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Effects of Shade Nets on Microclimatic Conditions, Growth, Fruit Yield, and Quality of Eggplant (*Solanum melongena* L.): A Case Study in Carnarvon, Western Australia

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Abstract: Carnarvon has a hot, semi-arid climate with high temperatures and solar radiation during spring–summer, which damages crops and limits the production season for the local vegetable industry. Protective cultivation is one of the promising approaches to mitigate these adverse weather conditions and avoid the resulting damage to vegetable crops. This study, which is part of the protected cropping research program for vegetable crops in Western Australia, was conducted to understand how the shade nets of a protective net house modify the microenvironment affecting the growth, physiology, and fruit yield of eggplants, a model vegetable crop. The eggplant crop was grown under four light regimes, i.e., three shade factors (11%, 21%, 30%) and the open field. There were three replicated blocks under each light regime and four eggplant varieties that were randomized within the replicated blocks. Other experimental conditions, e.g., fertilising, irrigation, pest, and disease management and other cultural practices were identical across light regimes. The results showed that shade nets created different microenvironments inside the net house, with a large variation in the light intensity, affecting photosynthetic-related traits. Eggplants grew taller and bushier and gave higher fruit yield under shade compared to the open field. Overall, our data suggest that the 21% shade net appeared to be the most suitable for growing eggplants during the autumn to early spring period in Carnarvon. The future perspective of protected cropping technology for vegetable crop production in Carnarvon is also discussed.

Keywords: protected cropping; net house; shade factor; semi-arid weather

1. Introduction

Carnarvon is a coastal town located approximately 900 km north of Perth, the capital city of Western Australia. The town hosts one of the key horticultural districts of the state, with approximately 170 plantations covering 2000 hectares of land along the Gascoyne River. The district grows various vegetable crops, such as tomato, capsicum, eggplant, zucchini, and pumpkin, predominantly for the Perth market. Annually, the district produces approximately 22,000 tonnes of vegetables, with a gross value of more than AUD 69 million [1]. Eggplant is an important, widely grown vegetable crop and ranks the fifth in vegetable production worldwide [2]. In Carnarvon, approximately 640 tonnes of eggplant is produced annually with a farm gate value of AUD 5.6 million, placing the crop third in economic importance of the local vegetable industry.

Due to its geographical location, Carnarvon has a hot, semi-arid climate with mild winters, high temperatures, high solar radiation, and strong winds in the spring–summer period. Rainfall and relative humidity (RH) are low throughout the year [3]. These conditions can reduce the yield and quality of eggplants and other vegetables, resulting in a low economic return to growers and an impact on the supply chain [4]. Adequate light is critical for optimum growth of vegetable crops; however, vegetable crops exposed to excessive direct solar radiation might be developmentally suboptimal [5]. Low humidity results in high vapour pressure deficit that can cause leaf water stress, depression of stomatal conductance and photosynthesis, flower drop, and a reduction in the number of fruits per plant, fruit weight, uniformity, and production [6–8]. High temperature and high radiation often cause marks or blemishes on vegetable fruits [9]. Strong, hot winds increase evapotranspiration, inducing moisture stress, retarding crop growth, and causing fruit scarring [10,11].

Using protected cultivation for vegetable production is one of the most appropriate approaches for coping with adverse natural conditions. Protected cropping can be defined as the production of crops in artificial structures with modified growing conditions that can protect them from unfavourable weather conditions and pest invasions [12]. Protected cropping minimizes the risk of vegetable production and increases the economic return to the growers. In Australia, the protected cropping industry was valued at approximately AUD 1.5 billion per annum at the farm gate and was fast-growing, with an annual growth rate of over 60% between 2014–2017 [13]. Protective structures, such as net houses, can modify the light intensity and spectrum to mitigate the adverse effects of excessive sunlight, high temperatures, and wind [14].

Although several growers in Carnarvon use net houses for growing capsicum, eggplant, and other vegetable crops, a thorough understanding of how the system functions is still limited. Some adverse effects of certain shade nets have also been reported, such as reduction of the fruit yield and quality of tomatoes [15]. The microclimatic conditions created by the nets must be evaluated to ensure that they are suitable for certain vegetables. For instance, the degree of shading should be evaluated to match the light levels required for certain vegetable crops; too much or suboptimal light conditions can affect crop production and compromise the initial investment costs of the structure [16].

This study was conducted to (i) understand how shade nets affect microclimatic conditions and (ii) evaluate the effects of the microclimates on the physiological characteristics and productivity of eggplants. The future perspective of protected cropping technology for vegetable crop production in Carnarvon is also discussed.

2. Materials and Methods

2.1. Experimental Conditions

The study was conducted at the Carnarvon Research Station, Department of Primary Industries and Regional Development (24°51′18.00″ S latitude, 113°43′46.33″ E longitude) in 2021. The eggplant experiment was planted on 11 March and completed on 14 September 2021. The trial site was located on red silty loam soil. The shade netting house was a flat roof type and constructed with high-density polyethylene fabrics and treated pine poles by Crop Nets, a local company in Carnarvon, WA. The quad-crossover netting fabric was supplied by the NetPro Group, Australia. The net fabric was used to completely cover the structure on all four sides and the roof. Three types of roof nets, 24 mm White Quad, 20 mm Black Quad, and 12 mm Black Quad, were installed for the shade netting of the house, which resulted in three corresponding shade factors: 11%, 21%, and 30%, respectively.

