

Article

Combined Influence of Grafting and Type of Protected Environment Structure on Agronomic and Physiological Traits of Single- and Cluster-Fruit-Bearing Cucumber Hybrids

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Abstract: Protected vegetable cultivation is a fast-growing sector in which grafting plays a crucial role for success. Cucumber is predominantly grown under protected conditions. The popular slicing (mini) cucumber comprises two segments, single- and cluster-fruit-bearing. In the present study, the performance of select fruit-bearing hybrids grafted as scions onto commercial Cucurbita hybrid rootstock 'NS-55' was evaluated under three different low-cost protected structures in arid regions. With respect to type of protected structure, cucumber performance was superior under a naturally ventilated polyhouse (NVP) than an insect net house (INH) or a shade net house (SNH). Micro-climate parameters inside NVP (air temperature, RH and PAR) were more congenial for cucumber than those in net houses, thereby facilitating improved physiology (chlorophyll fluorescence, chlorophyll and plant water potential) and leaf mineral status. Grafting invariably improved growth and yield parameters under all protected structures. Overall plant performance was better in the grafted cluster-fruit-bearing hybrid 'Terminator' than the single-fruit-bearing hybrid 'Nefer' or their non-grafted counterparts. Furthermore, NVP was found to be superior to net houses for water productivity, and grafted plants were more water use efficient than their counterpart non-grafted plants. Thus, NVP can be considered a suitable low-cost protected structure in conjunction with grafting to boost cucumber crop and water productivity in arid regions.

Keywords: *Cucurbita* rootstock; *Cucumis sativus* L.; protected cultivation; leaf mineral status; yield; water productivity; physiological status; sustainable horticulture



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1. Introduction

Greenhouse technology is a sustainable intensive production system; it is one of the alternatives to meet the demand for food of the burgeoning population in the present century [1]. The area under greenhouse cultivation is ever increasing around the world, ranging from high-altitude, temperate and hot-arid regions [2]. Innovations are occurring in this field, but for widespread adoption of greenhouse technology, their economic feasibility is important, including in the resource-constrained environments of arid regions. Protected structures vary from state-of-the-art, energy-intensive climate-controlled greenhouses to low-tech structures requiring minimal energy input. Crops raised under protected structures benefit from the alteration of micro-climatic parameters inside the structure, which results in optimal plant growth, development and extended period of crop harvest [3,4]. However, micro-climate modification inside low-cost protected structures such as naturally ventilated plastic house (polyhouse), walk in tunnel or net houses (insect or shade net) can vary as they are often affected by outside environments [2].

The type of protective cover and its characteristics cause changes in microclimate [5,6]. Greenhouses clad with polyethylene film have the ability to modify the incoming radiation, whereas the net covered structures allow radiation passing through them [7], depending on their shading factor. The light transmission properties of the cover material affect the air temperature and humidity inside protected structures, which in turn influences the respirational demand of the crops, thus can also alter water productivity. In another study, cucumber yields were recorded to be higher under white net cover [8], which was expected due to direct radiation cut, a significant transformation of radiation to diffuse radiation, which consequently resulted in higher productivity [9]. Furthermore, the altered microclimate parameters (e.g., light transmission, temperature and vapor pressure deficit) was more congenial in a double-layer polyethylene covered structure than those covered with UV-stabilised polyethylene, IR absorbers polyethylene and normal polyethylene [10]. Thus, the type of cladding material and the agro-ecological region are among the most important determinants of microclimate inside low-tech protected structures.

Cucumber (*Cucumis sativus* L.) is an economically important vegetable. Gynoecious and parthenocarpic cucumber hybrids have revolutionised the greenhouse industry around the world [4]. The high demand and poor productivity in open field conditions in arid regions due to various constraints make greenhouse cucumber cultivation an appealing option. In resource-limited arid regions, preference is given to low-tech protected structures. This prompts the question of which is the most feasible [11] for successful cultivation in arid environments. Additionally, grafting is used on a large scale to increase vegetable productivity under challenging growth environments [12]. Grafting cucumber onto *Cucurbita* rootstock for yield enhancement under different stressful conditions has been widely documented [2,13,14]. Furthermore, in mini-cucumber, there are different categories of gynoecious hybrids based on their bearing habit (single- and cluster-fruit bearing), with varying seed costs [4].

