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Grafting Hybrid and Monoecious Cucumbers onto Cucurbit Rootstocks Enhances Growth and Yield under Net House Conditions

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ABSTRACT

Grafting is an effective method to mitigate biotic and abiotic stresses while enhancing yield in horticultural crops. This study evaluated suitable cucurbitaceous rootstocks for improving cucumber yield and quality under net house conditions. Two cucumber cultivars, Green Long (GL an OPV (a monoecious, open-pollinated variety) and NS 408 (a F1 hybrid), were grafted onto five rootstocks: *Cucurbita ficifolia*, *Cucurbita moschata*, *Cucurbita maxima*, *Lagenaria siceraria*, and *Luffa cylindrica*. Results showed that NS 408 outperformed GL in both grafted and non-grafted conditions. Among the rootstocks, NS 408 grafted onto *C. maxima* (winter squash) had the highest graft survival (79 ± 1.8%), most extended vine length (700 ± 16 cm), and maximum fruit yield (8.3 ± 0.017 kg per plant, 118.42% increase over non-grafted NS 408). Grafting GL onto winter squash improved yield by 42.11% over non-grafted NS 408 and by 86.21% over GL control. Fruit quality parameters such as total soluble solids, palatability, ascorbic acid, and soluble protein were unaffected or improved, confirming that grafting did not negatively influence market quality. Economic analysis revealed the highest benefit-cost ratio (>2.5) in NS 408/WS, indicating that grafting is a cost-effective alternative to expensive hybrid seeds. These findings highlight the potential of grafting to optimize cucumber production, reduce reliance on pesticides, and improve profitability in protected cultivation.

Key words: Early flowering, Fruit quality, Fruit yield and rootstock, Grafting.

INTRODUCTION

Cucumber (*Cucumis sativus* L.) is an economically important vegetable crop cultivated globally for fresh consumption and processing. However, its production faces challenges from biotic and abiotic stresses, including soil-borne diseases like Fusarium wilt (*Fusarium oxysporum* f. sp. *cucumerinum*) and root-knot nematodes (*Meloidogyne incognita*), as well as

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drought and salinity (Patil et al., 2017; Bayoumi et al., 2021). These factors reduce yields and increase production costs, particularly for farmers using hybrid seeds, which are costlier than open-pollinated varieties.

Grafting has emerged as an effective horticultural technique to enhance resilience by combining the disease resistance and stress tolerance of rootstocks with the desirable traits of scions (Davis et al., 2008a; Guan et al., 2012). In cucumbers, grafting effectively mitigates biotic and abiotic stresses while improving yield under challenging conditions (Sarwar et al., 2019a, b; Davis et al., 2008b).

First introduced in Japan in the 1960s to combat Fusarium wilt and improve cold tolerance, cucumber grafting is now widely practiced in cucurbit crops to enhance resistance to soil-borne pathogens and increase plant vigor (Davis et al., 2008a). The success of grafting largely depends on the compatibility between the rootstock and scion. Rootstocks from cucurbit species such as *Cucurbita ficifolia, Cucurbita moschata,* and *Cucurbita maxima* are commonly used due to their strong root systems, improved water and nutrient uptake, and ability to confer resistance to soil-borne diseases (Heidari et al., 2012; Rouphael et al., 2012; Elsheery et al., 2020; Shehata et al., 2022). Grafting also enhances stress tolerance and crop performance under suboptimal growing conditions, leading to improved yields (Gaion et al., 2018; Sallaku et al., 2019; Bayoumi et al., 2021).

In addition to improving plant vigor and stress tolerance, grafting offers economic benefits by reducing reliance on chemical pesticides. Enhanced natural resistance in grafted plants lowers pesticide use, cutting production costs and minimizing environmental impact while promoting residue-free produce (Guan et al., 2012; Liu et al., 2015). Beyond yield improvements, grafting enhances fruit quality (Davis et al., 2008b; Izaba et al., 2021; Sakthivel et al., 2024). In high-tunnel systems, grafted cucumbers yield higher net returns and better benefit-cost ratios than non-grafted crops (Izaba et al., 2021). Its adoption is increasing in greenhouse and net house systems due to its role in sustainable, low-input farming.

Despite its advantages, research on the performance of monoecious cucumber cultivars grafted onto different *Cucurbita* rootstocks under net house conditions remains limited, particularly in the Indian subcontinent. This study addresses this gap by evaluating two cucumber cultivars—Green Long (monoecious) and NS 408 (hybrid)—grafted onto five cucurbit rootstocks. The study aims to assess grafting effects on plant growth, yield, and fruit quality, focusing on (1) rootstock influence on plant vigor and graft survival and (2) the impact of grafting on yield and fruit traits. These insights will contribute to optimizing cucumber production, reducing reliance on costly hybrid seeds and pesticides, and improving sustainability in net house cultivation systems.

MATERIALS AND METHODS

Experimental Site and Planting Materials

The present investigation was conducted at the College Orchard, Department of Vegetable Science, Tamil Nadu Agricultural University (TNAU), Coimbatore, India (11˚ N latitude, 76.9˚ E longitude, and 424 meters above mean sea level) from March to June 2022. Two monoecious cucumber cultivars and five cucurbit rootstocks were evaluated (Table 1). Green Long (GL) is a monoecious, open-pollinated variety (ECL Agrotech Limited, Bengaluru) with medium vine growth and uniform cylindrical fruits, while NS 408 is a vigorous F1 hybrid (Namdhari Hybrid Seeds Pvt. Ltd. Bengaluru) with high yield potential. Rootstock origins were specified as follows: *Cucurbita ficifolia* (landrace, Ooty), *C. moschata* cv. CO-2 (TNAU), *C. maxima* cv. Arka Suryamukhi (IIHR), *Lagenaria siceraria* CO-1 hybrid (TNAU), and *Luffa cylindrica* (landrace, Dehradun).