Four eggplant varieties, namely Fantastic, Monarca, Longo, and Lydia, were kindly provided by Rijk Zwaan seed company (Rijk Zwaan Australia Pty. Ltd., Daylesford, VIC, Australia) and were used in the experiment. Fantastic is a sturdy plant type, suitable for open field production with or without trellising. Monarca is a high-yielding variety, suitable for winter-protected cultivation in greenhouses. Longo is strong variety with good fruit setting under a wide range of conditions and is suitable for greenhouse or trellised field growing conditions. Lydia is a variety suitable for unheated production, performs well in the open field, and has high levels of vigour through winter.

The experiment was conducted in the shade netting house following the designing approach described previously by López-Marín et al. [17] and Mangino el al. [18]. In brief, eggplants were grown under four growing environments, i.e., three shade factors and the open field (OF) as the control. The experiment was an RCBD under each growing environment. There were three replicated blocks (I, II, and III), and four varieties were randomized within the replicated blocks three times (Supplementary Figure S1). Before planting, growth beds 60 cm wide and 10 cm high were formed, spaced 2 m apart. Polyethylene mulch and drip irrigation tape were laid when the beds were formed. Individual experimental blocks were overlaid on the growth beds. Ten one-month-old eggplant seedlings of individual varieties were planted on an experimental plot 6 m long on the growth beds with 60 cm spacing to achieve the final density of 6410 plants per hectare.

The fertilizing program of the eggplant experiment is detailed in Table S1. Urea, monoammonium phosphate, super copper-zinc molybdenum, potassium sulphate, potassium nitrate, magnesium nitrate, and calcium nitrate were applied to supply the following amounts of nutrients: 271 kg nitrogen, 97 kg phosphorus, 328 kg potassium, 37 kg magnesium, 429 kg calcium, 2.1 kg copper, 0.21 kg molybdenum, 7.75 kg manganese, 9.3 kg zinc. The basal fertilization was applied before laying the plastic mulch, and the weekly fertigation began two weeks after planting. Pruning and training plants to the trellis were carried out fortnightly from three weeks after the planting, following the standard practices in the region. Pests and diseases were monitored weekly and controlled by using appropriate chemicals.

2.2. Installation of Temperature, Humidity, and Light Sensors

A micro weather station Watchdog model 1450 from Spectrum Technologies, Inc. (distributed by John Morris Group, Bentley, WA, Australia) was installed. The weather station includes a built-in temperature and relative humidity sensors. An external quantum light sensor to measure photosynthetically active radiation (PAR) was also installed. All measurements were automatically logged every 15 min. These records were downloaded monthly and used to calculate daily light integral (DLI), daily mean temperature, and daily mean relative humidity (RH). The DLI was calculated by multiplying PAR received during the day with a conversion factor, i.e., 0.0864 as described elsewhere [19,20]

2.3. Measurements of Leaf Chlorophyll Content and Chlorophyll Fluorescence

To understand the effects of the microclimate beneath the nets, several handheld instruments were used to measure photosynthetic-related traits of the eggplant varieties under different growing conditions, i.e., leaf chlorophyll content and chlorophyll fluorescence. Chlorophyll levels were estimated with a portable SPAD meter (SPAD—502 Plus; Spectrum Technologies Inc., Aurora, IL, USA) following the procedure described in Nguyen et al., [21]. The second-youngest mature leaves of the six representative plants per plot at the mid- (27 July) and late growing season (8 September) were selected for the measurement. The readings taken by the SPAD meter (SPAD units) were the chlorophyll levels of the leaves.

The chlorophyll fluorescence parameters of eggplant leaves were determined with a portable chlorophyll fluorometer (Photon Systems Instruments, Drásov, Czech Republic) at the mid- (27 July) and late growing season (26 August). The fully mature second-youngest leaves from three plants per plot were chosen for the measurements. The leaves were dark-acclimated 30 min before the chlorophyll fluorescence was taken. The Chlorophyll Fluorescence Induction Kinetics (OJIP) protocol was applied as described by Strasser et al. [22]. The chlorophyll fluorescence transients recorded upon the transition from a dark to a saturating light were used to determine the maximum quantum efficiency of photosystem II (PSII) photochemistry, i.e., the Fv/Fm ratio, where Fv and Fm are the variable and maximum fluorescence intensity taken from the dark-adapted leaves, respectively [23].

2.4. Plant Height Measurement

The height of eggplants was determined just before the experiment was terminated. Five plants per experimental plot were randomly selected for the measurement. The height was measured from above the ground to the topmost terminus of the plant.

2.5. Marketable Fruit Number and Yield

Mature fruits of six representative eggplants per plot were harvested at 10–14 day intervals. Fruits of reasonably good size, similar to market standards, and free from marks and insect bites were graded as marketable; the remaining were classified as non-marketable (Figure 1). The number, average fruit weight, and weight of marketable fruits were determined. Total fruit weights from multiple harvests were used to calculate the fruit yield per hectare.