However, the effect of grafting cucumber hybrids of single and cluster fruit on yield has not been delineated under different low-cost protected conditions. Moreover, the rootstock may have different implications for the performance of different scion cultivars [15]. In the present investigation, we attempted to evaluate different low-cost protected structures for cucumber cultivation, in order to assess the performance of single- and cluster-fruit-bearing gynoecious cucumber hybrids with or without grafting onto commercial interspecific *Cucurbita* hybrid rootstock in an Indian arid region.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

The experiment was conducted in low-tech protected structures, namely naturally ventilated polyhouse (NVP), shade net house (SNH) and insect-proof net house (INH) (each with an area of 128 m²) during August–November, 2019 at ICAR Central Arid Zone Research Institute, Jodhpur (26°15' N latitude, 72°59' E longitude). The microclimatic parameters recorded in these structures during the cropping period are presented in Figure 1. The photosynthetically active radiation (PAR) was recorded with a line quantum sensor (MQ-301, Series#1178, Apogee, Logan, UT, USA), net radiation was recorded with a net radiometer (S. No. 1238, Middleton, Glenside, PA, USA), and air temperature and relative humidity were recorded with an Assmann psychrometer (Model MR-58, Hisamatsu, Tokyo, Japan). The commercial cucumber cultivars 'Nefer' and 'Terminator', single- and cluster-fruit-bearing hybrids, respectively (Yuksel Tohum, Antalya, Turkey), were used as a scion (Figure S1). The interspecific *Cucurbita* hybrid 'NS 55' (Namdhari Seeds, Bengaluru, India) was used as a rootstock. Rootstock seed was sown two days later than scion seed sowing as rootstock seedlings experience very fast growth after germination. Sowing was carried out in 52 mm cell plug-trays filled with soilless medium (vermiculite:cocopeat; 1:2 ratio *v/v*). The seedlings were fertigated twice a week with 0.2% water-soluble complex fertiliser N:P:K-19:19:19 (Gromor, Coromandel International Ltd., Secunderabad, India) along with 0.1% micronutrient mixture (Multiplex Group of Companies, Bengaluru, India). At the stage of first true leaf opening in both scion and rootstock, grafting was

performed following the cleft-grafting method [16]. The final expenses (INR = 0.013 USD) of grafted ‘Nefer’ and ‘Terminator’ plants are presented in Table 1. Immediately after grafting, seedlings were placed in a growth chamber where temperature and relative humidity ranged between 25 and 28 °C and 85% and 95%, respectively. High relative humidity (95%) and darkness was provided for the initial 36 h, then light intensity was increased gradually with a decrease in relative humidity to 85% over a period of 5–6 days. The grafted seedlings were hardened through shifting them to full light inside the fan and pad greenhouse for 4 to 5 days. Grafted cucumber plants were transplanted at 2–3 true leaf stage in paired rows by following zig-zag planting at 50 cm × 45 cm spacing on 90 cm-wide beds. One drip lateral (16 mm OD, 0.30 m spaced and 1.0 LPH discharge) per planting row was placed 8–10 cm away from the seedlings. Soil moisture was maintained close to the field capacity by daily morning irrigation. Plants were trained to a single stem by pinching of auxiliary shoots, and support was given by a UV-stabilised plastic thread attached to an overhead trellis wire. The experiment was laid out in a factorial randomised block design with three replications. Each experimental unit consisted of ten plants. Three randomly selected plants from each experimental unit were tagged for the recording of growth, yield, mineral contents and physio-biochemical observations.

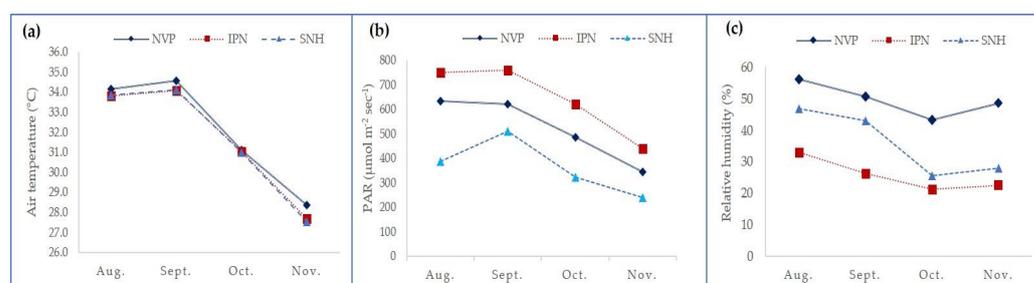


Figure 1. (a) Air temperature, (b) PAR and (c) relative humidity inside different protected structures.

Table 1. Grafted seedling cost in INR (INR = 0.013 USD) of cucumber used in the experiment.

Particulars	Grafted Seedling Cost (INR Plant ⁻¹)	
	‘Nefer’ (Single Fruiting)	‘Terminator’ (Multiple Fruiting)
F ₁ hybrid scion	1.5	6.0
Rootstock cost	2.0	2.0
Seedling production charges *	4.5	5.5
Final grafted seedling cost on site	8.0	13.5

* Including cost of grafting operation, healing/hardening facilities and seed germination/mortality and local transport for two graft combination.

