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Optimizing sweet pepper (*Capsicum annuum*) productivity and phytonutrient quality using photo selective shade nets under protected cultivation in Bangladesh

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Abstract

An experiment was conducted on sweet pepper (*Capsicum annuum* L.) at the Horticulture Farm of Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, during October 2019–April 2020 in a two-factor randomized complete block design with three replications. Factor A comprised three net environments: white net (CN, control net environment), green net (GN, 25% shade) and black net (BN, 40% shade). Factor B comprised three cultivars: F_1 hybrid 'Lalima' (R), 'Peperone Yolo Wonder' (G) and 'BARI Mistimorich 2' (Y). Thirty-day old seedlings were transplanted into 10 L polyethylene bags filled with a substrate mixture of soil, vermicompost, coco dust and mushroom compost in a 20:50:20:10 (v/v) ratio and placed inside walk in tunnels. Microclimate, growth, flowering, yield and fruit quality attributes were recorded and analyzed by analysis of variance, and treatment means were separated by LSD at $P \leq 0.05$. Net environment significantly affected plant growth, flowering, yield and fruit quality. GN produced the highest plant height, leaf number and leaf area, while BN resulted in inferior growth. Flowering was earliest and most profuse under GN, particularly in 'Lalima'. The GN × 'Lalima' combination recorded the highest fruit yield (34.52 t ha^{-1}). CN maintained the highest total soluble solids and vitamin C, whereas GN enhanced antioxidant activity and anthocyanin concentration. The results indicate that a moderate shade environment created by the green net improved sweet pepper performance under protected cultivation in Bangladesh.

Key words: Antioxidant activity, Colour shade net, Protected cultivation, Yield, Phytonutrient quality

Sweet pepper (*Capsicum annuum* var. *grossum* L., Solanaceae) is an economically important vegetable crop cultivated widely for its attractive fruit colour, flavour, nutritional value and market demand. The genus *Capsicum* includes about 20 species, of which five are domesticated and widely recognized, namely *C. annuum, C. frutescens, C. chinense, C. baccatum* and *C. pubescens* (Farris, 1988). Among these, *C. annuum* comprises a broad range of sweet and hot pepper types adapted to different agroclimatic conditions and consumer preferences. In Bangladesh, sweet pepper is commonly known as Capsicum and is still considered a minor vegetable crop, although its cultivation and consumption have been increasing, especially in urban and peri-urban markets (Hasanuzzaman, 1999; Paul, 2009). Recent work in Bangladesh has shown that protected structures such as net and net + polythene tunnels can improve growth, yield and profitability of sweet pepper compared with open-field cultivation, indicating considerable scope for expanding commercial production under controlled environments (Saha and Salam, 2004; Paul, 2009; Medany *et al.,* 2008; Ahmed *et al.*, 2016).

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Despite its economic potential, sweet pepper is highly sensitive to environmental stresses, particularly high temperature and excessive solar radiation (Rylski and Spigelman, 1982; Bhatt *et al.,* 1992). Optimum temperature for growth and fruit set generally lies within a moderate range, whereas exposure to supra-optimal temperatures, especially high night temperature, can reduce pollen viability, impair fruit set and increase flower abscission (Rylski and Spigelman, 1982; Díaz-Pérez, 2014). Under Bangladesh conditions, high temperature, intense solar radiation, erratic humidity and pest pressure often constrain successful sweet pepper production, leading to poor fruit set, reduced yield and lower fruit quality.

Protected cultivation using shade nets or net houses has emerged as an effective strategy to regulate crop microclimate and improve crop performance under stress-prone environments (Shahak, 2008; Arthurs *et al.*, 2013). Photo-selective shade nets are particularly important because they not only reduce incident radiation but also alter the spectral composition and diffusion of light reaching the crop canopy. These changes can influence canopy temperature, leaf physiology, transpiration, flowering behaviour, fruit set and the accumulation of pigments and bioactive compounds in fruits (Iglesias and Alegre, 2006; Shahak, 2014; Ilic *et al.*, 2017). In addition, shade nets provide partial protection against wind, hail, birds and some insect-borne viral diseases, thereby contributing to more stable production (Shahak, 2008; Fallik *et al.*, 2009; Goren *et al.*, 2011).