Table 1. Treatment details: Scion/ rootstock graft combinations used under study.

Treatment	Treatment denotation	Treatment details (graft combination with species details)
T1	Green Long (GL) OPV	GL (Non-grafted control)
T2	GL /FG	GL / FG (GL grafted onto Cucurbita ficifolia, fig leaf gourd)
T3	GL /PM	GL / PM (GL grafted onto Cucurbita moschata, pumpkin)
T4	GL /WS	GL / WS (GL grafted onto Cucurbita maxima, winter squash)
T5	GL /BG	GL / BG (GL grafted onto Lagenaria siceraria, bottle gourd)
T6	GL /SG	GL / SG (GL grafted onto Luffa cylindrica, sponge gourd)
T7	NS 408 (F1 Hybrid)	NS 408 (Non-grafted control)
T8	NS 408/ FG	NS 408/ FG (NS 408 grafted onto Cucurbita ficifolia, fig leaf gourd)
T9	NS 408/PM	NS 408/ PM (NS 408 grafted onto Cucurbita moschata, pumpkin)
T10	NS 408/WS	NS 408/ WS (NS 408 grafted onto Cucurbita maxima, winter squash)
T11	NS 408 /BG	NS 408/ BG (NS 408 grafted onto Lagenaria siceraria, bottle gourd)
T12	NS 408/SG	NS 408/ SG (NS 408 grafted onto Luffa cylindrica, sponge gourd)

Grafting, Healing, and Acclimatization

Seeds of the rootstock and scion were sown in pro-trays filled with enriched, composted, and sterilized coir pith. The seedlings of both the rootstock and scion were ready for grafting when they developed their first true leaves, typically 9 to 15 days after sowing. Grafting was performed using the hole-insertion method, as described by Davis et al. (2008a), wherein the scion was thinner and smaller than the rootstock at the time of grafting.

The growing point of the rootstock was removed, leaving only the cotyledons, and a hole was created using a bamboo toothpick. The scion was prepared by cutting the seedling stem 3-4 cm below the cotyledons and shaping the basal end into a wedge approximately 7-8 mm in length as per the standard method (Thangamani *et al*., 2019). The prepared scion was then carefully inserted into the hole of the rootstock.

Grafted seedlings were placed in a mist chamber at 90% relative humidity and 25–30°C. Grafts were kept in the dark for two days to promote union healing. After this initial period, the relative humidity was gradually reduced to 70% over a period of seven days. The plants were then transferred to a shade net house for six days to acclimate. Grafting clips were detached before transplanting.

Seedling Transplanting and Aftercare

Both grafted and non-grafted seedlings were transplanted under insect-proof net house conditions. The experiment was laid out in a randomized block design (RBD) with three replications. Blocking was done across the length of the net house to account for variations in light and temperature. Each treatment had 25 plants per replication, and observations were recorded on five representative plants per plot. Spacing was maintained at 1.5 m between rows and 1.0 m between plants. Inside temperature was 2–3°C lower than the open field, with natural ventilation and 10% shade nets; no humidifiers were used. All recommended cultural practices, including fertilizers, plant protection measures, trailing, and pollination, were uniformly applied.

Growth, Floral Traits, and Yield Parameters

Five healthy plants from each treatment and replication were tagged for growth, floral, and yield data. The graft survival percentage was recorded 30 days after transplanting. Floral traits (days to first female flower, node number, male: female ratio, and days to first harvest) were observed. Vine length (cm) and root length (cm) were measured with a measuring tape, stem diameter (mm) with a digital vernier caliper, and root weight (g) with a digital balance. Primary branches were manually counted. Fruit count, mean fruit weight (g), and total yield per plant (kg) were recorded at each harvest.

Fruit Quality Parameters

At peak harvest (55 days after transplanting), ten fruits per treatment were analyzed for physical and biochemical traits. Total soluble solids (°Brix) were measured with a digital refractometer (ATAGO, Japan). Total sugars were estimated using the Anthrone method (Hedge & Hofreiter, 1962), ascorbic acid content as per AOAC (2001), and calcium by Mani et al. (2007). The soluble protein was determined by the method of Lowry et al. (1951). An organoleptic evaluation was conducted by a semi-trained panel of 20 members using a nine-point Hedonic Scale (Kumar et al., 2019a).

Statistical Analysis

Data were analyzed using a two-way ANOVA (scion, rootstock, and interaction effects). Graft survival percentage was arcsine transformed. Tukey's Honest Significant Difference (HSD) test ($p < 0.05$) was used for mean comparisons. All analyses were conducted in R (R Core Team, 2022) using the "agricolae" package (Mendiburu & Yaseen, 2020).

Economics

Economic analysis included cost of grafting labor, nursery preparation, cultivation practices, gross returns, net returns, and benefit-cost (BC) ratio, calculated following Izaba et al. (2021).