The soil had the following characteristics: pH 7.9, organic carbon (OC) 0.21%, total N 0.03%, available P 16.3 kg ha⁻¹ and available K 221.5 kg ha⁻¹. The soil at the experiment site contained 85% sand, 8.1% silt and 5.5% clay. Twenty-five tons ha⁻¹ compost was added by tilling the top 15 cm of soil during the final soil preparations. The fertiliser (200:200:250 kg ha⁻¹ N:P:K), along with 50 kg Ca and 15 kg Mg and 37.5 kg S ha⁻¹, was given through fertigation during the entire cropping period. In addition, twice a week, a commercial-grade micronutrient mixture (Multiplex Group of Companies, Bengaluru, India) was applied through fertigation. Uniform crop protection measures to control pests and diseases were followed equally in all the structures during the period of study.

2.2. Plant Growth, Fruit Yield and Quality Parameters

At the final harvest, after 110 days after transplanting, the vine length of tagged plants was measured. Plants were separated into leaf and stem, and their dry weight was determined after oven-drying at 65 °C until constant weight was obtained. Moreover, the

stem girth was measured above the collar region with a digital calliper. The leaf area was measured with a LI3100c leaf area meter (LI-COR, Inc., Lincoln, NE, USA). The fruit yield (kg plant^{-1}) and fruit number were determined by combining the fruits obtained from each harvest. Mean fruit weight, fruit length and fruit girth were measured by averaging the fruits from three different harvests. Fruit quality analysis was conducted on freshly harvested fruits during peak harvesting period. Total soluble solids (TSS) were determined with a digital handheld refractometer (Bellingham and Stanley, Tunbridge Wells, UK). Fruit firmness was measured using a fruit hardness tester (model no FR-5120, Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan). Fruit dry matter content was determined by weighing the dried fruits kept in a forced air oven at $70\text{ }^{\circ}\text{C}$ until constant weight was obtained.

Fruit colour analysis was performed with a handheld colorimeter (Hand-held colorimeter WR10, Shenzhen Wave Optoelectronics Technology Co., Ltd., Shenzhen, China). L^* value (lightness), a^* value (redness to greenness) and b^* value (yellowness to blueness) of the cucumber samples were recorded. The measurements were taken on five samples and the average of L^* , a^* and b^* values was recorded. Water productivity (WP, kg m^{-3}) was computed according to Dermitas and Ayas [17], expressed as a ratio of total yields to total water applied, including irrigation water, during the entire growing period.

2.3. Physio-Biochemical Parameters

During active growth period of the crop at reproductive stage F_v/F_m was measured with a chlorophyll fluorescence meter (OS-30p, Opti-Sciences, Inc., Hudson NH, USA). Actively growing leaves were used for estimation of total chlorophyll content. Total chlorophyll concentration in fresh leaf tissues was estimated following Arnon's protocol [18]. Plant water potential was measured with a pressure chamber (Model 600, PMS Instrument Co. Corvallis, OR, USA).

2.4. Leaf Mineral Analyses

The vine leaves were oven dried at $65\text{ }^{\circ}\text{C}$ until constant weight was obtained. Dried leaf samples were then grounded in a Willy Mill. Nitrogen content was determined by micro-Kjeldahl procedure of digestion, distillation and titration to AOAC procedure [19]. A diacid ($\text{HNO} + \text{HClO}$ in 9:4 ratio) mixture was used and analysed for phosphorus by vanadomolybdo-phosphoric acid yellow colour method [20]. Potassium content was determined by flame photometry as described by Chapman and Pratt [21], whereas calcium and magnesium were determined using versene titration [22]. Sulphur content was estimated by a colorimetric method using barium chromate [23]. The concentration of total micronutrients, namely copper, manganese, zinc and iron, in diacid-digested samples was determined by Atomic Absorption Spectrophotometer (GBC 932 AA).

2.5. Statistical Analyses

The experimental data were statistically analysed by analysis of variance using SPSS software package (SPSS version 16). Duncan's Multiple Range Test (DMRT) was performed and mean values of three replicates within columns are separated ($p = 0.05$). The descriptive statistics and homogeneity test were applied while analysing the data.

3. Results

3.1. Microenvironment

The cladding materials significantly affected the microenvironment inside the protected cultivation structures (Figure 1a–c). Average day temperature as well as relative humidity (RH) under protected structures covered with plastic, such as naturally ventilated polyhouses (NVP), was higher than those covered with either shade nets or insect-proof nets. However, photosynthetically active radiation (PAR) values were moderate in the insect-proof net house (IPN) and NVP, while the values in the shade net house (SNH) were lower throughout the cropping period. Temperature, RH and PAR followed similar trends

with respect to the structures, except comparatively low PAR values at the initial growth stage and a sudden drop in RH at a later growth stage in the SNH.

3.2. Growth Parameters

The growth parameters significantly differed between the two cucumber hybrids. Except for leaf dry mass, which did not differ between the two hybrids, the record of all the growth parameters (i.e., stem dry mass, leaf area, vine length, node number and stem girth) was significantly higher in non-grafted plants of ‘Terminator’ than that of ‘Nefer’, regardless of protected structures (Table 2).

Table 2. Effect of structures and graft combinations on growth parameters.