A growing body of research has demonstrated that coloured or photo-selective nets can significantly affect yield and fruit quality of sweet pepper. Ilic *et al.* (2017) reported that coloured shade nets modified fruit structure, total soluble solids (TSS), vitamin C content and total yield of sweet pepper, with pearl and red nets creating favourable growing conditions under high-radiation environments. In Mediterranean and semi-arid regions, moderate shade levels improved plant water status, fruit yield and marketable quality of bell pepper compared with unshaded conditions (Díaz-Pérez, 2014; López-Marín *et al.,* 2012). Postharvest studies have further indicated that coloured nets such as pearl and yellow can reduce decay incidence and help maintain pepper quality during storage and shelf- life (Fallik *et al.*, 2009; Goren *et al.*, 2011; Selahle *et al.*, 2015). These findings suggest that both shade intensity and spectral properties of netting are important in determining crop response.

The response of sweet pepper to shade-net environments, however, is highly dependent on cultivar, season, local climate and net characteristics (Mashabela *et al.*, 2015; Milenković *et al.,* 2012). Information generated in Mediterranean or arid regions cannot be directly extrapolated to the humid subtropical conditions of Bangladesh, where temperature, humidity and radiation dynamics differ considerably. Although protected cultivation of sweet pepper is gaining interest in Bangladesh, location-specific information on the use of photo-selective shade nets for improving growth, yield and fruit quality remains limited. This gap justifies further evaluation of net environments under local production systems.Therefore, study was undertaken to evaluate the effects of different photo-selective shade net environments on growth, flowering, yield and fruit quality of sweet pepper under protected cultivation.

MATERIALS AND METHODS

The experiment was conducted at the Horticulture Farm of Sher-e-Bangla Agricultural University (SAU), Dhaka 1207, Bangladesh (23°74′ N, 90°35′ E; AEZ-28, Modhupur Tract) during October 2019 to April 2020. The soil was analyzed prior to transplanting at the SRDI Farmgate Laboratory, Dhaka. Treatments were laid out in a randomized complete block design with three replications in walk-in-tunnel structures (1.8 m × 3.0 m × 1.5 m). In the experiment, three separate coloured net houses were constructed, and each replication contained 27 plants, giving a total of 81 experimental plants. The experiment followed a two-factor factorial arrangement: Factor A consisted of three photo-selective shade nets—white net (CN, control net environment), green net (GN, 25% shade) and black net (BN, 40% shade) as specified by the manufacturer—while Factor B comprised three sweet pepper cultivars: F_1 hybrid ‘Lalima’ (R), ‘Peperone Yolo Wonder’ (G) and ‘BARI Mistimorich 2’ (Y).

Thirty-day-old seedlings were transplanted into cylindrical polyethylene grow bags of approximately 12 L capacity (25 cm diameter × 25 cm height). Each bag was filled with a pulverized substrate mixture of soil, vermicompost, coco dust and mushroom compost in a 20:50:20:10 (v/v) ratio and placed inside the corresponding tunnel under its designated shade net. Standard intercultural practices, including irrigation, staking, pruning and plant protection measures, were applied uniformly to all treatments in accordance with local recommendations for sweet pepper cultivation. Microclimate parameters inside the tunnels, including air temperature, relative humidity, UV irradiance, solar radiation, soil temperature and soil moisture, were recorded daily at 12:00 h. Temperature (°C) and relative humidity (%) were measured with a digital thermo-hygrometer; UV irradiance (mW cm^{-2}) with a UV light meter (SP-82UV, Lutron, USA); solar radiation (W m^{-2}) with a solarimeter (TM-201L, TENMARS Electronics Co. Ltd., Taiwan); soil temperature (°C) with a soil thermometer (HI145, Hanna Instruments, Romania); and soil moisture (%) with a portable soil moisture meter. Monthly means for each parameter were computed for the different shade nets and, where relevant, for shade net × cultivar combinations.