RESULTS AND DISCUSSION

Effect of grafting on survival, vine growth, and root development

The graft survival percentage, vine length, primary branch number, root length, and root weight of grafted cucumber plants and non-grafted controls showed significant differences across treatments (Table 2). Graft survival ranged from 49.03 ± 0.31% (GL/SG) to 79 ± 1.8% (NS 408/WS), with NS 408/WS demonstrating the highest survival. The most extended vine length was observed in NS 408/WS (700 ± 16 cm), significantly outperforming the control plants and other graft combinations. The number of primary branches was highest in NS 408/WS and NS 408/FG (4.6 ± 0.11 and 4.50 ± 0.094, respectively), with significant differences observed between treatments. Root length and root weight also varied, with NS 408/WS showing the highest values for both parameters (110 ± 0.65 cm and 120 ± 3.1 g, respectively), indicating superior root development compared to other combinations.

Although graft survival percentages were moderate compared to solanaceous crops, all combinations except GL/SG exhibited normal growth and vigor, confirming compatibility between most scion-rootstock pairs. The GL/SG combination showed reduced vigor, suggesting partial incompatibility.

In contrast, GL and NS 408 self-rooted control plants exhibited comparatively lower biometric performance in all parameters. All the measured traits, including graft survival, vine length, number of primary branches, root length, and root weight, were significantly influenced by the graft combination with graft survival and a highly significant level of difference ($p < 0.05$) for all traits.

The significant variation in graft survival, vine growth, and root development across the treatments highlights the importance of selecting the right rootstock to enhance plant vigor. The highest graft survival and vine length in NS 408/WS suggest superior compatibility, a stronger root system, and better resource acquisition, aligning with recent reports that *C. maxima* promotes both above- and below-ground growth in cucumbers (Rouphael et al., 2010; Asghar et al., 2024; Sakthivel et al., 2024). In contrast, the lower performance of GL/SG highlights potential incompatibility issues with certain scions, resulting in suboptimal growth.

Table 2. Graft survival percentage and biometric characters of cucumber grafts and self rooted control plants.

Graft combinations	Graft survival percentage (30 DAT)	Vine length at final harvest (cm)	Number of primary branches	Root length (cm)	Root weight (g)
GL	-	400 ± 6.1^{g}	3.6 ± 0.075^{cd}	51 ± 0.9^{g}	35 ± 0.46^{f}
GL / FG	78 ± 1.6^{a}	460 ± 5.2^{ef}	3.6 ± 0.033^{cd}	68 ± 1.1^{e}	60 ± 0.21^{d}
GL /PM	72 ± 0.22^{bc}	470 ± 10^{df}	3.3 ± 0.07^{de}	83 ± 1.9^{d}	46 ± 0.072^{e}
GL /WS	75 ± 0.12^{ab}	530 ± 1.4^{c}	4.1 ± 0.049^{b}	98 ± 2.5^{b}	99 ± 1^{b}
GL /BG	68 ± 0.6^{cd}	440 ± 9.5^{fg}	2.2 ± 0.037^{f}	86 ± 1.5^{cd}	48 ± 0.38^{e}
GL / SG	49 ± 0.31^{f}	270 ± 0.83^{h}	2.2 ± 0.048^{f}	59 ± 0.99^{f}	33 ± 0.6^{f}
NS 408	-	500 ± 4.7^{cd}	4.4 ± 0.041^{ab}	68 ± 1.2^{e}	47 ± 0.098^{e}
NS 408/ FG	71 ± 0.15^{bc}	600 ± 8.4^{b}	4.5 ± 0.094^{a}	92 ± 0.38^{bc}	74 ± 0.35^{c}
NS 408/ PM	75 ± 0.079^{ab}	670 ± 9.4^{a}	3.7 ± 0.065^{c}	90 ± 0.28^{c}	45 ± 0.16^{e}
NS 408/ WS	79 ± 1.8^{a}	700 ± 16^{a}	4.6 ± 0.11^{a}	110 ± 0.65^{a}	120 ± 3.1^{a}
NS 408/ BG	64 ± 0.76^{d}	480 ± 12de	3.2 ± 0.072^{e}	92 ± 1.5^{bc}	46 ± 0.81^{e}
NS 408/ SG	54 ± 0.25^{e}	300 ± 7.4^{h}	2.5 ± 0.062^{f}	65 ± 1^{ef}	36 ± 0.45^{f}

Values are means ± SEM.
Means in a row without a common superscript letter indicate significant differences based on pair wise comparison at $p<0.05$ as analyzed by one-way ANOVA and the TUKEY test.

Effect of grafting on earliness and male:female ratio

The earliness and male:female ratio (sex ratio) of cucumber grafts and self-rooted control plants varied significantly across treatments (Table 3). The days to first female flower appearance ranged from 14 ± 0.081 days in NS 408/FG to 18 ± 0.057 days in GL/PM. Among the grafted plants, NS 408/FG and NS 408/PM showed earlier flowering with 14 ± 0.081 and 14 ± 0.16 days, respectively. The node number to first female flower appearance was lowest in GL/PM (12 ± 0.15 days) and highest in GL/BG (18 ± 0.057 days). Lowest male:female ratios observed in NS 408/FG (20:1) and NS 408/WS (21:1), indicating a favorable balance between male and female flowers.

In terms of days to first harvest, NS 408/PM exhibited the shortest period to first harvest (26 ± 0.46 days), followed closely by NS 408/FG (26 ± 0.35 days) and NS 408/BG (26 ± 0.24 days).