Treatments	Dry Mass (g Plant ⁻¹)		Leaf Area (m ² Plant ⁻¹)	Vine Length (cm)	Node Number	Stem Girth (cm)
	Leaf	Stem				
			Structures (S)			
NVP	74.68a	28.50a	1.21a	3.76	51.00a	1.29a
IPN	72.25ab	25.45b	1.20a	3.68	50.08a	1.20b
SNH	66.85b	21.74c	1.03b	3.55	41.16b	1.03c
			Grafting (G)			
Nefer	56.24c	19.32c	1.00c	3.12c	41.37b	0.87d
Nefer/NS 55	73.88b	22.36b	1.10b	3.53bc	45.14b	1.13c
Terminator	61.91c	23.65b	1.16b	3.81ab	50.07a	1.30b
Terminator/NS 55	93.00a	35.56a	1.35a	4.11a	53.07a	1.38a
Significance						
S	NS	***	***	NS	***	***
G	***	***	***	**	***	***
S × G	NS	*	NS	NS	NS	NS

Mean values of three replicates within columns are separated by different letters using Duncan’s multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance *, **, *** at $p < 0.05$, 0.01 and 0.001, respectively.

Among the three protected structures, most of the growth parameters, regardless of grafting treatment, were recorded highest in NVP, while the lowest were recorded in SNH. Except vine length, the mean values of all the growth parameters were significantly higher in NVP than SNH, whereas only stem dry mass and stem girth were found to be significantly higher in NVP in comparison with IPN (Table 2).

The effect of grafting was clearly evident in two cucumber hybrids (Table 2). The values of all the growth parameters were recorded as higher in grafted ‘Terminator’ plants than grafted ‘Nefer’ plants, regardless of the protected structures. The effect of grafting for leaf and stem dry mass and leaf area was more prominent in ‘Terminator’ scion, with the recorded increase of 50.2%, 50.4% and 16.4%, respectively, over its non-graft control, whereas the increases in vine length, node number and stem girth were recorded to be higher (i.e., 13.1%, 9.1% and 29.9%, respectively) in grafted ‘Nefer’ over its control (Table 2). Although node number was higher in ‘Terminator’ than ‘Nefer’, no variation was observed between their grafted and non-grafted plants. Overall, the growth parameters in cucumber plants were relatively higher in NVP, and grafted ‘Terminator’ was superior to other grafting treatments.

3.3. Fruit Yield Parameters and Water Productivity

The protected structures and grafting treatments significantly affected fruit number and mean fruit weight (Table 3). The fruit yield in different structures ranged from 2.06 to 3.85 kg plant⁻¹ and was in the order NVP > IPN > SNH. Grafting with interspecific *Cucurbita* hybrid rootstock NS55 increased fruit yield by 19% and 28% in grafted ‘Terminator’ and grafted ‘Nefer’ over their respective non-grafted controls. Yield in grafted ‘Nefer’ were statistically on par with that obtained from non-grafted ‘Terminator’. Type of structure and grafting treatment affected the fruit number in a similar fashion as noted for fruit yield (Table 3). The fruit number in the cluster-bearing hybrid ‘Terminator’ was on average 22% higher (over grafted and non-grafted plants) than the single-fruit-bearing hybrid ‘Nefer’. Further, fruit

number in grafted 'Terminator' and 'Nefer' plants was 16.5% and 22.4% higher than their respective control. Mean fruit weight was influenced by structures, where NVP and IPN had similar fruit weight, but it was lower in SNH. Grafting, however, had no apparent effect on mean fruit weight (Table 3). There was no interaction effect of structures and grafting treatments observed for yield and its attributing traits. Overall, grafting response for yield enhancement was more pronounced in 'Nefer' than 'Terminator'. The water productivity was similar between NVP and IPN structures; for grafting treatments, it was the highest in grafted 'Terminator', followed by non-grafted 'Terminator' and grafted 'Nefer'.

Table 3. Effect of structures and graft combinations on yield parameters and water productivity (WP).

Treatments	Fruit Number (Plant ⁻¹)	Mean Fruit Weight (g)	Fruit Yield (kg Plant ⁻¹)	WP (kg m ⁻³)
		Structures (S)		
NVP	26.33a	145.64a	3.85a	31.11a
IPN	23.81b	141.75a	3.37b	27.24a
SNH	16.04c	128.00b	2.06c	18.17b
		Grafting (G)		
Nefer	17.88c	132.86	2.40c	19.79c
Nefer/NS 55	21.88b	140.02	3.07b	25.36b
Terminator	22.39b	137.78	3.15b	25.93ab
Terminator/NS 55	26.08a	143.20	3.75a	30.94a
Significance				
S	***	**	***	***
G	***	NS	***	***
S × G	NS	NS	NS	NS

Mean values of three replicates within columns are separated by different letters using Duncan's multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance **, *** at $p < 0.01$ and 0.001 , respectively.