Growth, flowering and yield data were recorded from five randomly selected central plants per treatment in each replication, excluding border plants. Recorded growth parameters were plant height (cm), number of leaves $plant^{-1}$ and leaf area (cm^2). Reproductive and yield attributes included days to first flowering, days to 50% flowering, number of flowers $plant^{-1}$, number of fruits $plant^{-1}$, fruit length (cm), fruit diameter (cm), individual fruit weight (g), fruit yield $plant^{-1}$ (g) and total yield (t ha^{-1}). Harvesting of fruits started 80 days after transplanting (DAT) and continued up to the final harvest based on marketable fruit size and colour. Fruits were harvested manually in the morning by hand picking with an upward twist, leaving the fruit stalk attached. For fruit quality analysis, three market-mature fruits were randomly harvested from the sampled plants in each treatment per replication and pooled to form a composite sample for TSS, vitamin C, colour, antioxidant activity and anthocyanin determinations. TSS (°Brix) was measured in fruit juice using a digital refractometer. Vitamin C content was determined by the 2,4-dinitrophenylhydrazine (DNPH) colorimetric method after extraction in acidified solution and expressed as mg ascorbic acid 100 g^{-1} fresh weight (Hamner *et al.,* 1945). Fruit surface colour attributes (L*, a*, b*) were measured at two opposite equatorial positions on each fruit using a portable colour meter (3nh Technology Co., Ltd, China); Chroma was calculated. Antioxidant activity of methanolic extracts was evaluated using the DPPH radical scavenging assay and expressed as percentage inhibition of DPPH. Total monomeric anthocyanin content was determined by the pH-differential spectrophotometric method and expressed as mg cyanidin-3-glucoside equivalents 100 g^{-1} fresh weight.

All data were analyzed using Statistix 10 software. Analysis of variance appropriate for the factorial RCBD was performed, and treatment means were separated using the least significant difference (LSD) test at P ≤ 0.05.

RESULTS AND DISCUSSION

Shade nets significantly altered the microclimate inside the tunnels, particularly air temperature, relative humidity and radiation. Maximum midday air temperature was generally highest under the white net (CN) and lowest under the black net (BN), whereas relative humidity showed the reverse trend. Solar radiation and UV irradiance were substantially reduced with increasing shade density, being greatest under CN and least under BN. Soil moisture was higher under shaded conditions, especially with greater shade intensity, indicating improved water conservation (Figs 1 and 2). These findings agree with earlier reports that photo-selective nets can reduce canopy temperature, increase relative humidity and decrease incident radiation, thereby creating a more favourable microclimate for horticultural crops (Ahmed *et al*., 2016; Arthurs *et al*., 2013; Shahak, 2008).The observed patterns support the interpretation that treatment response reflects a combined effect of net colour and shade intensity. Therefore, responses are discussed in terms of net environments or shade-net treatments rather than colour alone, except where spectral effects are specifically addressed.

