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Control of Transmitted Solar Radiation Using Photoselective Covering Materials Improves Spinach (*Spinacia oleracea* L.) Yield during Summer

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Abstract

Spinach (*Spinacia oleracea* L.) is resistant to cold but develops physiological disorders under high temperatures. Shading is one of the practical countermeasures to reduce heat in the field. However, the reduction in light intensities caused by shading can lead to growth retardation. Specific radiation ranges, such as blue, red, or far-red, induce morphological changes; therefore, it is important to selectively shade radiation to minimize growth losses. This study investigated the effects of different radiation spectra, from photosynthetically active radiation (PAR) to near-infrared radiation (NIR), on spinach cultivation using photoselective covering materials over rain shelters. The experiment was conducted in summer in Japan. Two different photoselective shading treatments (PS-1 and PS-2) were designed with different transmittance levels of PAR and NIR regions. Leaf biomass, including fresh weight and leaf area, under treatments, was significantly higher than that under uniform shading (US), which uniformly reduced the entire solar spectrum. Compared with the US treatment, fresh weight under the PS-1 and PS-2 treatments was 40.2% and 52% higher, respectively, and leaf area was 51.5% and 47.3% higher, respectively. These results suggest that photoselective shading treatment has a positive effect on spinach cultivation compared with the US treatment during the hot season.

Discipline: Agricultural Engineering
Additional key words: heat insulation, near-infrared radiation, photosynthetically active radiation, shading technique

Introduction

According to the Ministry of Agriculture, Forestry and Fisheries of Japan, the annual production of spinach (*Spinacia oleracea* L.) in 2018 was approximately 230,000 tons, and its market size of approximately 88 billion yen ranks fourth among leafy vegetables in Japan. The wholesale number was markedly reduced in summer compared with that in winter. In 2018, the wholesale number of spinaches was decreased by approximately 70% in August compared with that in March in Japan. In contrast, the wholesale price is approximately 2.5 times more expensive in August compared with that in March; hence, there is a demand for spinach cultivation in summer.

The lowest production of spinach occurs during the hot season because of environmental conditions such as heat, air humidity, and day length. One of the primary factors inhibiting spinach production is heat. The optimum germination and growth temperatures for spinach are approximately 18°C-20°C and 15°C-20°C, respectively (Kagawa 1973, Katzman et al. 2001). Spinach is cold-tolerant (Boese & Huner 1990), but high temperatures induce morphological and physiological disorders such as decrease in germination rate (Katzman 2001) or leaf biomass (Cantliffe 1972). Therefore, we must consider a method of cultivation to be used during the hot season that will enable year-round cultivation of spinach. In addition, exploring methods of cultivation at high temperatures would contribute to preparations for global warming.

Shading with covering materials is one of the most practical ways to reduce heating load in field or greenhouse cultivation. The removal of excess solar

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radiation with covering materials reduces temperature in greenhouses and alleviates high-temperature stress (Bakker 1995, Luo et al. 2005). The use of shading materials has led to a reduction in physiological disorders such as cracks in tomatoes (Cockshull et al. 1992, Gent 2007, Kittas et al. 2012, Yoshida & Sato 2012) and cracks, blossom-end rot, and pericarp lignification in sweet pepper (Díaz-Pérez 2014, Ilić et al. 2017), as well as a reduction in the respiration rate and heat stress of leaves in melon (Murakami et al. 2017). Although shading affects the reduction of heat, the timing of shading is important to avoid reducing biomass caused by the reduction of light (Gijzen 1992, Papadakis et al. 2000, Luo et al. 2005).

Thermal radiation includes wavelength ranging approximately from 200 to 1,000,000 nm (Iqbal 1983). Radiation above the infrared spectrum is the primary heat factor and constitutes approximately 50% of the total solar radiation (Spaargaren et al. 2001). Previous research on thermal insulation has focused on the effects of reducing near-infrared radiation (NIR; 800 nm-2,500 nm) during summer season in greenhouses on tomato (Ishigami et al. 2013), bedding plants (Blanchard & Runkle 2010), watermelon (Fukuoka et al. 2009), and melon (Murakami et al. 2017). These photoselective investigations revealed a temperature reduction effect on leaf, fruit, or shoot. In terms of plant morphogenesis and metabolites, the proportion of blue (B; 400 nm-500 nm), red (R; 600 nm-700 nm), and far-red (FR; 700 nm-800 nm) are important. Artificial light experiments showed that low R/FR ratio condition induces a reduction of leaf area or branching and a change in chlorophyll content (Smith 1982). A higher proportion of B fluorescent lamp in R light-emitting diodes induced a reduction of the hypocotyl length of lettuce seedlings in the controlled-environment room (Hoenecke et al. 1992). In a greenhouse investigation, *Perilla frutescens* was grown under two different colored films that reduced photosynthetically active radiation (PAR; 400 nm-700 nm), and their fresh weight did not decrease compared with when it was grown under control film (Grbic et al. 2016). Casierra-Posada et al. (2012) have reported that absolute and relative growth rates (RGR) under a green film, which shaded maximum absorption ranges for chlorophyll such as B and R radiations, are lower than those under other films in strawberry. Several studies using photoselective films in sunflower, cabbage, tomato, and cucumber have suggested that plant height is affected by the R/FR ratio (Cui et al. 1995, Murakami et al. 1996). Thus, controlling the transmittance of light quality using photoselective films from PAR to NIR spectral ranges would reduce heat load as well as maintain spinach yield and quality.