3.4. Fruit Quality

Grafting significantly influenced all the studied fruit quality parameters except fruit firmness, whereas the structure influenced fruit length, girth and fruit dry matter percentage (Table 4). Most of the quality parameters were highest in NVP. Fruit length, as well as fruit girth, was lowest in non-grafted 'Nefer', followed by its grafted counterpart. Conversely, fruit dry matter was apparently higher in non-grafted 'Nefer' than the others. Fruit TSS was not influenced by structures, and grafting also did not increase TSS, as non-grafted plants of both the hybrids recorded higher levels (Table 4).

Table 4. Effect of structures and graft combinations on fruit quality parameters.

Treatments	Fruit Length (cm)	Fruit Girth (cm)	Fruit Firmness (kg cm ⁻²)	TSS (%)	Fruit Dry Matter (%)
		Structures (S)			
NVP	14.30a	4.07a	3.83	3.28	3.63a
IPN	13.95b	3.95b	3.76	3.21	3.20b
SNH	13.63c	3.88c	3.84	3.20	2.88c
		Grafting (G)			
Nefer	13.32c	3.86b	3.89	3.39a	3.52a
Nefer/NS 55	13.98b	3.93b	3.83	2.99b	3.12b
Terminator	13.96b	4.09a	3.77	3.50a	3.10b
Terminator/NS 55	14.57a	3.97ab	3.75	3.03b	3.12b
Significance					
S	**	**	NS	NS	***
G	**	**	NS	***	**
S × G	NS	NS	NS	*	NS

Mean values of three replicates within columns are separated by different letters using Duncan's multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance *, **, *** at $p < 0.05$, 0.01 and 0.001 , respectively.

The CIELab colour space expresses colour as values of L* for lightness from black (0) to white (100), a* from green (<0) to red (>0) and b* from blue (<0) to yellow (>0). The protected structures had a significant effect on L* but not on a* and b*, while the effects of grafting and its interaction with protected structures were apparent for a* and b* colour coordinates (Table 5). The L* value was distinctly higher in the fruits of NVP and IPN than those of SNH. Among graft combinations, fruits of non-grafted ‘Terminator’ followed by grafted ‘Terminator’ were recorded with higher values of L* and a*. The opposite response of graft combination was observed for b*.

Table 5. Effect of structures and graft combinations on fruit colour determinants.

Treatments	L*	a*	b*
		Structures (S)	
NVP	88.86a	−53.06	9.81
IPN	88.83a	−53.03	8.93
SNH	87.85b	−53.22	9.32
		Grafting (G)	
Nefer	85.58c	−48.71d	3.74a
Nefer/NS 55	85.79c	−49.84c	5.23b
Terminator	92.51a	−58.16a	1.52c
Terminator/NS 55	90.17b	−55.69b	1.31d
Significance			
S	*	NS	NS
G	***	***	***
S × G	NS	***	***

Mean values of three replicates within columns are separated by different letters using Duncan’s multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance *, ***, at $p < 0.05$ and 0.001 , respectively.

3.5. Physio-Biochemical Parameters

Chlorophyll content was distinctly higher in NVP and SNH than INH (Table 6). The grafted plants exhibited higher, though significantly similar, chlorophyll content than non-grafted plants. Among the non-grafted plants, ‘Terminator’ had higher chlorophyll content than ‘Nefer’. The studied structures did not influence leaf water potential. However, grafting, irrespective of the scion used, resulted in less leaf water deficit compared to non-grafted plants. PSII efficiency was higher in NVP and IPN than SNH. Additionally, the F_v/F_m values of grafted plants were higher than non-grafted plants, regardless of cucumber hybrid. The extent of improvement in F_v/F_m was statistically similar in grafted and non-grafted plants in both the hybrids.

Table 6. Effect of structures and graft combinations on physiobiochemical parameters.

Treatments	Total Chlorophyll ($\mu\text{g mL}^{-1}$)	WP (-bars)	PSII (F_v/F_m)
		Structures (S)	
NVP	15.08a	5.87	0.827a
IPN	12.46b	5.75	0.822a
SNH	14.27a	5.75	0.784b
		Grafting (G)	
Nefer	11.66c	6.16b	0.802b
Nefer/NS 55	15.08a	5.50a	0.816a
Terminator	13.35b	6.15b	0.802b
Terminator/NS 55	15.67a	5.33a	0.823a
Significance			
S	***	NS	***
G	***	***	**
S × G	NS	NS	NS

Mean values of three replicates within columns are separated by different letters using Duncan’s multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance **, *** at $p < 0.01$ and 0.001 , respectively.

3.6. Mineral Composition

The effect of protected structure, grafting and their interaction on the concentration of macro and micro elements in cucumber leaves is presented in Tables 7 and 8, respectively. The total N content was recorded as the highest in NVP, followed by IPN and SNH, whereas the opposite trend was observed for K content with respect to protected structures. The contents of P and Ca were higher, though similar to each other, in IPN and SNH than in NVP. The content of S was higher in NVP and IPN than SNH. The Mg content did not change due to the structure's influence. Among the graft combinations, the macro element contents such as P, K, Ca and S were high in grafted 'Terminator', whereas non-grafted 'Nefer' was characterised with the lowest content for most of these elements. However, it was the opposite for the Mg content, which was the highest in non-grafted 'Nefer' and the lowest in grafted 'Terminator' plants.