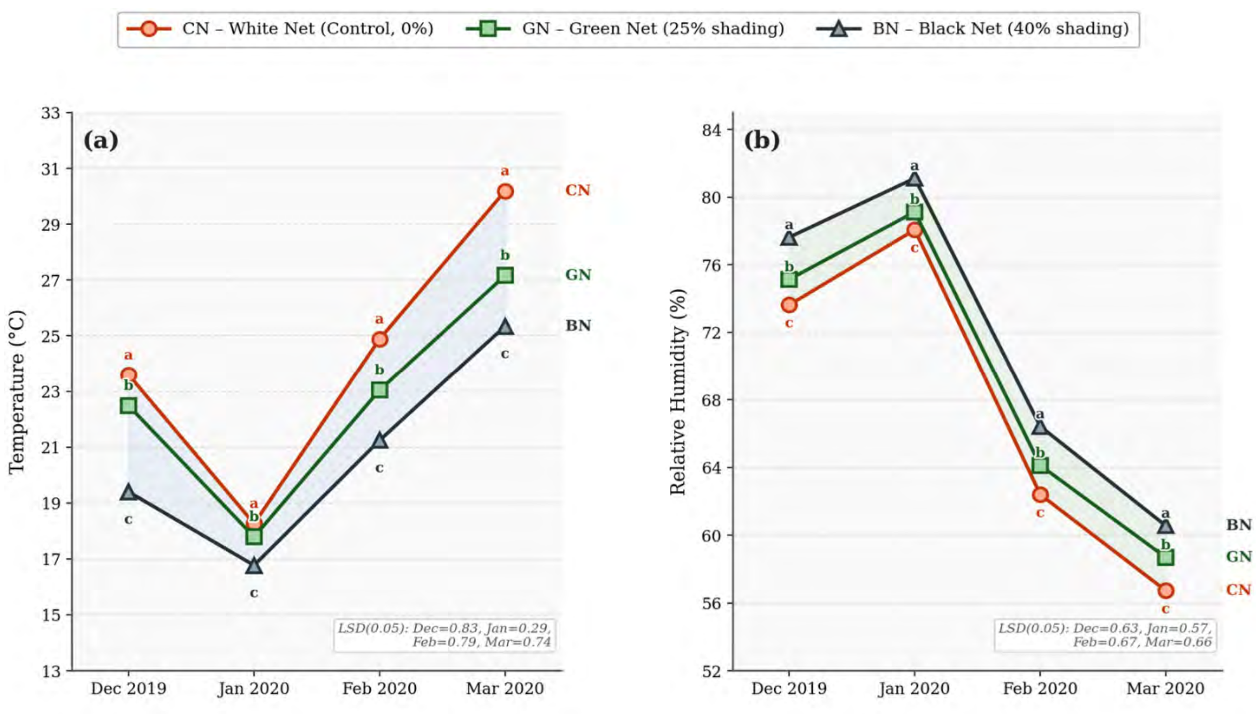


Fig. 1 : Mean (a) temperature (°C) (b) relative humidity (%) recorded at 12.00 noon under different color shade nets. Significance letters beside markers indicate LSD comparisons within each month (P ≤ 0.05.). CN – White net (control); GN – Green net (25%); BN – Black net (40%). Within a column, means with the same letter(s) do not differ significantly at P ≤ 0.05.