The significant variation in earliness, sex ratio, and time to first harvest among cucumber graft combinations highlights the impact of rootstock selection on reproductive traits and yield potential. Earlier flowering and favorable male: female ratios in NS 408/FG and NS 408/PM suggest that these rootstocks enhance reproductive efficiency, likely due to improved hormonal balance and nutrient uptake (Lee et al., 2010; Sakthivel et al., 2024). In contrast, the higher sex ratios and delayed harvest times in GL and NS 408/SG indicate suboptimal compatibility, which may limit yield potential (Rouphael et al., 2010).

Table 3. Performance of cucumber grafts and self-rooted control plants for earliness and sex ratio.

Graft combinations	Days to first female flower appearances	Node number to first female flower appearance	Sex ratio (No. of male/ female flower)	Days to first harvest
GL	16 ± 0.042^{b}	16 ± 0.25^{b}	30 ± 0.22^{a}	29 ± 0.54^{cd}
GL / FG	16 ± 0.037^{b}	15 ± 0.21^{c}	24 ± 0.084^{c}	27 ± 0.026^{de}
GL /PM	18 ± 0.057^{a}	12 ± 0.15^{gh}	22 ± 0.16^{de}	28 ± 0.55^{cd}
GL /WS	15 ± 0.39^{bd}	14 ± 0.26^{cde}	24 ± 0.11^{cd}	30 ± 0.12^{c}
GL /BG	17 ± 0.43^{a}	18 ± 0.057^{a}	27 ± 0^{b}	34 ± 0.67^{b}
GL / SG	14 ± 0.21^{cde}	12 ± 0.16^{h}	27 ± 0.13^{b}	42 ± 0.35^{a}
NS 408	14 ± 0.34^{e}	15 ± 0.054^{bc}	28 ± 0.15^{b}	26 ± 0.38^{e}
NS 408 / FG	14 ± 0.081^{de}	13 ± 0.19^{fh}	20 ± 0.36^{f}	26 ± 0.35^{e}
NS 408 /PM	14 ± 0.16^{de}	14 ± 0.085^{df}	22 ± 0.34^{de}	26 ± 0.46^{e}
NS 408 /WS	16 ± 0.24^{bc}	13 ± 0.25^{efg}	21 ± 0.48^{ef}	28 ± 0.098^{de}
NS 408 /BG	15 ± 0.31^{be}	14 ± 0.0074^{cd}	23 ± 0.024^{cd}	26 ± 0.24^{e}
NS 408 / SG	15 ± 0.12^{be}	13 ± 0.3^{fh}	30 ± 0.65^{a}	41 ± 0.55^{a}

Values are means ± SEM.
Means in a row without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Yield performance, crop duration

The yield parameters, crop duration, and total harvests of cucumber grafts and self-rooted control plants showed significant variation across the treatments (Table 4). The highest number of fruits per vine (21 ± 0.12) and fruit weight (400 ± 4.6 g) were recorded in NS 408/WS, resulting in a maximum fruit yield of 8.3 ± 0.017 kg per vine. This treatment also had the longest crop duration (140 ± 2.7 days) and highest number of harvests (15 ± 0.22), significantly outperforming other combinations and controls. Among the Green Long combinations, GL/WS performed best, with 15 ± 0.14 fruits per vine, a fruit weight of 320 ± 8 g, and a yield of 5.4 ± 0.13 kg per vine, with crop duration of 120 ± 0.063 days and 12 ± 0.12 harvests.

Across all treatments, grafting significantly improved yield-related parameters compared to non-grafted controls, with significant differences ($p < 0.05$) for all traits. The superior yield and extended crop duration in NS 408/WS confirm the advantage of *C. maxima* rootstocks in promoting vigorous root systems, high water and nutrient uptake, and improved vegetative growth, aligning with reports by Davis et al. (2008a) and Bayoumi et al. (2021). Similarly, GL/WS showed strong performance among Green Long combinations. In contrast, GL/SG recorded poor yields and shorter crop duration, indicating compatibility limitations of *Luffa cylindrica*.

Table 4. Evaluation of cucumber grafts and self-rooted control plants for yield characters, crop duration and total harvests.

Graft combinations	Number of fruits per vine	Fruit weight (g)	Fruit yield per vine (kg)	Crop duration (days)	Total number of harvests
GL	10 ± 0.24^{f}	280 ± 0.58^{cd}	2.9 ± 0.034^{g}	97 ± 1.4^{fg}	8.4 ± 0.096^{d}
GL / FG	13 ± 0.31^{d}	270 ± 3.7^{de}	3.6 ± 0.031^{ef}	120 ± 1.5^{c}	11 ± 0.22^{bc}
GL /PM	8.7 ± 0.086^{g}	250 ± 2.3^{ef}	2.6 ± 0.062^{h}	120 ± 2.7^{cd}	10 ± 0.11^{c}
GL /WS	15 ± 0.14^{c}	320 ± 8^{b}	5.4 ± 0.13^{c}	120 ± 0.063^{c}	12 ± 0.12^{b}
GL /BG	12 ± 0.078^{e}	280 ± 4.7^{cd}	3.4 ± 0.0017^{f}	100 ± 1.5^{ef}	6 ± 0.063^{f}
GL / SG	7.5 ± 0.027^{h}	230 ± 4.3^{f}	2.3 ± 0.024^{i}	85 ± 0.044^{h}	5.9 ± 0.098^{f}
NS 408	13 ± 0.027^{d}	300 ± 7.5^{bc}	3.8 ± 0.002^{e}	120 ± 0.31^{cd}	11 ± 0.26^{bc}
NS 408/ FG	19 ± 0.38^{b}	380 ± 9.5^{a}	7.1 ± 0.12^{b}	140 ± 1.1^{ab}	15 ± 0.078^{a}
NS 408/ PM	12 ± 0.11^{de}	290 ± 2.5^{cd}	3.4 ± 0.048^{f}	130 ± 1.2^{b}	11 ± 0.13^{b}
NS 408/ WS	21 ± 0.12^{a}	400 ± 4.6^{a}	8.3 ± 0.017^{a}	140 ± 2.7^{a}	15 ± 0.22^{a}
NS 408/ BG	13 ± 0.13^{d}	300 ± 5^{bc}	4.2 ± 0.0088^{d}	110 ± 2.6^{de}	7.5 ± 0.14^{e}
NS 408/ SG	9.4 ± 0.0049^{g}	280 ± 3.6^{ce}	3 ± 0.019^{g}	89 ± 0.88^{gh}	6.5 ± 0.058^{f}

