on ash gourd resulted in lower fruit quality, including reduced weight, yield, and chlorophyll content, likely due to weaker graft unions or compatibility issues. Bottle gourd rootstock showed mixed results depending on the grafting technique, with hole insertion grafting producing higher moisture content and splice grafting leading to the smallest fruit diameter. These findings highlight the importance of optimizing grafting methods and selecting appropriate rootstock to enhance cucumber production and quality. Similar reports were observed in the fruit, yield, and quality characteristics of cucumber-grafted plants (15-17).

Correlation

The Pearson correlation matrix (Table 3) reveals significant relationships between grafted cucumber growth, yield, and quality characteristics. Notably, days to the first female flower appearance show a strong negative correlation with fruit weight and yield ($r = -0.763$ and $r = -0.783$, respectively), indicating that earlier flowering is associated with higher fruit weight and yield. Conversely, the number of nodes to the first female flower appearance positively correlates with fruit weight and yield ($r = -0.933$ and $r = -0.861$), suggesting that a higher number of nodes can lead to improved yield outcomes. Vine length positively correlates with fruit diameter ($r = 0.994$) and fruit weight ($r = 0.843$), highlighting the importance of vine growth in fruit development. Additionally, TCC exhibits strong positive correlations with weight ($r = 0.883$) and yield ($r = 0.938$), indicating that higher chlorophyll levels contribute to better fruit quality and quantity. The analysis suggests that optimizing growth characteristics can significantly enhance yield and quality traits in grafted cucumbers, emphasizing the potential for targeted breeding and management strategies to improve cucumber production. The correlation between fruit length and TCC (0.905) shows a strong positive correlation, indicating that longer fruits tend to have higher chlorophyll levels, possibly due to better overall health and photosynthetic capacity in the fruit tissues. Positive correlations were found between the growth of grafted cucumber plants and the protective isozyme similarity between grafted and non-grafted plants (18). Negative correlations indicate that as one variable increases, the other decreases. In earlier studies, there has been evidence of a correlation matrix growth, yield and quality characters in grafted and non-grafted cucumber plants (19-21).

Principal component analysis

The PCA results (Table 4) for grafted cucumber plants show that the first principal component (F1) is the most important, explaining the largest part of the variation with an eigenvalue of 8.965, which accounts for 74.71% of the total variance. The second principal component (F2) contributes an additional 9.44%, resulting in a total of 84.10% variance explained. The third (F3) and fourth (F4) components account for 6% and 3.93%, respectively, bringing the total explained variance to 94.08%. The remaining components (F5 to F8) contribute progressively smaller amounts, with F8 accounting for only 0.047%. Collectively, all components explain 100% of the variance. The scree plot confirms that F1 and F2 account for most of the variation, while the other components are less critical for explaining cucumber traits. The scree plot (Fig. 3) displays the eigenvalues of each component in descending order, with F1 being the highest. The cumulative percentage line illustrates that the initial components capture most of the total variability in the data. Similar results for the PCA of grafted and non-grafted cucumber plants have been reported in other investigations (22, 23).

Correlations between variables and factors

The correlation analysis between cucumber variables and PCA factors reveals that certain variables correlate highly with

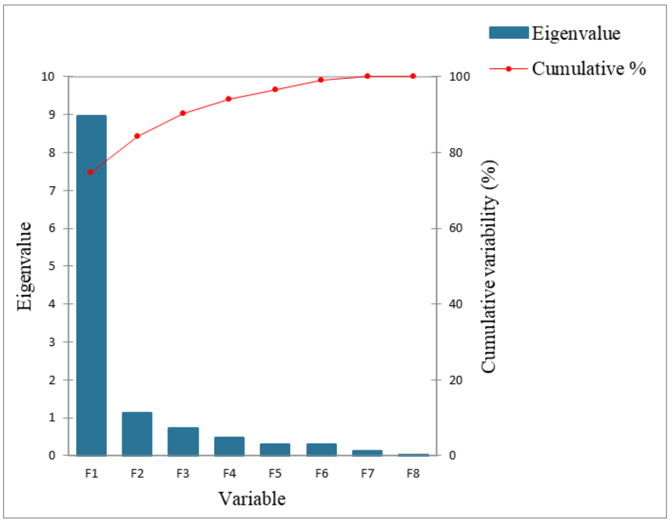


Fig. 3. Scree plot of eigenvalues (principal components).

specific factors. For instance, fruit weight, yield, and TCC exhibit strong positive correlations with Factor 1 (F1), with coefficients of 0.985, 0.969, and 0.930, respectively. This suggests that F1 is a dominant factor influencing these variables. In contrast, days to the first female flower appearance show a strong negative correlation with F1 (-0.775). At the same time, the number of nodes to the first female flower appearance and days to the first harvest also display negative correlations with F1. Other variables, like number of primary branches and TSS, exhibit more complex patterns, showing significant correlations with multiple factors, particularly F1 and F2, as shown in Table 5.