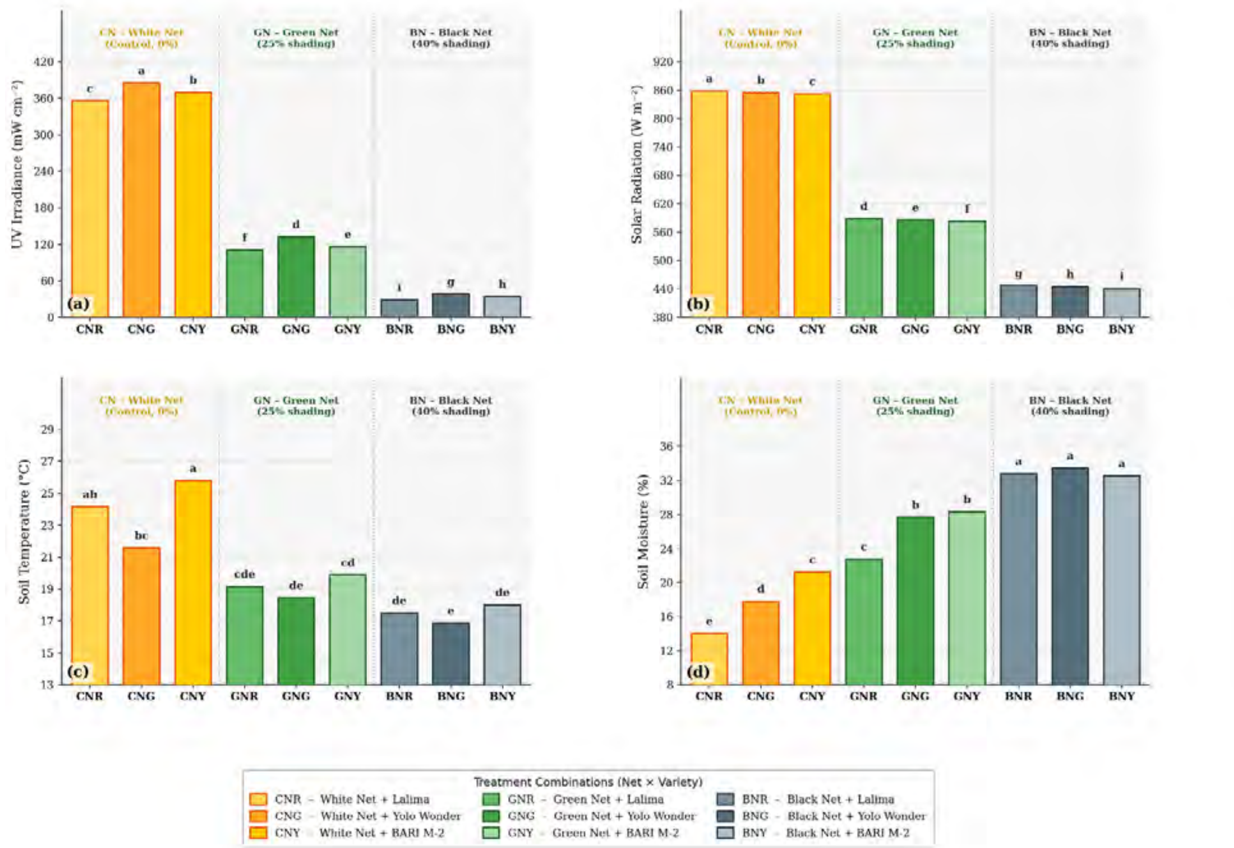


Fig. 2 : Fig. 2: (a) UV irradiance (mW cm^{-2}), (b) solar radiation (W m^{-2}), (c) soil temperature (°C), and (d) soil moisture (%) under different shade nets and varieties. CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Growth attributes of sweet pepper were significantly influenced by shade net, cultivar and their interaction. Among the shade nets, GN produced the tallest plants, highest leaf number and greatest leaf area, whereas BN recorded the lowest values. The GNR combination (green net × 'Lalima') achieved the maximum plant height (75.17 cm), leaf number (54.83 $plant^{-1}$) and leaf area (305.33 cm^2), while BNG (black net × 'Peperone Yolo Wonder') consistently produced the poorest growth (Table 1). Enhanced vegetative growth under GN may be attributed to improved diffusion of photosynthetically active radiation and moderated temperature, which together favour canopy development compared with the high-radiation control (CN) or heavily shaded BN environment. Similar promotive effects of coloured shade nets on vegetative growth have been reported in other crops where light scattering and altered spectral composition increased light interception and photosynthesis (Nissim-Levi *et al.*, 2008; Appling, 2012; Milenković *et al.,* 2012).

Shade nets and cultivars significantly influenced fruit quality traits. TSS was highest under CN (9.08%) and in the CNR combination (10.23%), with values declining as shade intensity increased and reaching a minimum under BNG (3.80%). This inverse relationship between shading and TSS has been documented for sweet pepper and other horticultural crops, reflecting reduced sugar accumulation under lower light (Rylski and Spigelman, 1986; Díaz-Pérez, 2014). Colourimetric analysis indicated that GNR fruits exhibited the greatest redness (a*), whereas GNY (green net × 'BARI Mistimorich 2') recorded the highest lightness (L*) and yellow chromaticity (b* and Chroma), while BNR showed the lowest L* values (Table 2). These patterns suggest that green nets favour the accumulation of carotenoids and anthocyanins in red-fruited cultivars, in line with previous observations on the influence of modified light quality on pigment biosynthesis (Zhang *et al.*, 2014; Ilic *et al.*, 2017).