Table 7. Effect of structures and graft combinations on accumulation macroelements in leaves (g kg^{-1} dry weight; DW).

Treatments	N	P	K	Ca	Mg	S
Structures (S)						
NVP	60.7a	2.1b	16.8c	47.0b	4.0	2.0a
IPN	46.3b	2.4a	20.2b	52.5a	4.0	2.0a
SNH	41.1c	2.5a	30.4a	52.2a	4.2	1.7b
Grafting (G)						
Nefer	50.6	2.1c	20.1b	48.7b	7.2a	1.6c
Nefer/NS 55	50.5	2.4ab	21.2b	49.8b	4.2b	2.0b
Terminator	48.1	2.2bc	24.4a	50.2b	3.1c	1.7c
Terminator/NS 55	48.3	2.6a	24.1a	53.6a	1.4d	2.3a
Significance						
S	***	**	***	***	NS	***
G	NS	***	***	**	***	***
S × G	***	NS	***	*	***	***

Mean values of three replicates within columns are separated by different letters using Duncan's multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance *, **, *** at $p < 0.05$, 0.01 and 0.001, respectively.

Table 8. Effect of structures and graft combinations on accumulation microelements in leaves (mg kg^{-1} dry weight; DW).

Treatments	Cu	Mn	Zn	Fe
Structures (S)				
NVP	3.05a	68.13a	13.92b	73.95b
IPN	1.99b	48.64c	8.51c	92.21a
SNH	1.90b	61.95b	16.10a	92.88a
Grafting (G)				
Nefer	2.59a	58.67	13.53	88.55
Nefer/NS 55	2.26bc	62.38	13.66	86.84
Terminator	2.07c	57.74	12.65	84.76
Terminator/NS 55	2.34b	59.52	11.54	85.23
Significance				
S	***	***	***	***
G	**	NS	NS	NS
S × G	*	NS	NS	***

Mean values of three replicates within columns are separated by different letters using Duncan's multiple-range test (DMRT) $p = 0.05$. NS—not significant; significance *, **, *** at $p < 0.05$, 0.01 and 0.001, respectively.

The concentration of micro elements was significantly different between the structures. The concentration of Cu and Mn was the highest in NVP, whereas the concentration of Zn and Fe was the highest in SNH. Graft combinations did not show any significant difference for micro elements except Cu, where its concentration was the highest in 'Nefer'. The

structure \times grafting interaction was displayed for Cu and Fe contents in the leaves of cucumber plants.

4. Discussion

The different protected structures and scion-rootstock combinations may have a substantial effect on the performance of greenhouse vegetables. In this study, the effect of protected structures and grafting was clearly evident on various growth, yield and quality parameters of cucumber. The present study reveals how distinctly characterised single-fruit- ('Nefer') versus cluster-fruit ('Terminator')-bearing parthenocarpic hybrids and their grafts with interspecific *Cucurbita* hybrid 'NS 55' rootstock perform under different low-tech protected structures in an arid environment.

Protective covering in low-tech greenhouses influences the micro-environment primarily as a result of alteration in light intensity and quality; these interact with various physio-biochemical plant processes, thereby affecting plant growth and development [7,24]. In protected structures, NVP showed a more positive effect on the growth of cucumber plants than the net houses (INP and SNH), whereas among the net houses, INH was better for various growth parameters. The NVP was clad with a polyethylene sheet, which characteristically controls UV radiation while allowing transmission of photosynthetically active radiation (PAR) with good light diffusion, favouring plant growth [7]. On the other hand, the nets in net houses could only moderate the entry of direct radiation with no effect on light diffusion. Nevertheless, the amount of PAR energy depends upon location, time of the year and atmospheric conditions [25]. Furthermore, it is believed that poly-house microclimate also depends on the type of screen or cladding material, structure configuration, and climatic condition of the site [26]. Likewise, in our study, the NVP had better microclimate variables, resulting in better vegetative growth as well as reproductive parameters. PAR is a very important environmental parameter that drives photosynthesis and its availability inside a structure is greatly influenced by the type of cladding materials used [7]. The PAR value was consistently higher in IPN while it was moderate in NVP, but was inconsistent in SNH. In SNH, very low PAR at the early growth stage was caused by over-shading due to high net shading (50%) that may coincide with cloudy days. The NVP had optimal PAR values with the least variation; this might have led to better growth promotion. A greater reduction in PAR under shade conditions has deleterious effects on plant growth [27].