The biplot (Fig. 4) visualizes the correlations, with each line representing a variable and its relationship with the factors. The plot indicates that F1 has the most substantial impact on most variables, while the influence of other factors is relatively smaller. This diagram is a PCA biplot showing the distribution of variables along two principal axes, F1 (74.71%) and F2 (9.44%), accounting for 84.15% of the total variance. The arrows represent different variables, with their directions and magnitudes indicating their contributions to the principal components. A PCA linkage map of all the variables explained 94.7% of the overall variation. The first two components represent the majority of the data's structure, with subsequent components contributing progressively less, as

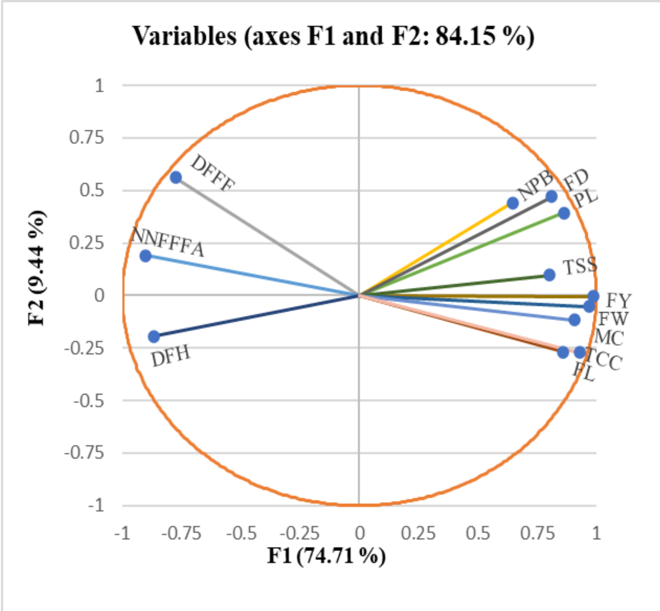


Fig. 4. Biplot displaying eigenvectors and scores for principal components (F1 and F2).

DFFF-Days to first female flower appearance, NPB-Number of primary branches, NNFFFA-Number of nodes to first female flower appearance, PL-Vine length, DFH-Days to first harvest, FL-Fruit length, FD-Fruit diameter, FW-Fruit weight, FY-Fruit yield, TSS-Total soluble solids, MC-Moisture content, TCC-Total chlorophyll content

shown by the dramatic drop in eigenvalues. This analysis highlights the importance of increased shoot length, fresh and dry weight, fruit weight, and chlorophyll content, consequently enhancing yield. Similar results were reported in another study (24).

Conclusion

This study evaluated the impact of different rootstocks and grafting techniques on cucumber plants, revealing significant variations in vegetative growth, fruit characteristics, yield, and quality. Among the treatments, pumpkin rootstock with hole insertion grafting consistently demonstrated superior performance, particularly in early flowering, vine length, fruit weight, diameter, yield, and the highest TSS and chlorophyll content. These findings highlight the efficacy of pumpkin rootstock in promoting overall plant vigor and productivity. In contrast, splice grafting generally showed lower

Table 3. Pearson correlation matrix for growth, yield, and quality characteristics of grafted cucumber

Variables	DFFF	NPB	NNFFFA	PL	DFH	FL	FD	FW	FY	TSS	MC	TCC
DFFF	**1**	-0.295	**0.785**	-0.461	0.549	**-0.709**	-0.370	**-0.763**	**-0.783**	-0.541	**-0.802**	**-0.883**
NPB	-0.295	**1**	-0.497	0.555	-0.625	0.400	0.542	0.610	0.621	**0.689**	0.449	0.541
NNFFFA	**0.785**	-0.497	**1**	-0.662	**0.813**	**-0.769**	-0.593	**-0.933**	**-0.861**	**-0.734**	**-0.802**	**-0.815**
PL	-0.461	0.555	-0.662	**1**	**-0.813**	0.626	**0.994**	**0.843**	**0.803**	0.645	**0.812**	**0.686**
DFH	0.549	-0.625	**0.813**	**-0.813**	**1**	**-0.671**	**-0.771**	**-0.850**	**-0.880**	-0.507	**-0.699**	**-0.761**
FL	**-0.709**	0.400	**-0.769**	0.626	**-0.671**	**1**	0.580	**0.828**	**0.856**	**0.699**	**0.777**	**0.905**
FD	-0.370	0.542	-0.593	**0.994**	**-0.771**	0.580	**1**	**0.792**	**0.747**	0.622	**0.764**	0.619
FW	**-0.763**	0.610	**-0.933**	**0.843**	**-0.850**	**0.828**	**0.792**	**1**	**0.958**	**0.834**	**0.864**	**0.883**
FY	**-0.783**	0.621	**-0.861**	**0.803**	**-0.880**	**0.856**	**0.747**	**0.958**	**1**	**0.728**	**0.813**	**0.938**
TSS	-0.541	**0.689**	**-0.734**	0.645	-0.507	**0.699**	0.622	**0.834**	**0.728**	**1**	**0.680**	**0.671**
MC	**-0.802**	0.449	**-0.802**	**0.812**	**-0.699**	**0.777**	**0.764**	**0.864**	**0.813**	**0.680**	**1**	**0.870**
TCC	**-0.883**	0.541	**-0.815**	**0.686**	**-0.761**	**0.905**	0.619	**0.883**	**0.938**	**0.671**	**0.870**	**1**