Table 1. Effect of color shade nets and varieties on growth parameters

Treatment	Plant height (cm)	Leaf number plant^{-1}	Leaf area (cm^2)	Days to 1st flower	Days to 50% flower	Flowers plant^{-1}
Effect of color nets						
CN	66.50 b	41.89 b	213.39 b	56.00 b	91.44 b	12.33 b
GN	73.89 a	50.01 a	270.42 a	46.22 c	82.11 c	15.33 a
BN	52.50 c	32.78 c	109.17 c	83.56 a	118.00 a	9.67 c
LSD0.05	0.76	0.99	19.06	1.31	1.17	0.89
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15
Effect of varieties						
R	65.50 a	44.89 a	227.28 a	59.89 c	95.44 c	13.78 a
G	63.11 c	38.46 c	171.78 c	64.22 a	99.11 a	11.00 c
Y	64.28 b	41.33 b	193.92 b	61.67 b	97.00 b	12.56 b
LSD0.05	0.76	0.99	19.06	1.31	1.17	0.89
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15
Combined effect						
CNR	67.50 c	44.67 c	249.17 bc	54.00 d	89.67 d	13.33 c
CNG	65.50 d	38.52 e	194.33 d	58.00 c	93.33 c	11.00 d
CNY	66.50 cd	42.50 d	196.67 d	56.00 cd	91.33 cd	12.67 c
GNR	75.17 a	54.83 a	305.33 a	44.67 f	80.67 f	17.00 a
GNG	72.67 b	46.35 c	232.33 c	48.00 e	83.67 e	14.00 bc
GNY	73.83 b	48.83 b	273.59 ab	46.00 ef	82.00 ef	15.00 b
BNR	53.83 e	35.17 f	127.33 e	81.00 b	116.00 b	11.00 d
BNG	51.17 g	30.50 h	88.67 f	86.67 a	120.33 a	8.00 e
BNY	52.50 f	32.67 g	111.50 ef	83.00 b	117.67 b	10.00 d
LSD0.05	1.32	1.71	33.02	2.27	2.03	1.54
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid ‘Lalima’; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Table 2. Effect of color shade nets and varieties on yield parameters and total soluble solids

Treatment	Fruits plant^{-1}	Fruit length (cm)	Fruit diam. (cm)	Fruit wt. (g)	Yield plant^{-1} (g)	Yield (t ha^{-1})	TSS (%)
Effect of color nets							
CN	4.36 b	6.64 b	5.40 b	47.97 b	209.37 b	22.76 b	9.08 a
GN	5.51 a	8.55 a	6.92 a	50.39 a	278.11 a	30.23 a	7.14 b
BN	3.22 c	5.70 c	4.67 c	46.34 c	149.62 c	16.26 c	5.01 c
LSD0.05	0.34	0.33	0.08	0.44	16.83	1.83	0.29
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13
Effect of varieties							
R	4.86 a	7.64 a	6.00 a	49.08 a	240.48 a	26.14 a	7.98 a
G	3.95 c	6.30 c	5.37 c	47.29 c	188.54 c	20.49 c	6.22 c
Y	4.28 b	6.95 b	5.62 b	48.33 b	208.08 b	22.62 b	7.03 b
LSD0.05	0.34	0.33	0.08	0.74	16.83	1.83	0.29
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13
Combined effect							
CNR	4.75 bc	7.13 cd	5.70 d	48.58 cd	230.85 cd	25.09 cd	10.23 a
CNG	4.08 d	6.20 ef	5.10 f	47.33 ef	193.25 ef	21.01 ef	8.23 c
CNY	4.25 cd	6.60 de	5.40 e	48.00 de	203.99 de	22.17 de	8.77 b
GNR	6.17 a	9.88 a	7.40 a	51.50 a	317.58 a	34.52 a	7.60 d
GNG	5.12 b	7.23 c	6.57 c	49.17 c	251.59 bc	27.35 bc	6.63 e
GNY	5.15 b	8.53 b	6.80 b	50.50 b	265.17 b	28.82 b	7.20 d
BNR	3.67 de	5.90 fg	4.90 g	47.17 fg	173.00 fg	18.80 fg	6.10 f
BNG	2.67 f	5.47 g	4.43 i	45.37 h	120.77 h	13.13 h	3.80 h
BNY	3.33 e	5.73 fg	4.67 h	46.50 g	155.08 g	16.86 g	5.13 g
LSD0.05	0.59	0.56	0.14	0.76	29.15	3.17	0.50
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid ‘Lalima’; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