Values are means ± SEM.
Means in a row without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Fruit characteristics and quality

The fruit characters and quality of cucumber grafts and self-rooted controls varied significantly across treatments (Table 5). NS 408/WS had the highest fruit length (29 ± 0.51 cm) and diameter (5.4 ± 0.11 mm), followed by NS 408/FG (28 ± 0.057 cm and 5.4 ± 0.059 mm). Total soluble solids (TSS) were highest in NS 408/WS (4.2 ± 0.042 °Brix), NS 408/FG, and NS 408 (4.2 ± 0.028 °Brix). Total sugars were also highest in NS 408 (2.9 ± 0.027 mg 100 g^{-1}), NS 408/FG (2.9 ± 0.023 mg 100 g^{-1}), and NS 408/PM (2.8 ± 0.04 mg 100 g^{-1}).

No negative effects were observed on critical fruit quality attributes such as TSS, visual appearance, or texture, confirming that grafting maintained or improved market quality. The larger fruit size, high TSS, and sugar content in NS 408/WS and NS 408/FG validate the positive impact of *Cucurbita* rootstocks on nutrient transport and assimilation (Rouphael et al., 2010). Poor fruit quality in GL/SG further supports incompatibility issues, as this rootstock produced smaller fruits with lower sugar content.

Table 5. Evaluation of cucumber grafts and self-rooted plants for fruit characters and fruit quality.

Graft combinations	Fruit length (cm)	Fruit diameter (mm)	TSS (°brix)	Total sugars (mg 100g^{-1})
GL	20 ± 0.02^{h}	4.8 ± 0.02^{c}	3.5 ± 0.087^{de}	2.5 ± 0.045^{bc}
GL / FG	23 ± 0.22^{ef}	4.8 ± 0.12^{bc}	3.8 ± 0.021^{bc}	2.4 ± 0.018^{cd}
GL /PM	22 ± 0.023^{fg}	4.8 ± 0.038^{bc}	3.5 ± 0.055^{de}	2.2 ± 0.05^{de}
GL /WS	25 ± 0.56^{cd}	5.1 ± 0.032^{ab}	3.5 ± 0.035^{de}	2.3 ± 0.0071^{de}
GL /BG	21 ± 0.053^{gh}	4.6 ± 0.077^{cd}	3.7 ± 0.054^{cd}	1.9 ± 0.019^{f}
GL / SG	20 ± 0.43^{h}	3.5 ± 0.015^{f}	3.3 ± 0.012^{e}	1.6 ± 0.0065^{g}
NS 408	26 ± 0.16^{cd}	5.2 ± 0.033^{a}	4.2 ± 0.028^{a}	2.9 ± 0.027^{a}
NS 408/ FG	28 ± 0.057^{ab}	5.4 ± 0.059^{a}	4.2 ± 0.028^{a}	2.9 ± 0.023^{a}
NS 408/ PM	25 ± 0.16^{cd}	5.2 ± 0.057^{a}	4 ± 0.0083^{ab}	2.8 ± 0.04^{a}
NS 408/ WS	29 ± 0.51^{a}	5.4 ± 0.11^{a}	4.2 ± 0.042^{a}	2.6 ± 0.045^{b}
NS 408/ BG	24 ± 0.48^{de}	4.5 ± 0.063^{d}	4 ± 0.052^{ab}	2.3 ± 0.019^{de}
NS 408/ SG	26 ± 0.66^{bc}	3.9 ± 0.002^{e}	3.9 ± 0.087^{bc}	2.2 ± 0.054^{e}

Values are means ± SEM.
Means in a row without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Fruit Biochemical Composition

The fruit quality traits, including palatability, total sugars, ascorbic acid, and soluble protein content, varied significantly across grafted and non-grafted cucumber plants (Tables 5 and 6). The highest palatability score was recorded for NS 408/PM, showing that grafting onto *Cucurbita moschata* improved taste and texture. Conversely, GL/PM (6.6 ± 0.12) and GL/WS (6.6 ± 0.093) had the lowest scores.

Ascorbic acid content was highest in NS 408/FG (0.82 mg 100 g^{-1}), followed by GL/WS (0.8 ± 0.0042 mg 100 g^{-1}), while GL/SG had the lowest (0.47 ± 0.002 mg 100 g^{-1}). For soluble proteins, GL/SG showed the highest content (13 ± 0.17 mg g^{-1}), and GL/BG the lowest (6.3 ± 0.052 mg g^{-1}). Calcium was highest in NS 408/PM (8.9 ± 0.18 mg 100 g^{-1}).