There is a gap in knowledge concerning the effect of photoselective covering materials on spinach yield or quality compared with other species. Fukuoka et al. (2019) have demonstrated an increase in fresh weight with the use of an NIR-filtering net owing to the suppression of heat stress. Thus far, no study has investigated the combination of or the relationship between shading using covers that filter radiation in the PAR to NIR range in spinach fields. In the present study, we aimed to evaluate the effect of photoselective shading around PAR and NIR spectra and compare it with general shading with uniform filtering of the entire solar spectrum on spinach cultivation in the hot season.

Materials and methods

1. Covering materials and treatment method

The experiment was conducted during summer season (June 11-July 23, 2019) to evaluate the effects of shading materials on spinach cultivation at Zentsuji, Kagawa Prefecture, Japan (34.2°N, 133.8°E). The experiment was conducted in 12 rain shelters (width × length × height: 300 × 200 × 90 cm-120 cm) covered with polyolefin (PO) films (0.15-mm thick; Hanayaka; Sumikasekisui Film Co., Ltd., Tokyo, Japan) (Fig.1). Four different shading treatments were set on rain shelters: uniform shading (US), PS-1, PS-2, and nontreated (NT). The US treatment comprised a cover with the PO film and a coating of a shading agent (ReduSol; ReduSystems, Baarle-Nassau, Netherlands), which uniformly reflected radiation over the entire solar spectrum. For the PS-1 treatment, the shelters were covered with PO film and sprayed with a NIR-reflecting shading agent (ReduHeat; ReduSystems, Baarle-Nassau, Netherlands) and a photoselective nonwoven fabric reflecting primarily the green (G; 500 nm-600 nm) and R spectra (Ao-paopao; Mitsubishi Chemical Agri Dream Co., Ltd., Tokyo, Japan). For the PS-2 treatment, the shelters were covered with PO film and sprayed with ReduHeat, and a photoselective film was used to filter out primarily the B, FR, and NIR regions (Mega-cool; Mitsubishi Chemical Agri Dream Co., Ltd., Tokyo, Japan). The shading percentage over the whole measurement period for each shading treatment was 35.7%-37.9% (see Sect. 2. Environmental measures). For the NT treatment, only the PO film was used as a cover.

2. Environmental measures

(1) Solar radiation measurements

During the experimental period, radiation in rain shelters was measured for all treatments using pyranometers (MS-01; measuring range: 400 nm-

1,100 nm; EKO Instruments Co., Ltd., Tokyo, Japan). The pyranometers were set at plant height, 50 cm above the ground surface, and the measurements were collected from June 25 to July 23. The shading percentage for each treatment was calculated based on the sum of radiation data (MJ m^{-2}) for NT treatment after transferring into each treatment.

(2) Spectroradiometer and photosynthetic photon flux

Daylight spectrum using a photon flux (µmol m^{-2} s^{-1}) passing through the covering materials was measured using a spectroradiometer (MS-720; field of view: 180°; measuring range: 350 nm-1,050 nm; EKO Instruments Co., Ltd., Tokyo, Japan) on June 20, 2019, at approximately 12:00 pm. Therefore, the NIR range in our measurements was 800 nm-1,050 nm. Transmittance was based on the corresponding radiation transmission under the NT treatment. Photosynthetic photon flux (PPF) under all treatments was measured on June 20, 2019, at approximately 12:00 pm.

(3) Temperature measurement

Average air temperature was measured using thermal recorders from June 25 to July 23, 2019, during the experimental period after transplanting (RTC-22; ESPEC MIC Corporation, Aichi, Japan). The thermal recorder, which was set in a radiation shield with a built-in fan, was set 80 cm above the ground in the middle of the rain shelter subjected to each treatment. Average soil temperature was calculated from measurements conducted over six consecutive days (July 18-23) using thermal recorders (RT-32S; ESPEC MIC Corporation, Aichi, Japan). Daytime air and soil temperatures were measured from 5:00 am to 7:00 pm according to the