Additionally, despite the openings at the top and side walls that facilitate natural ventilation, the average day air temperature and RH inside NVP were slightly higher due to the plastic cover compared to the net houses (Figure 1a–c). As evidenced from overall growth parameters (Table 2), the relatively high temperature coupled with high relative humidity in NVP, especially during the early growth stage, likely helped accelerate early crop growth. The favourable response of high temperatures and relative humidity on the early growth of cucumber plants has been documented [4,28]. Moreover, the hybrids used in the study are well adapted to the high-temperature conditions of the summer and the rainy seasons in these areas, making the effect of high day temperature and RH quite obvious on plant growth. Similarly, the average temperature in the NVP was also higher during the later crop stage prior to winter, which might favour fruit production, development and quality.

The interspecific *Cucurbita* hybrid rootstocks have shown promising results on cucumber performance under different growing conditions [12,13,29]. The high-performing interspecific hybrid rootstock 'NS 55' from our previous experiments was chosen in this study. Grafting with this rootstock increased most of the growth parameters of both cucumber hybrids, though the response was more pronounced for cluster-bearing hybrid 'Terminator' than single-fruit-bearing hybrid 'Nefer' (Table 2). Comparing the differences of non-grafted 'Terminator' with non-grafted 'Nefer' for stem dry mass, leaf area, vine length, node number and stem girth clearly indicates that the hybrid 'Terminator' was superior to hybrid 'Nefer' in growth habit, and thus was more productive when grafted

to the characteristically vigorous root system of interspecific rootstock. Overall, grafting increased leaf area, vine length, node number and stem girth, and finally resulted in an increase in aboveground dry mass of grafted plants (Table 2). Similarly, a report by Omar and El-hamahmy [30] supports that the increase in vegetative parameters of grafted cucumber was due to the increase in its biomass-associated parameters. The improved growth in grafted plants could be the result of the better ability of rootstocks to adapt to variable growth environments [31] such as arid regions.

Microclimate variables such as radiation, air temperature and relative humidity were relatively favourable in NVP, which resulted in a positive response not only in vegetative growth but in reproductive growth and development, as reflected by higher fruit number and fruit weight and ultimately fruit yield (Table 3). Grafting has a greater effect on fruit number than fruit weight. The fruit number per plant was higher in grafted 'Terminator' than grafted 'Nefer,' which was ascribed to longer vine length and a greater node number in the former. However, fruit number and weight and thus fruit yield were similar in grafted 'Nefer' compared to non-grafted 'Terminator'. The structures affected the water productivity irrespective of grafting; grafted 'Terminator' recorded the highest water productivity. As compared to non-grafted plants, the four interacting genomes in grafted plants involving F1 hybrids of scion and rootstock might have resulted in a robust root system which could acquire more water [32]. The heterotic effect of hybrid rootstock and also of scion influence growth and ultimately the fruit yield. The increased water productivity of grafted plants also correlates with a proportionately higher rate of net CO₂ assimilation to that of transpiration [33].

Similar to the growth- and yield-related parameters, the better microclimate inside NVP also exerted a favourable response on some of the fruit quality traits, such as fruit length and girth, and fruit dry matter content (Table 4). The SNH again proved to be the least beneficial to fruit quality, while the response of IPN was better than that of SNH but lower than NVP. The response of grafting was apparent for fruit length, which was higher in grafted plants than non-grafted for the hybrids. Fruit girth was apparently different between both non-grafted plants. In contrast, the TSS content was reduced in grafted plants, which might be due to dilution effects of the soluble solids. This proposition is supported by the fact that non-grafted 'Nefer', which produced the lowest yield, had the highest fruit dry matter content. These results are in agreement with the finding of Omar and El-hamahmy [30], which might be due to vigorous root system interspecific rootstock able to acquire more nutrients and water. Our results are in contradiction with the reports of Uysal et al. [34] for fruit quality as a result of grafting. There was a decrease in fruit TSS in grafted plants compared to non-grafted plants, because grafted plant fruits also have low fruit dry matter content, which might be due to diluted soluble solids. Similarly, Omar and El-hamahmy and Davis et al. [30,35] reported low TSS in grafted cucumber plants in their studies. Due to better micro-climate, fruit girth and fruit dry matter contents were found to be higher in NVP as compared to other structures. Among both the hybrids, fruits were much better in 'Terminator' than 'Nefer'; even grafted 'Terminator' had better skin colour values. Surface colour is the most important parameter evaluated by consumers and it can influence product acceptance [36]. Fruits from single-fruit-bearing hybrid 'Nefer' are less luminous and dark green due to lower L* and higher a* and b* values (Table 5), which is probably due to the genetic difference between the hybrids. A higher L* value in 'Terminator' was translated into higher luminosity in the skin than 'Nefer'. Similarly, the higher L* value was an indicator of its higher luminosity in the local variety of *Cucumis melo* and in self-grafted cucumber plants [34,37].