These results demonstrate that grafting improved or maintained all measured biochemical traits, with *Cucurbita* rootstocks exhibiting superior effects on vitamin *C, calcium*, and protein content, consistent with the findings of Aslam et al. (2020). The enhanced biochemical values indicate that grafting improves nutrient uptake and fruit nutritional quality, reinforcing its agronomic advantage.

Table 6. Evaluation of cucumber grafts and self-rooted plants for fruit quality.

Graft combinations	Reducing Sugars	Ascorbic Acid	Calcium	Soluble Protein	Palatability score
GL	0.56 ± 0.013^{cd}	0.65 ± 0.013^{b}	8.2 ± 0.0042^{bcd}	9.5 ± 0.22^{de}	7.1 ± 0.14^{cd}
GL / FG	0.6 ± 0.013^{bc}	0.49 ± 0.0076^{c}	8.1 ± 0.036^{bcd}	13 ± 0.18^{b}	7.2 ± 0.041^{cd}
GL /PM	0.39 ± 0.003^{g}	0.64 ± 0.0023^{b}	7.8 ± 0.081^{cd}	11 ± 0.061^{c}	6.6 ± 0.12^{d}
GL /WS	0.44 ± 0.0055^{f}	0.8 ± 0.0042^{a}	8.2 ± 0.068^{bc}	8.8 ± 0.13^{f}	6.6 ± 0.093^{d}
GL /BG	0.53 ± 0.003^{de}	0.65 ± 0.016^{b}	8.2 ± 0.16^{bc}	6.3 ± 0.052^{h}	7.6 ± 0.024^{ac}
GL / SG	0.64 ± 0.013^{ab}	0.47 ± 0.002^{c}	8.1 ± 0.08^{bcd}	13 ± 0.17^{a}	6.7 ± 0.16^{d}
NS 408	0.46 ± 0.01^{f}	0.65 ± 0.012^{b}	8.4 ± 0.0087^{ac}	9.1 ± 0.019^{ef}	8 ± 0.17^{ab}
NS 408/ FG	0.42 ± 0.00022^{fg}	0.82 ± 0^{a}	8.2 ± 0.2^{bc}	7.6 ± 0.19^{g}	7.6 ± 0.12^{ac}
NS 408/ PM	0.67 ± 0.013^{a}	0.49 ± 0.0051^{c}	8.9 ± 0.18^{a}	9.3 ± 0.049^{ef}	8.2 ± 0.2^{a}
NS 408/ WS	0.51 ± 0.0027^{e}	0.65 ± 0.0017^{b}	8.1 ± 0.14^{bcd}	9.2 ± 0.1^{ef}	7.8 ± 0.065^{ac}
NS 408/ BG	0.31 ± 0.0044^{h}	0.62 ± 0.013^{b}	7.6 ± 0.099^{d}	6.3 ± 0.092^{h}	7.4 ± 0.031^{bc}
NS 408/ SG	0.56 ± 0.0038^{cd}	0.49 ± 0.0038^{c}	8.6 ± 0.14^{ab}	10 ± 0.12^{cd}	7.8 ± 0.16^{ab}

Values are means ± SEM.
Means in a row without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

The highest palatability scores were observed in *Cucurbita moschata* grafts, indicating that this rootstock can enhance fruit sensory attributes such as taste and texture. This suggests that *Cucurbita moschata* rootstocks may facilitate better nutrient translocation and metabolism, contributing to improved flavour (Aslam *et al*., 2020). In contrast, the lower palatability scores recorded in GL/PM and GL/WS indicate that these rootstocks might not be as effective in enhancing the sensory appeal of cucumbers. Total soluble solids (TSS), a key indicator of sweetness and fruit quality, were significantly higher in grafted plants such as NS 408/WS and NS 408/FG, highlighting the potential of *Cucurbita* rootstocks to enhance sugar accumulation in cucumber fruits. These findings align with earlier research that suggests grafting improves the plant's ability to accumulate carbohydrates, resulting in sweeter fruits (Rouphael *et al*., 2010; Bayoumi *et al*., 2021). Similarly, total sugar content was highest in NS 408 and its graft combinations, further supporting the positive impact of *Cucurbita* rootstocks on enhancing sweetness. Soluble protein content was also significantly higher in grafted plants, particularly in GL/SG and GL/FG, compared to non-grafted controls.

The increased protein content in these grafts suggests that grafting can enhance nitrogen assimilation and protein synthesis, which are essential for overall fruit nutritional quality. These findings agree with previous reports that grafting improves protein content due to the enhanced metabolic activity in grafted plants (Kumar *et al*., 2019b). Ascorbic acid (vitamin C) content, an important antioxidant, was highest in NS 408/FG and GL/WS, surpassing their non-grafted counterparts. The higher ascorbic acid levels in these grafted plants may be attributed to improved nutrient absorption and plant metabolism, which is commonly enhanced in grafted plants. The improved ascorbic acid content in these grafts not only enhances the nutritional value of the fruits but also contributes to longer shelf life and better post-harvest quality. Calcium content, crucial for fruit firmness and texture, was also significantly higher in grafted plants, particularly in NS 408/PM and NS 408/SG. These findings suggest that grafting onto *Cucurbita* rootstocks improves calcium uptake, which is critical for maintaining fruit structure and reducing post-harvest losses. The enhanced calcium content in these graft combinations supports the role of grafting in improving fruit firmness and overall quality (Davis *et al*., 2008b, Aslam *et al*., 2020; Asghar et al., 2024).