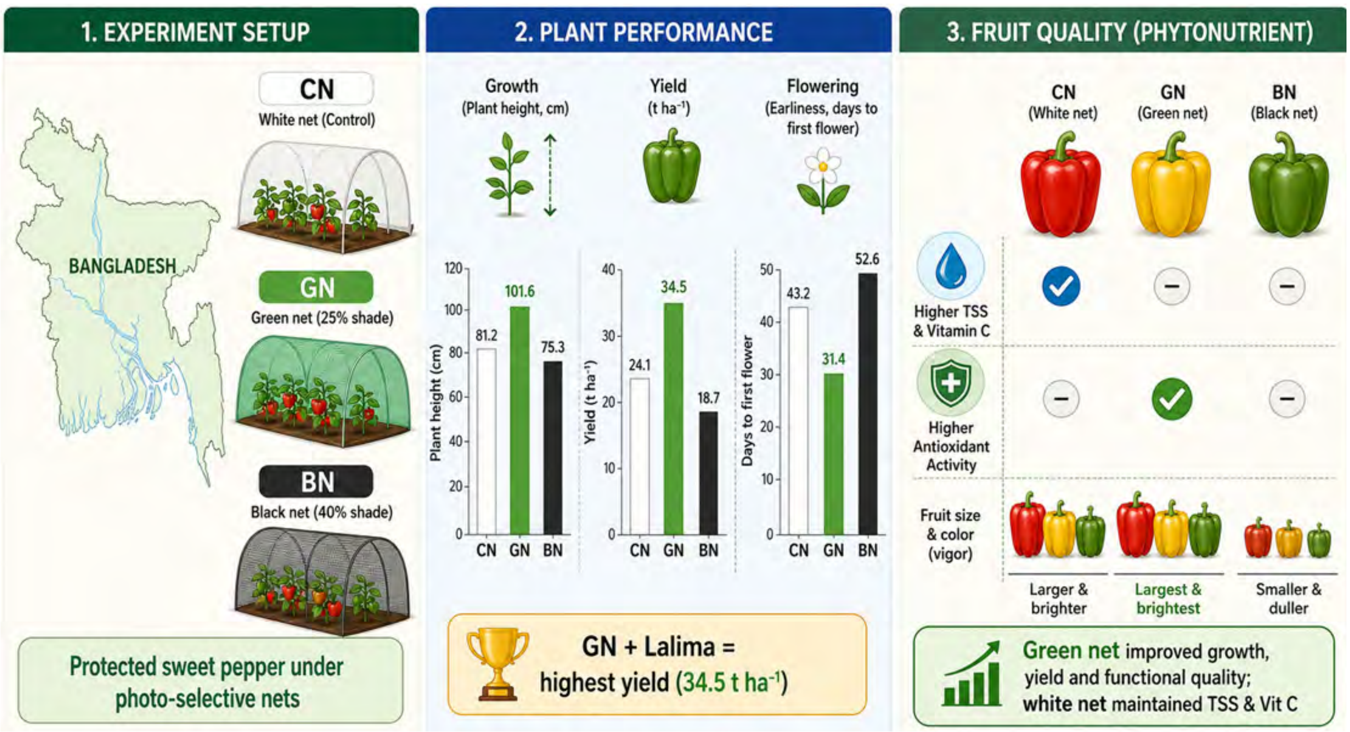
Vitamin C content was highest under CN and in the CNG combination and lowest in BNY, indicating that ascorbic acid biosynthesis benefited from higher light intensity, consistent with earlier findings in tomato and pepper (Hamner *et al.*, 1945; Mashabela *et al.*, 2015). In contrast, antioxidant activity and anthocyanin concentration were greatest under GN (78.80%; 7.71 mg 100 g^{-1} FW) and in GNR (81.16%; 10.47 mg 100 g^{-1} FW), and lowest under BN and BNG (Table 3). The selective enhancement of antioxidant compounds by green nets, despite moderate shading, may reflect wavelength-specific stimulation of flavonoid biosynthetic pathways, conferring improved health-promoting value to fruits harvested from GNR plots (Zhang *et al.,* 2014; Mashabela *et al.,* 2015; Selahle *et al.,* 2015).