DFFF-Days to first female flower appearance, NPB-Number of primary branches, NNFFFA-Number of nodes to first female flower appearance, PL-Vine length, DFH -Days to first harvest, FL-Fruit length, FD-Fruit diameter, FW-Fruit weight, FY-Fruit yield, TSS-Total soluble solids, MC-Moisture content, TCC-Total chlorophyll content

Table 4. Principal component analysis of variance, cumulative proportion, eigenvalues for grafted cucumber plants

Principal component	Eigenvalue	Percentage of variance	Cumulative percentage of variance
F1	8.965	74.707	74.707
F2	1.133	9.441	84.147
F3	0.720	6.000	90.147
F4	0.472	3.933	94.080
F5	0.298	2.484	96.565
F6	0.291	2.426	98.991
F7	0.115	0.962	99.953
F8	0.006	0.047	100.000

Table 5. Correlations between variables and factors in grafted cucumber plants

Variables	F1	F2	F3	F4	F5	F6	F7	F8
DFFF	-0.775	0.561	-0.001	0.038	0.263	-0.051	0.103	0.003
NPB	0.646	0.441	0.551	-0.188	-0.120	0.174	0.065	0.001
NNFFFA	-0.901	0.190	-0.062	0.096	0.020	0.359	-0.100	0.012
PL	0.862	0.394	-0.295	0.104	-0.046	0.022	-0.046	-0.011
DFH	-0.867	-0.193	0.140	0.417	-0.075	0.094	-0.052	-0.003
FL	0.860	-0.270	0.001	0.103	0.389	0.133	0.090	0.005
FD	0.812	0.471	-0.307	0.144	-0.017	0.036	-0.040	-0.011
FW	0.985	-0.005	0.023	0.027	0.009	-0.149	-0.076	-0.009
FY	0.969	-0.051	0.007	-0.138	0.082	0.046	-0.167	0.048
TSS	0.803	0.098	0.418	0.388	0.042	-0.128	-0.047	0.001
MC	0.907	-0.118	-0.188	0.185	-0.213	0.090	0.201	0.030
TCC	0.930	-0.273	0.018	-0.074	0.026	0.229	-0.011	-0.044

performance, with splice grafting on ash gourd and bottle gourd showing delayed flowering, reduced fruit size, weight, yield, and lower quality indicators than hole insertion grafting. The variable results with bottle gourd rootstock underscore the need for optimizing grafting techniques to improve compatibility and performance.

Correlation analysis further emphasized the interconnectedness of growth parameters with yield and fruit quality. Positive correlations between vine length, fruit diameter, and weight suggest that vigorous plants support better fruit development. Conversely, longer days to the first female flower appearance were negatively correlated with yield and fruit quality, highlighting the advantage of early flowering for maximizing productivity. PCA confirmed the first principal component (F1) is crucial in explaining the variance in plant traits and is strongly linked to fruit weight, yield, and chlorophyll content. These results confirm effective rootstock selection and grafting techniques enhance cucumber growth and fruit quality. The study advocates using vigorous rootstocks like pumpkins and hole insertion grafting to achieve optimal cucumber production.

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Authors' contributions

MS carried out the experiments and prepared the original draft. MK helped in experiments, identified rootstocks, and graft production, and guided in the research work. CIR supervised the work and edited the manuscript. KD helped in identifying the farmers' fields and managed crops from pests and diseases. KV provided inputs during graft compatibility, recording periodical observation, and sequence alignment and editing. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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While preparing this work, the authors used Chatgpt-4 to improve language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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