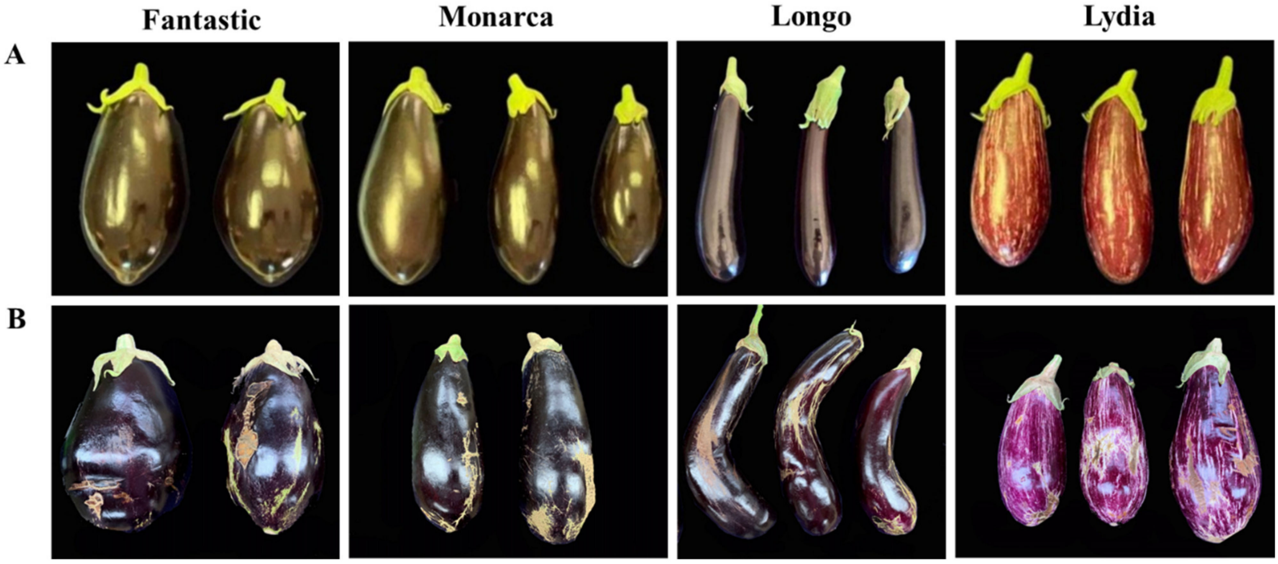

Figure 1. Fruit classification of four eggplant varieties. (**A**) Marketable grade fruits; (**B**) reject fruits.

2.6. Total Soluble Solids and pH Measurements

The juice was extracted from five representative eggplant fruits per plot by a juice extractor. The total soluble solids (°Brix) were measured from fruit juice using a digital refractometer Atago RP-1 (Atago Co., Ltd., Fukaya-shi, Japan). The pH of the fruit juice was determined by using a digital pH meter (smartCHEM—Titro, TPS Pty Ltd., Brendale, QLD, Australia).

2.7. Statistical Analyses

The data analysis approach followed the procedure described by the previous studies for horticultural crops grown under different growing environments [17,18]. In brief, Two-way Analysis of Variance (ANOVA) was performed to analyse shade factor effects, varietal effects, and their interaction by using GENSTAT statistical software version 21 (VSN International Ltd., Hemel Hempstead, UK). The blocking structure was specified in such a way that the shading main effect was assessed based on the replicate means within the shading blocks. While there was only one area of each shading treatment, this data analysis was considered a reasonable approach given the close proximity of the shaded treatments (Supplementary Figure S1), and later examination of the spatial variability in marketable yield within each shading block gave no indication of large spatial trends at the site. Means were compared at 5% probability according to a least significant difference (l.s.d) test.

3. Results

3.1. Effects of Shade Nets on the Microclimate

The eggplant experiment was grown from autumn to early spring, the common season for the crop in the Carnarvon region. The weather conditions varied considerably throughout the trial period. Shade nets created different microenvironments inside the net house compared to the OF control, with a significant difference in mean DLI (Figure 2A). The PAR is the solar radiation with a wavelength between 400 to 700 nm that plants use for their photosynthetic process. The DLI is a function of PAR intensity per day and is expressed as moles of light per square meter per day. In this experiment, the OF control had the highest mean DLI. The DLI levels were lower for the shade net groups; the higher the shade factor, the lower the DLI level. In comparison to the OF control, on average, there was approximately 12.6%, 22.6%, and 30.8% DLI reduction for 11%, 21%, and 30% shade factor, respectively. During the experiment, the light levels gradually declined from March, were lowest in the winter months between June–July, and increased from August.