Table 3. Effects of different color shade nets on fruit quality parameters of capsicum: fruit colorimetry (L*, a*, b*, Chroma), vitamin C content (mg 100 g^{-1} FW), antioxidant activity (%); and anthocyanin concentration (mg 100 g^{-1} FW).

Treatment	L*	a*	b*	Chroma	Vit. C (mg 100 g^{-1} FW)	Antioxidant (%)	Anthocyanin (mg 100 g^{-1} FW)
CNR	35.83 g	35.17 b	21.03 g	40.98 e	163.17 b	75.82 cd	9.17 b
CNG	38.83 e	7.92 gh	25.15 e	26.37 h	164.50 a	74.37 de	4.97 f
CNY	61.35 b	15.57 e	57.55 b	59.62 b	162.00 b	75.00 d	6.90 d
GNR	37.37 f	37.10 a	21.50 g	42.88 d	157.50 d	81.16 a	10.47 a
GNG	41.06 d	8.51 g	26.80 d	28.12 g	159.30 c	76.75 c	5.40 ef
GNY	63.28 a	17.36 d	69.01 a	71.16 a	156.00 e	78.48 b	7.27 d
BNR	34.57 h	33.06 c	18.63 h	37.96 f	148.83 f	73.43 ef	8.23 c
BNG	37.62 f	7.42 h	23.66 f	24.80 i	149.50 f	71.75 g	4.23 g
BNY	52.86 c	10.55 f	54.73 c	55.76 c	146.63 g	72.63 fg	5.73 e
CV (%)	1.37	3.12	1.06	1.05	0.44	1.12	4.65
LSD(0.05)	1.06	1.05	0.65	0.78	1.20	1.47	0.56

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Harnessing Photo-Selective Color Shade Nets to Improve Flowering, Yield and Postharvest Quality of Capsicum In Protected Cultivation



CONCLUSION

Photo-selective shade nets significantly modified the microclimate, growth, yield and fruit quality of sweet pepper under protected cultivation in Bangladesh. Among the treatments, the green net (25% shading) combined with F_1 hybrid 'Lalima' (GNR) consistently produced superior vegetative growth, earliest and most profuse flowering, highest fruit yield (34.52 t ha^{-1}) and enhanced antioxidant activity and anthocyanin content. White net treatments maintained higher TSS and vitamin C but were inferior to GNR in overall agronomic and biochemical performance. The study demonstrates that moderate green shading together with a suitable red-fruited hybrid is a promising technology package for commercial sweet pepper production in protected environments in Bangladesh and similar subtropical conditions. Validation across seasons and locations is, however, recommended before large-scale adoption.

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Conflict of interest

The authors declare no conflict of interest.

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Author contributions

Conceptualization: A.H.M. Solaiman; Methodology: A.H.M. Solaiman, S.A. Sumona; Investigation: S.A. Sumona; Data curation: S.A. Sumona; Formal analysis: S.A. Sumona; Supervision: A.H.M. Solaiman; Visualization: S.A. Sumona; Writing – original draft: S.A. Sumona; Writing – review and editing: A.H.M. Solaiman. All authors have read and approved the final manuscript.

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