The structures and grafting had a significant influence on physio-biochemical parameters. The NVP had higher chlorophyll content and better PSII efficiency among the structures, which might be due to the favourable effect of a better diffuse radiation (up to 60%) from the cladding film [38]. In contrast, high direct radiation is detrimental to the plant and may adversely affect photosynthetic activity. Though SNH had similar content of chlorophyll to that of NVP, the low PSII efficiency in the former one is an indication of

relatively low photosynthetic performance that was eventually reflected in lower shoot and fruit mass production. The grafted 'Terminator' plants had higher total chlorophyll content as well as PSII efficiency due to the effect of *Cucurbita* hybrid rootstock. Similarly, Rouphael et al. [39] also observed that cucumber plants grafted onto the *Cucurbita* hybrid rootstocks maintained a higher production potential by sustaining photosynthetic processes. In our study, both the grafted hybrids had higher chlorophyll content, PSII efficiency and plant water status, as reflected by lower leaf water potential as compared to their respective non-grafted plants. The higher yield in grafted plants is obviously due to better plant water balance and PSII efficiency, and a vigorous root system which is capable of taking up nutrients and water more efficiently than non-grafted plants [36,38]. Similarly, higher leaf water potential and photosynthesis of grafted cucumber was also observed; the grafted plants in both the hybrids registered less leaf water deficit in terms of leaf water potential (less negative; Table 6) and were more photosynthetically efficient according to high F_v/F_m [40].

The concentration of macroelements in leaves was the highest in NVP for N and S, which indicates that the uptake and translocation of these elements were in equilibrium. This was also reflected by the better growth and physiological functioning under NVP. The content of P, K and Ca was higher in leaves of IPN and SNH, meaning that their translocation to the fruit might be minor due to relatively less favourable environments, as also corroborated by observed low PSII efficiency in net structures. The microclimate dissimilarity in different protected structures has been shown to affect the water and nutrient uptake and translocation [41,42]. There are reports which indicate that root zone temperature affects nutrient uptake, particularly N, P and K, and their allocation in cucumber seedlings [43]. In our study, the microclimates under different growing environments might have differently affected the uptake and mobilisation of macroelements, as observed by different plant physiological functioning. Some reports indicate that there was no significant difference in grafted and non-grafted plants for N accumulation [44]. The significant difference in K accumulation in leaves of grafted and non-grafted cucumber was reported [39,45]. However, in our study we could not record any increase in leaf K content due to grafting in both the hybrids, but the K content was significantly higher in both grafted and non-grafted plants of 'Terminator' than those of 'Nefer'. This probably was the result of the intrinsic character of the scion cultivars, suggesting that rootstock and scion (hybrid) characters affect the nutrient accumulation in the leaves of cucumber plants. The highest concentration of macroelements in leaves of grafted plants can also be attributed to the vigorous root system, which might result in better uptake of water and minerals [46,47]. Hence, the highest content of macroelements in grafted plants resulted in better vegetative dry mass, maintained physiological functioning due to higher chlorophyll content and improved PSII efficiency, which further resulted in higher fruit yield.

The effect of structures was pronounced for microelements, whereas in the case of grafting it was significant only for Cu content. The Cu and Mn accumulation and utilisation might be better in NVP, whereas the content of Zn and Fe was lower, probably due to their translocation to the fruits. In grafting, only Cu content in leaves showed a significant difference, where it was the highest in non-grafted 'Nefer', which reveals that non-grafted plants were not able to effectively translocate it to sink from source. There are reports which indicate that grafting could not change microelements such as Zn in cucumber leaves [2,44]. Further, the availability of microelements may also change depending on scion characteristics, as well as the environmental conditions [47,48]. Similarly, this was observed in the structures which had different microclimate and graft combinations in our study.

5. Conclusions

Growth and production differ for single- and cluster-fruit-bearing cucumber hybrids. Grafted plants were more productive than their non-grafted counterparts, though in terms of improvement in yield, grafting response was more conspicuous for the single-fruit-bearing hybrid 'Nefer'. Grafting caused yield increment, which was higher in grafted

'Nefer' than 'Terminator', whereas the overall yield was recorded as being the highest in grafted 'Terminator'. The seed cost of the cluster-fruit-bearing hybrid was equivalent to the cost of grafted seedlings of single-fruit-bearing hybrid 'Nefer'. Hence, besides obtaining a similar yield to normal cucumber, growers can achieve additional benefit of using grafted 'Nefer' for soil-borne disease resistance characteristically offered by the 'NS-55' rootstock. However, the fruit quality is to be compromised to some extent due to the reduction in luminosity. The grafted plants were very efficient in water and nutrient acquisition and utilisation, due to their vigorous root system that helped to maintain a proper plant water status. Thus, the yield increment can be enhanced in both single-fruit-bearing commercial hybrid 'Nefer' and cluster-fruit-bearing hybrid 'Terminator' by grafting to a greater extent if they are grown in a naturally ventilated polyhouse rather than in net houses to take advantage of the synergistic effect of microclimate as well as grafting in cucumber.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11081604/s1>: Figure S1: Single-(Nefer—left) and multiple-fruit (Terminator—right)-bearing cucumber hybrids.

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