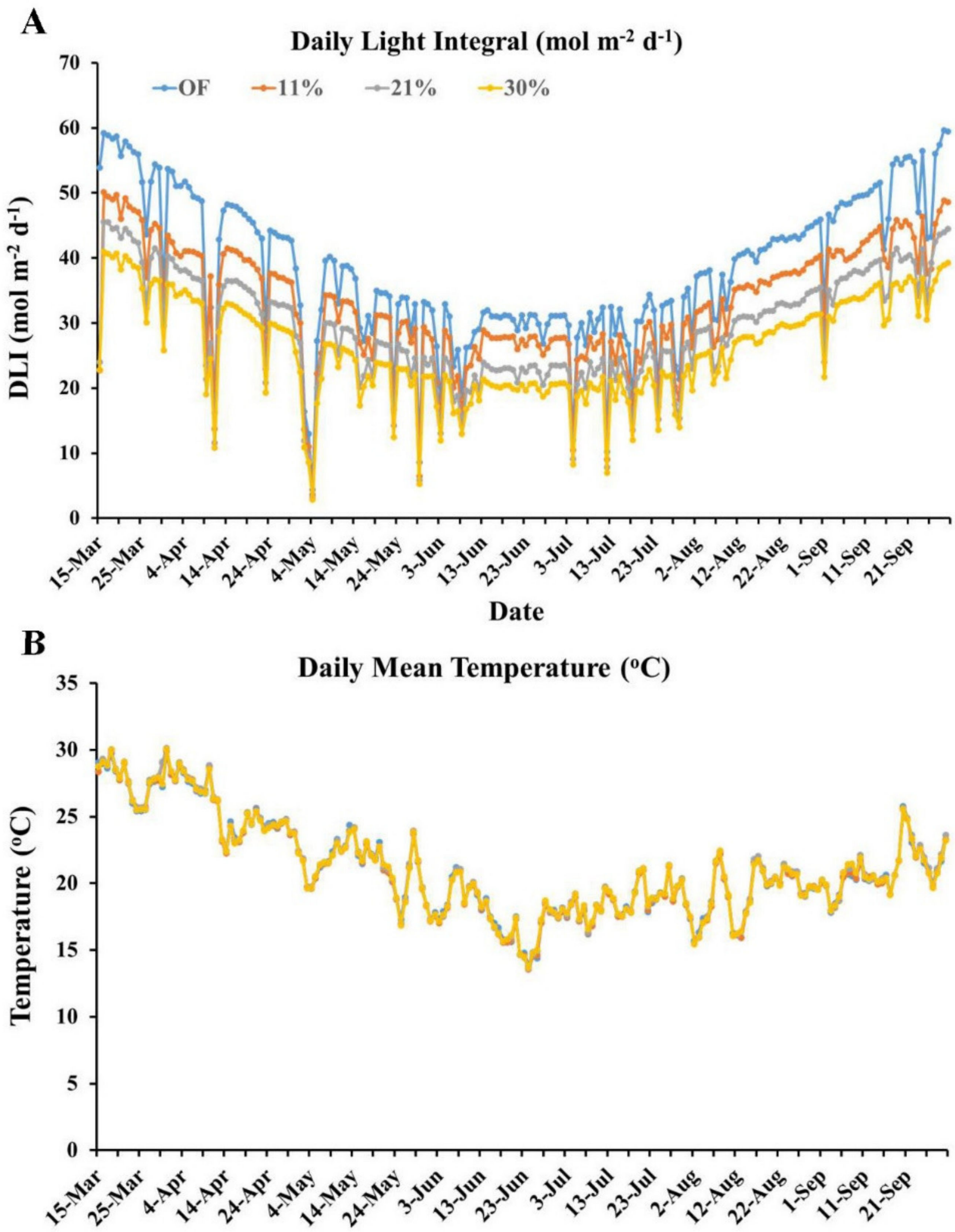

Figure 2. *Cont.*

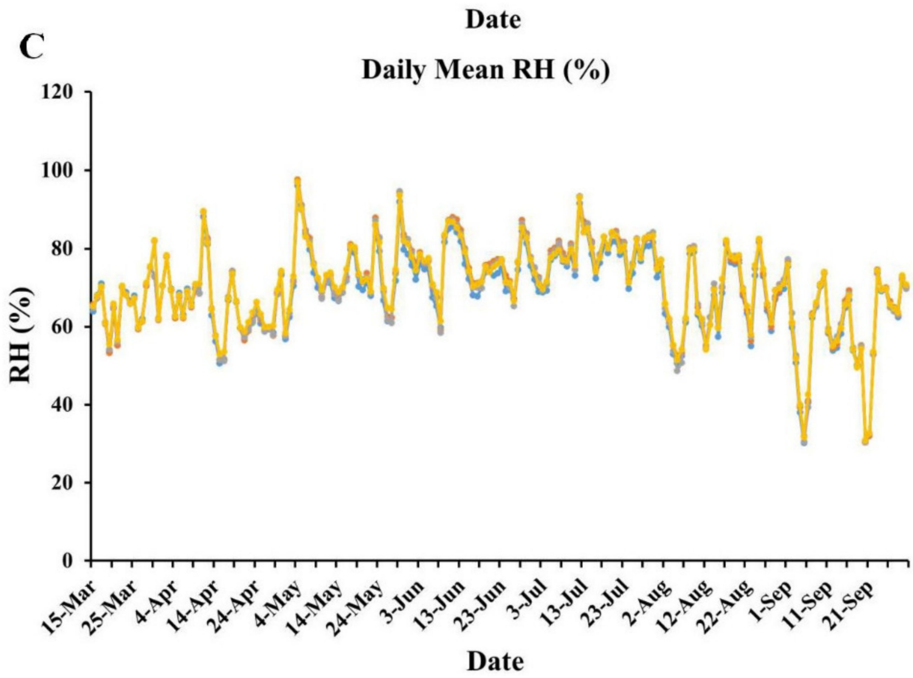

Figure 2. Effect of different shade nets on the inside microclimates. (**A**) Daily light integral (DLI) under 11%, 21%, and 30% shade nets and open field (OF); (**B**) daily mean temperature; (**C**) daily mean relative humidity (RH).

In contrast to the light levels, daily mean temperatures and RH were similar between shade nets and OF (Figure 2B,C). The RH was highest from May to July, which coincided with the winter season in Carnarvon.

3.2. Shade Nets Affected Photosynthetic Parameters

Environmental conditions have a huge impact on crop growth and production of horticultural crops. The results showed that eggplants grown under the shade nets had lower chlorophyll content, as indicated by lower SPAD units. However, this difference in chlorophyll content between the shade nets and OF was only statistically significant in the late growing season (Table 1A; $p = 0.005$) in contrast to the mid-season. In the late growing season, eggplants grown in the OF had the highest average SPAD value (63.3), while those under 30% shade had the lowest SPAD value (56.6). On average, there was approximately a 7.0%, 5.7%, and 10.6% reduction in SPAD value for 11%, 21%, and 30% shade factor, respectively. Among the varieties, Lydia had the highest mean SPAD value (61.4), whereas Fantastic, Longo, and Monarca had similar mean SPAD values.