Significantly higher fruit yield per plant (8.3 ± 0.017 kg) was observed in the NS 408/WS graft combination. The enhanced yield in grafted plants is primarily attributed to the vigorous root system and improved water balance provided by *Cucurbita* rootstocks, allowing more efficient resource acquisition compared to non-grafted plants. This finding aligns with Khapte *et al*. (2021), who identified interspecific *Cucurbita* hybrids as the best rootstocks for increasing cucumber yield. Figure 2 demonstrates significant differences in economic yield, gross income, cost of cultivation, net return, and BC ratio between grafted and non-grafted treatments. In this study, fruit yields ranged from 2.3 ± 0.024 to 8.3 ± 0.017 kg per plant, with the highest yields following the order: NS 408/WS > NS 408/FG > GL/WS > NS 408/BG > NS 408 > GL/FG > GL/BG > NS 408/SG > GL > GL/PM > GL/SG. Grafting increased yields by 118.42% in NS 408/WS and 86% in NS 408/FG compared to non-grafted NS 408. Similarly, GL/WS showed an 86.21% increase over GL control and a 42.11% increase over NS 408 control. Notably, the yield increase in the grafted open-pollinated variety (GL/WS) over the non-grafted hybrid (NS 408) was 42.11%, highlighting the cost-effectiveness of grafting OPVs onto resistant rootstocks over using expensive hybrid seeds. Kumar et al. (2019a) also reported a 30% yield increase in grafted cucumber plants (*Cucurbita ficifolia* rootstock) compared to non-grafted plants.

Correlation Analysis of Growth Traits and Yield

Pearson correlation analysis revealed strong and significant positive associations between vegetative and root traits with fruit yield in grafted cucumber plants (Figure 1). Root weight showed the highest correlation with fruit yield ($r = 0.89$, $p < 0.0001$), followed by root length ($r = 0.74$, $p < 0.0001$), vine length ($r = 0.70$, $p < 0.0001$), and number of primary branches ($r = 0.70$, $p < 0.0001$). Root weight also exhibited strong correlations with vine length ($r = 0.68$) and root length ($r = 0.78$). The strong correlations between yield and root system attributes highlight the central role of root vigor in resource acquisition and overall productivity. Enhanced root weight and length in grafted combinations such as NS 408/WS (*C. maxima* rootstock) were associated with superior shoot growth and higher fruit yields, underscoring the contribution of grafting to improved water and nutrient uptake. Similar findings have been reported in cucurbits, where vigorous rootstocks enhanced nutrient transport, photosynthetic activity, and fruit set, leading to greater yields (Rouphael et al., 2010; Bayoumi et al., 2021; Asghar et al., 2024). The positive correlations between vine length, primary branches, and yield reflect the strong influence of shoot architecture on reproductive output. Plants with extended vine growth and more branches likely provided increased sites for flowering and fruiting, contributing to higher productivity. These relationships suggest that both shoot and root traits should be considered key selection criteria in grafting studies and breeding programs aimed at optimizing yield potential.

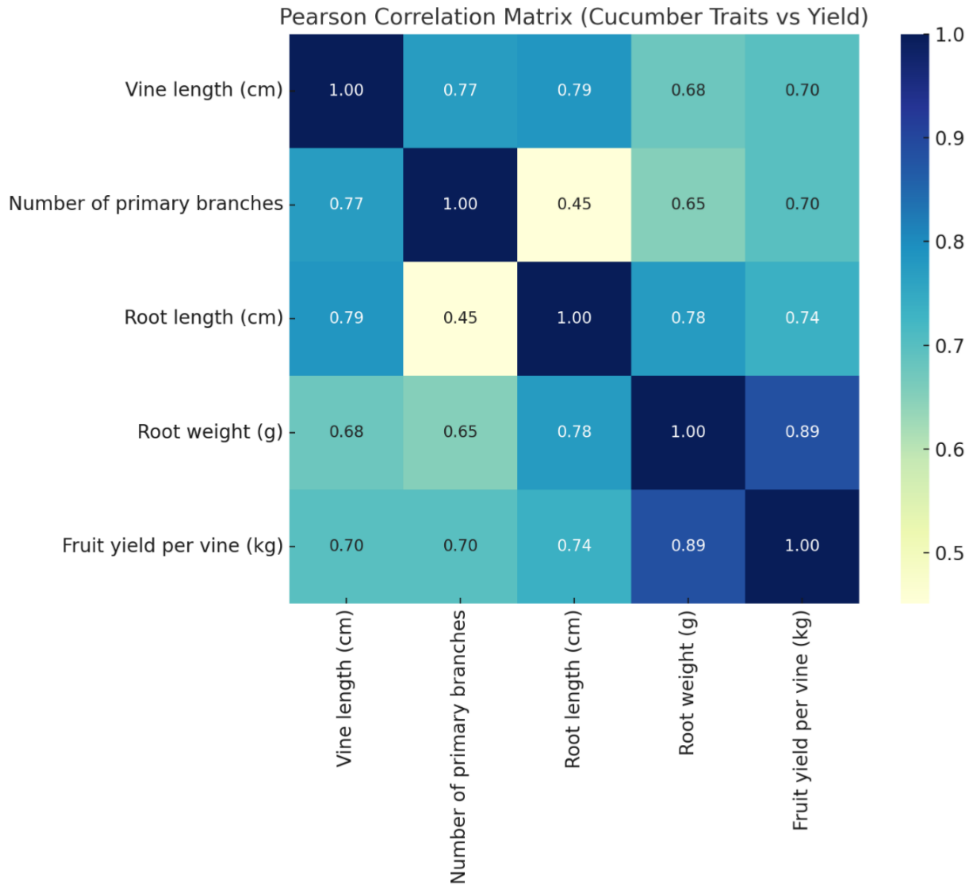

Fig 1. Pearson correlation heatmap showing relationships between key vegetative traits (vine length, number of primary branches, root length, root weight) and fruit yield in grafted cucumber plants. Darker blue-green colors represent stronger positive correlations (r-values closer to +1). Root weight and root length exhibited the strongest associations with yield ($p < 0.0001$), highlighting the importance of root vigor in productivity under net house conditions.