The Fv/Fm ratio (an indicator of the maximum quantum yield of PSII photochemistry) of eggplants grown in the shade was lower than those grown in the OF in the mid-growing season (Table 1B; $p = 0.02$). On average, there was a 2.1% reduction in Fv/Fm under 11% shade factor, whereas it was a 4.2% and 3.6% reduction in Fv/Fm under 21% and 30% shade factor, respectively. However, the maximum quantum yields were not significantly different between shade treatments in the late growing season. Interestingly, the seasonal timing of differences in the chlorophyll fluorescence was opposite to that observed with chlorophyll content.

Table 1. Photosynthetic-related traits of eggplant leaves during the mid- and late growing season. (**A**) Chlorophyll content as indirectly represented by SPAD units; (**B**) maximum quantum yield of primary PSII photochemistry (*Fv*/*Fm*) measured by chlorophyll fluorescence under 11%, 21%, and 30% shade nets and open field (OF). Means of the main effects in the same row (or column) that include a common letter are not significantly different at 5%. The *p* values indicate the statistical significance at 5%; s.e.d, standard error difference of the means; l.s.d, least significant difference at 5%.

(A)

Variety	**SPAD-Mid-Season**					**SPAD-Late Season**				
	OF	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***
Fantastic	56.9	54.0	52.8	53.5	54.3 ^{a}	61.4	58.2	59.4	54.7	58.4 ^{a}
Longo	54.9	54.6	57.6	56.6	55.9 ^{ab}	62.5	58.0	59.0	55.9	58.9 ^{a}
Lydia	57.9	58.0	57.9	57.8	57.9 ^{b}	63.8	61.4	60.5	60.0	61.4 ^{b}
Monarca	55.2	56.4	53.8	53.2	54.7 ^{a}	65.3	57.9	59.8	55.7	59.7 ^{a}
Mean	56.2 ^{a}	55.7 ^{a}	55.5 ^{a}	55.3 ^{a}		63.3 ^{c}	58.9 ^{ab}	59.7 ^{b}	56.6 ^{a}	
ANOVA	Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety	
s.e.d	0.67	0.97		1.94		1.26	0.82		1.16	
p	0.575	0.005		0.346		0.005	0.006		0.386	
l.s.d (*p* = 0.05)	-	2.00		-		2.91	1.69		-	

(B)

Variety	***Fv*/*Fm*-Mid-Season**					***Fv*/*Fm*-Late Season**				
	OF	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***
Fantastic	0.81	0.79	0.77	0.79	0.79 ^{a}	0.79	0.80	0.72	0.74	0.76 ^{a}
Longo	0.80	0.79	0.77	0.77	0.78 ^{a}	0.79	0.81	0.80	0.83	0.81 ^{a}
Lydia	0.81	0.80	0.80	0.79	0.80 ^{a}	0.71	0.78	0.72	0.81	0.76 ^{a}
Monarca	0.82	0.80	0.77	0.78	0.79 ^{a}	0.82	0.79	0.81	0.83	0.81 ^{a}
Mean	0.81 ^{b}	0.79 ^{ab}	0.78 ^{a}	0.78 ^{a}		0.78 ^{a}	0.80 ^{a}	0.76 ^{a}	0.80 ^{a}	
ANOVA	Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety	
s.e.d	0.01	0.01		0.01		0.04	0.03		0.07	
p	0.021	0.064		0.457		0.694	0.218		0.855	
l.s.d (*p* = 0.05)	0.02	-		-		-	-		-	

3.3. Agronomic and Yield Attributes

Eggplants grew taller and bushier under the shade nets (Figure 3, Table 2; $p < 0.001$). There was no significant interaction between shade and plant, height indicating that the varieties responded in a similar way to the shading treatments. Eggplants grown under shade factors 21% and 30% had similar height (~166.9 cm), whereas eggplants in the 11% shade were significantly shorter (153.6 cm). Eggplants grown in the shade were about 10% to 19.6% taller than those in the OF. On average, Longo was the tallest variety (170.2 cm), followed by Lydia (160.2 cm) and Fantastic (151.9 cm). Monarca was the shortest variety (144.6 cm).

The marketable fruit yields varied significantly between the shade factors and varieties (Table 3; p <0.001). However, there was no significant interaction between shade factors and varieties for the marketable fruit yield. Between treatments, the 21% shade factor had the highest marketable fruit yield (37.3 tonnes ha^{-1}), followed by 30% shade factor (34.8 tonnes ha^{-1}) and 11% shade factor (29.8 tonnes ha^{-1}). On average, there was approximately a 48.4%, 85.7%, and 73.0% increase in marketable fruit yields for eggplants grown under 11%, 21%, and 30% shade factor, respectively. Between varieties, Lydia (36.3 tonnes ha^{-1}) and Fantastic (33.3 tonnes ha^{-1}) significantly outperformed Monarca (28.2 tonnes ha^{-1}), which was significantly higher than Longo (24 tonnes ha^{-1}).

Figure 3. Performance of eggplants under different shades and open field. Eggplants grown under 30% shade and open field (OF).

Table 2. The height of eggplants under 11%, 21%, and 30% shade nets and open field (OF). Means of the main effects in the same row (or column) that include a common letter are not significantly different at 5%. The *p* values indicate the statistical significance at 5%; s.e.d, standard error difference of the means; l.s.d, least significant difference at 5%.

Variety	Plant Height (cm)				
	OF	**11%**	**21%**	**30%**	***Mean***
Fantastic	134.9	149.5	162.5	160.7	151.9^{a}
Longo	156.3	160.3	180.6	183.5	170.2^{c}
Lydia	137.3	157.7	174.2	171.5	160.2^{b}
Monarca	129.7	146.8	150.5	151.6	144.6^{a}
Mean	139.6^{a}	153.6^{b}	166.9^{c}	166.9^{c}	
ANOVA	Shade	Variety		Shade × Variety	
s.e.d	2.5	3.5		7.0	
p	<0.001	<0.001		0.607	
l.s.d (p = 0.05)	5.8	7.2		-	

Table 3. Marketable fruit yields, fruit per plant, and fruit weight under 11%, 21%, and 30% shade nets and open field (OF). Means of the main effects in the same row (or column) that include a common letter are not significantly different at 5%. The *p* values indicate the statistical significance at 5%; s.e.d, standard error difference of the means; l.s.d, least significant difference at 5%.

Variety	Marketable Fruit Yield (t ha^{-1})					Fruits per Plant					Fruit Weight (g)				
	OF	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***
Fantastic	22.8	31.2	40.4	39.0	33.3^{c}	8.0	10.9	12.6	13.6	11.3^{a}	450.3	452.2	499.2	446.9	462.2^{a}
Longo	16.7	23.1	32.9	23.4	24.0^{a}	10.7	13.5	20.0	16.4	15.2^{b}	246.6	266.5	256.4	223.5	248.3^{a}
Lydia	22.2	34.6	42.5	45.9	36.3^{c}	12.9	17.1	21.5	26.0	19.4^{c}	268.1	315.0	308.0	275.5	291.7^{b}
Monarca	18.6	30.2	33.5	30.6	28.2^{b}	7.5	10.3	12.7	12.9	10.8^{a}	384.5	458.0	413.6	372.1	407.1^{c}
Mean	20.1^{a}	29.8^{b}	37.3^{c}	34.8^{d}		9.8^{a}	12.9^{b}	16.7^{c}	17.2^{c}		337.4^{a}	372.9^{b}	369.3^{b}	329.5^{a}	
ANOVA	Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety	
s.e.d	0.8	1.9		3.9		0.5	0.8		1.5		9.3	10.5		21.1	
p	<0.001	<0.001		0.221		<0.001	<0.001		0.011		0.003	<0.001		0.199	
l.s.d (p = 0.05)	1.83	4.01		-		1.09	1.60		3.19		21.40	21.76		-	

The number of marketable fruits per plant significantly differed between treatments and varieties with a significant interaction between the two (Table 3; $p = 0.011$). Despite interactions, all varieties were similar in having fruits per plant significantly higher at 21% and 30% shading compared to OF. Between varieties, Lydia and Longo had the highest and second-highest number of fruits per plant at each shading level, with Lydia significantly higher than Fantastic and Monarca at all shading levels. There was a high correlation between the fruit number per plant and marketable fruit yield (r = 0.7, data table not shown).

The fruit weight significantly varied between shade treatments ($p = 0.003$) and varieties ($p < 0.001$) (Table 3). Shade factors 11% and 21%, which had similar fruit weight, had significantly higher average fruit weight than shade factors 30% and OF, suggesting that a certain level of shade might be required for the optimum fruit weight.

3.4. Quality Traits

Total soluble solids (°Brix) and pH are key quality traits of eggplant fruit [24,25]. In the current study, our data showed that there was no significant difference between shade factors for the total soluble solids and pH measured at the early and the late harvests (Table 4, $p > 0.05$). This might indicate that the shade nets did not affect the quality of eggplant fruit in comparison to the OF control.

Table 4. Quality traits of eggplant fruit at the early and late growing season harvests. (**A**) Brix (%); (**B**) pH under 11%, 21%, and 30% shade nets and open field (OF). Means of the main effects in the same row (or column) that include a common letter are not significantly different at 5%. The *p* values indicate the statistical significance at 5%; s.e.d, standard error difference of the means; l.s.d, least significant difference at 5%.

(A)

Variety	**°Brix—Early Season Harvest**					**°Brix—Late Season Harvest**				
	OF	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***
Fantastic	3.90	3.87	4.03	3.90	3.93 ^{ab}	4.10	4.20	4.20	3.90	4.10 ^{a}
Longo	4.23	4.79	4.30	4.20	4.38 ^{c}	4.90	4.20	4.50	4.50	4.53 ^{b}
Lydia	3.87	3.73	3.80	3.77	3.79 ^{a}	4.40	4.00	3.90	3.60	3.98 ^{a}
Monarca	4.10	4.27	3.83	4.07	4.07 ^{b}	4.30	4.00	4.10	3.70	4.03 ^{a}
Mean	4.03 ^{a}	4.09 ^{a}	3.99 ^{a}	3.98 ^{a}		4.50 ^{a}	4.10 ^{a}	4.20 ^{a}	3.90 ^{a}	
ANOVA	Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety	
s.e.d	0.13	0.07		0.10		0.18	0.09		0.20	
p	0.81	<0.01		0.02		0.10	<0.001		0.07	
l.s.d ($p = 0.05$)	-	0.14		0.29		-	0.18		-	

(B)