Economics

Economic analysis revealed substantial differences between grafted and non-grafted treatments (Figure 2). NS 408/WS had the highest economic yield (8.3 ± 0.017 kg/plant) and BC ratio (>2.5), while NS 408/FG and NS 408/BG also performed well (BC ratio >2.0). GL/WS outperformed the non-grafted hybrid, showing a 42.11% yield advantage over the NS 408 control and an 86.21% yield advantage over the GL control.

Non-grafted GL, NS 408, and GL/SG were less profitable, with BC ratios below 1.0, demonstrating that grafting significantly improves profitability in protected cultivation. The data confirm that grafting monoecious cultivars onto resistant rootstocks like *C. maxima* is a cost-effective alternative to hybrid seeds.

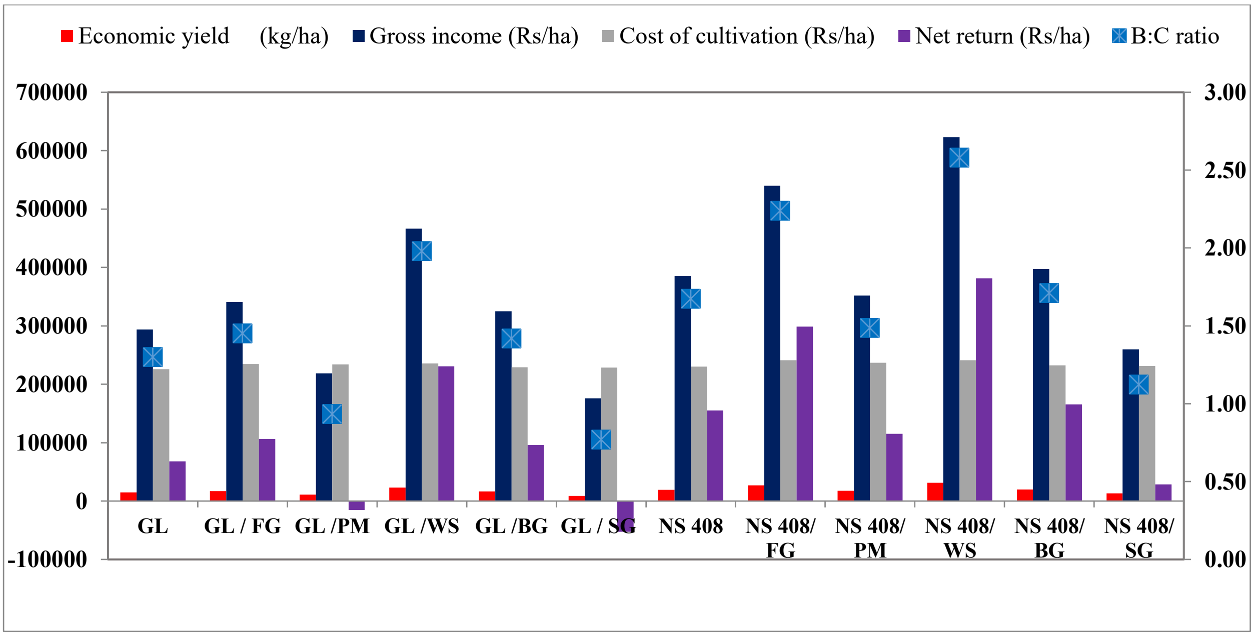

Fig 2. Yield and economics of monoecious cucumber grafted and non-grafted conditions.

Conclusion

This study demonstrates the significant impact of rootstock selection on the growth, yield, and fruit quality of grafted cucumber plants. Grafting onto *Cucurbita maxima* (NS 408/WS) resulted in increased fruit yield compared to non-grafted controls, along with improvements in fruit size, total soluble solids, and ascorbic acid content. Similarly, grafting onto *Luffa cylindrica* enhanced soluble protein and calcium content, although it did not match the overall performance of *C. maxima*. These findings highlight the importance of selecting suitable rootstocks to improve productivity, quality, and profitability in cucumber cultivation. The study is the first to demonstrate under Indian net house conditions that a grafted monoecious open-pollinated cultivar (GL/WS) can outperform a non-grafted hybrid, highlighting grafting as a practical and cost-effective alternative to expensive hybrid seeds. Results align with previous research (Rouphael et al., 2010; Sarwar et al., 2019a; Asghar et al., 2024) showing that *Cucurbita* rootstocks enhance stress tolerance, root vigor, and nutrient acquisition, leading to improved market quality and higher returns. Overall, grafting is a promising, scalable solution for sustainable cucumber production, particularly in resource-limited settings, offering reduced pesticide dependence, lower input costs, and improved farmer profitability.

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