Variety	**pH—Early Season Harvest**					**pH—Late Season Harvest**				
	OF	**11%**	**21%**	**30%**	***Mean***	**OF**	**11%**	**21%**	**30%**	***Mean***
Fantastic	5.61	5.58	5.42	5.47	5.52 ^{a}	5.18	5.09	4.92	5.05	5.06 ^{a}
Longo	5.44	5.43	5.55	5.50	5.48 ^{a}	5.29	5.25	5.36	5.26	5.29 ^{b}
Lydia	5.39	5.49	5.49	5.40	5.44 ^{a}	5.07	5.20	5.03	4.98	5.07 ^{a}
Monarca	5.39	5.56	5.41	5.44	5.45 ^{a}	5.27	5.13	5.01	4.97	5.09 ^{a}
Mean	5.46 ^{a}	5.52 ^{a}	5.47 ^{a}	5.45 ^{a}		5.20 ^{a}	5.17 ^{a}	5.08 ^{a}	5.06 ^{a}	
ANOVA	Shade	Variety		Shade × Variety		Shade	Variety		Shade × Variety	
s.e.d	0.07	0.03		0.07		0.06	0.06		0.12	
p	0.725	0.093		0.030		0.200	0.002		0.413	
l.s.d ($p = 0.05$)	-	-		0.14		-	0.12		-	

4. Discussion

4.1. Shade Netting Protected Eggplants from Extreme Light Conditions and Enhanced Crop Growth and Fruit Yield

The overall aim of this study was to provide an insight into the mechanism of shade netting effects on eggplant production under the semi-arid weather conditions in Carnarvon, which is part of the protected cropping research program for vegetable crops in Western Australia [26]. In this manuscript, we have provided evidence demonstrating how the shade nets modified microclimatic conditions that promoted the growth, physiology, and fruit yield of eggplants, a model vegetable crop.

Shade netting is one of the most cost-effective methods for protecting vegetable crops from adverse climatic conditions to ensure better yield and quality. However, the availability of various types of commercial shade nets in the local market requires thorough investigation and understanding before the most suitable netting type can be chosen for a particular vegetable crop [16]. The climatic data collected from this experiment demonstrated that the major difference in the microclimate between shade nets and OF was the light intensity (DLI, Figure 2A). Each vegetable crop requires a certain level of DLI for its optimum growth and production. For instance, the tomato crop requires a DLI higher than 30 mol m^{-2} d^{-1}; capsicum only needs a DLI around 13.9 mol m^{-2} d^{-1} for its maximum productivity [27]; whereas eggplant requires DLI between 20–30 mol m^{-2} d^{-1} for its optimal production [28]. Plants usually respond to the shade or low-light conditions by producing smaller and thinner leaves [29,30]. We did not observe such phenomena in the current study; our eggplants grew more healthily and thicker even under shade conditions (Figure 3). This weather data might indicate that the light (DLI) levels under our shade nets, which were all between 20–30 mol m^{-2} d^{-1} on average throughout the growing season (Figure 2A), were not yet at a limiting or a suboptimum level.

The height of eggplants is an important agronomic trait that affects the fruit set and fruit colour and is highly related to agricultural performance [31]. Under the currently reduced DLI levels, eggplants grew taller and bushier, leading to a higher number of fruits per plant (Table 3). As a result, the fruit yields of eggplants under the reduced DLI treatments were higher than those under the higher light intensity. The present study showed that eggplants performed best under the 21% shade net for growth, physiology, and fruit yield with stable quality. This finding suggests this net house type and this shade level can be possibly applied for large-scale production of eggplants at the commercial scale. High correlation between the fruit number per plant and marketable fruit yield indicates that the marketable yield is highly dependent on the number marketable fruits per plant.

Since there was an interaction between shade factors and varieties on several observations (Tables 3 and 4), further research could be done to determine if there are more suitable genotypes (or species) for specific shade nets [32,33]. The netting only resulted in a slightly higher RH than that in the OF (Figure 2C). An optimum RH is critical for vegetable crops' growth, health, and productivity [34]. For instance, a low RH may cause water stress and calcium deficiencies, whereas too high RH can lead to poor crop growth and development and fungal disease infection or hamper pollination [35]. However, it appears that netting is likely to have a minimal impact on RH in the current study.

4.2. The Underlying Physiological Mechanism of the Shade Effects on Eggplants

Light is one of the most critical environmental factors determining how well vegetable crops can grow productively, and it has been used as an indispensable criterion to predict crop growth, biomass production, and yield potential [5]. Vegetables require a certain level of light intensity and quality for their optimum growth, morphology, and physiology; higher or lower light levels and quality than the standard requirements might affect their photosynthetic activity, biomass accumulation, and overall production [36]. Indeed, low light conditions have been reported to negatively affect various agronomic, physiological, and biochemical traits of horticultural crops [37–39]. Marcelis et al. [40] demonstrated that on average, a 1% light intensity decrease can result in 0.8–1% yield reduction in various horticultural crops. However, strong light intensity causes excessive accumulation of energy in the thylakoid membrane, which causes photoinhibition and damage to photosynthetic reaction centres [41]. Excessive light has been shown to cause photodamaging to crops, detrimentally affecting the crops' light-harvesting complex and photosynthetic activities [30,42], which was also observed in our experiment. Chlorophyll fluorescence has been widely used as a precise tool to examine the photosynthetic performance of crops and indirectly assess the effects of extreme environmental conditions on them such as temperature and radiation stresses [23,43]. In the current study, the low light level in the mid-season resulted in a similar chlorophyll content of eggplant varieties and higher level of the quantum yield of primary PSII photochemistry of the OF treatment. However, in the late season, when the light level was high, the chlorophyll content of the OF treatment was significantly higher and the maximum quantum yield of primary PSII photochemistry remained unchanged (Table 1).

The seasonal and yearly variations in chlorophyll content and the maximum quantum yield of primary PSII photochemistry of several crop species are well documented [5]. Kyparissis et al. [44] reported the seasonal and the annual variations in chlorophyll content of eight field-grown Mediterranean plant species between months of two years, i.e., 1996 and 1997, as affected by light conditions and other environmental factors. The level of chlorophyll content of most species decreased in the summer, while it stayed stabilized during other seasons [44]. Likewise, Ain-Lhout et al. [45] observed variations in the chlorophyll content and PSII efficiency of six Mediterranean shrub species between the summer and winter seasons within two years, 1998 and 1999, which were shown to be affected by the irradiation levels and other ecological conditions. The variations were species-specific, where several species showed a decline in the chlorophyll content and the quantum yield of primary PSII photochemistry in either summer or winter, some species showed an opposite pattern [45]. It is probable that the fluctuations of chlorophyll content and fluorescence between the mid- and late growing seasons observed in the present study indicate that variations in light intensity resulted in significant impacts on photosynthetic-related parameters.

Chlorophyll is vital light harvesting apparatus of plants that makes photosynthe-sis occurred. Previous studies showed that under certain suboptimal light conditions, e.g., an unoptimized ratio of red/blue light, leaf chlorophyll content changed to improve light absorption [46]. Under shade treatments, where the light levels were low, decreased levels of chlorophyll content were already reported for several crop species, such as purple pak-choi (*Brassica campestris* ssp.) [47], soybean [48], and lettuce [49]. In the current study, higher levels of chlorophyll content were observed in the OF compared to the shade treatments, while quantum efficiency remained unchanged, suggesting that this might be due to the eggplant's adaptive responses to the irradiation stress in the late growing season. Overall, the variation in the light intensity caused by different shade nets was probably a major factor affecting the growth, physiological responses, and fruit yield of eggplants.

4.3. Future Perspective of Protected Cropping for the Vegetable Production under the Semi-Arid Conditions

Climate change and global warning are making a tremendous impact on the global vegetable industry and agricultural production as a whole, affecting food security for a growing world population [6]. Consequently, climate variability is becoming one of the issues that critically affects the horticulture industry, e.g., more unpredictable weather, higher average temperatures, more frequent heatwaves, and higher insect pest and disease pressures. Adverse weather conditions, which are further induced and exacerbated by climate change, can result in negative impacts on vegetable crop growth, productivity, and quality while increasing production costs [6,9,50]. In semi-arid climatic regions such as Carnarvon, unpredictable extreme weather conditions create a huge impact on the local vegetable industry and other crop production. For instance, high irradiation during summer results in excessive sunlight and heat, causing sunburnt vegetable fruits, severely affecting productivity [17,51,52]. Variability in weather conditions can increase the chance of survival of pests and the incidence of insect-transmitted diseases [53].

Therefore, protected cropping is an important solution for minimizing the harmful effects of adverse environmental conditions on vegetable production and offering a certain level of insurance against the negative impacts of extreme conditions. For horticultural production areas, such as Carnarvon—which has a small average farm size and high pest and disease pressure [26]—protective structures, such as net houses, can undoubtedly protect vegetable crops from irradiation and heat stresses, low humidity, and pest intrusion to increase productivity and stabilize horticultural production. Specially designed protective cultivation, such as photoselective netting greenhouses, can perform dual functions: safeguarding the crops from unfavourable environmental conditions (by physical shading) and restricting insect pest invasion, infestation, and transmission of viral diseases (via photoselective repelling effects) [54–56].

Shade greenhouses can be designed and installed with either permanent or retractable nets. The use of fixed nets has certain advantages, such as ease of operation and low cost. However, on the downside, it can only offer a fixed level of shade and thus is only suitable for growing certain crops. At times, it cannot provide sufficient light and maintain a warm temperature at night or diffuse heat efficiently during hot days (Figure 2). The use of other types of protected cropping, such as retractable-roof greenhouses, can be an alternative cost-effective option for semi-arid regions [57]. Unlike permanent netting greenhouses, the internal microclimatic conditions of retractable-roof greenhouses can be manipulated by the opening and closing of the roof and sidewalls depending on the weather conditions to ensure that the plants inside are always maintained in the most optimal environment. A retractable-roof greenhouse can be equipped with a low-cost evaporative cooling system, such as fogging or misting, to improve its capability in climatic manipulations. Studies suggest that such evaporative cooling systems can potentially reduce internal air temperature by 10 °C on hot days [58]. We are conducting experiments on various vegetable crop species and cultivars in a retractable-roof greenhouse in Carnarvon [26]. Preliminary results showed that a retractable-roof greenhouse was more versatile in mitigating adverse weather conditions for a better crop growth and yield of vegetables (unpublished data), and this will be the topic of our further studies.

5. Conclusions

In the current study, we have demonstrated that a 21% shade net is the most suitable option for growing eggplants in the autumn–spring period, the main vegetable cropping season in Carnarvon. Excessive solar radiation is the primary cause for the variation in growth, physiological performance, and fruit yield of eggplants between shade nets and OF conditions. Shade nets protected eggplants from possible irradiation stress and photodamage. It is recommended that further studies be extended to different highly valuable fruit vegetables, such as capsicum and cucumber, to validate the suitability of 21% shade nets on their growth and production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae8080696/s1, Figure S1: Experimental layout of four eggplant varieties under different shade nets and open field (OF); Table S1: Fertilizing program of the eggplant trial.

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