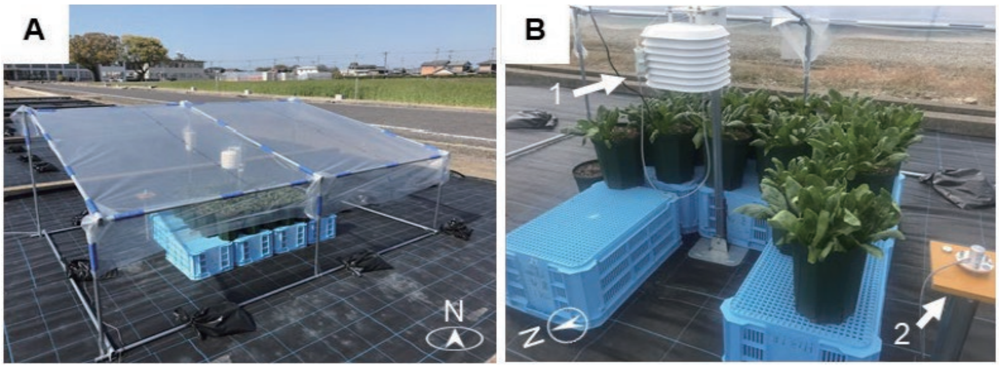

Fig. 1. Spinach in the middle of a rain shelter

The rain shelter consisted of pipe and the shading material for covering the top surface (width × length × height: 300 × 200 × 90 cm-120 cm) (A). Environmental measuring instruments were under the rain shelter (B). The thermal recorder in the radiation shield was set 80 cm above the ground (B-1).

The pyranometer was set 50 cm above the ground (B-2).

Table 1. Details of light environment under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

Treatment	Total shading (%)[a]	Transmittance (%) vs NT[b,d]						R/FR[c,d]
		B	G	R	PAR	FR	NIR	
US	35.7	73.8	75.5	77.3	75.7	79.9	83.1	1.07
PS-1	37.9	65.3	50.4	43.0	51.8	57.0	72.0	0.83
PS-2	37.9	63.4	78.0	75.2	73.0	59.0	60.6	1.41
NT	0	100	100	100	100	100	100	1.11

[a] Total shading (%): shading percentage during the whole measurement period after transplanting compared with that during the NT treatment

[b] Transmittance (%) vs NT treatment: transmittance percentage compared with that of the NT treatment; B, blue radiation (400 nm-500 nm); G, green radiation (500 nm-600 nm); R, red radiation (600 nm-700 nm); PAR, photosynthetically active radiation (400 nm-700 nm); FR, far-red radiation (700 nm-800 nm); NIR, near-infrared (800 nm-1,050 nm)

[c] R/FR: red/far-red ratio

[d] Transmittance (%) vs NT and R/FR were measured on June 20, 2019 at approximately 12:00 pm.

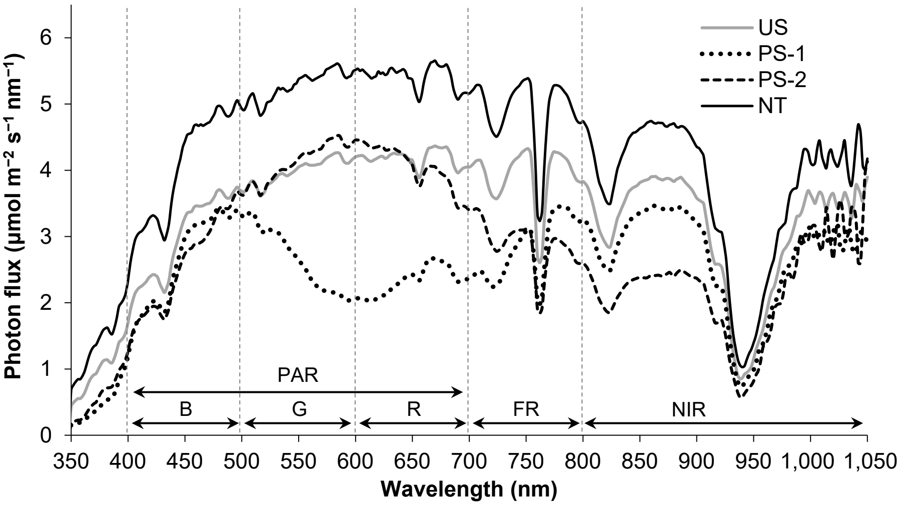

Fig. 2. Spectral distribution of the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

B, blue radiation (400 nm-500 nm); G, green radiation (500 nm-600 nm); R, red radiation (600 nm-700 nm); PAR, photosynthetically active radiation (400 nm-700 nm); FR, far-red radiation (700 nm-800 nm); NIR, near-infrared (800 nm-1,050 nm)

All treatments were measured on June 20, 2019 at approximately 12:00 pm.

detection of solar radiation during the experimental period after transplanting. The remaining time was defined as nighttime. Leaf temperature was measured using a thermal imaging camera (FLIR; CPA-0300, CHINO Corporation, Tokyo, Japan) on July 22. Leaf temperature was measured six times, and the average is shown in Table 3.

3. Plant materials and analysis

We used spinach "Summer-sky R7" (TAKII & Co., Ltd., Kyoto, Japan) grown for 14 days after seeding (DAS) in plastic pots (diameter: 180 mm; height: 205 mm) in the same greenhouse. The seedlings were then transferred to rain shelters for each of the four treatments. The experiment was conducted in triplicates in a randomized block design (*n* = 29-30). Three different rain shelters for each treatment were set at random, and nine or ten spinaches were harvested from each rain shelter. The last day of harvest was 42 DAS.

Fresh and dry weights were determined for shoots without roots. Plants were dried in an oven at 80°C for at least 72 hours. Leaf area was measured using the ImageJ software (http://rsbweb.nih.gov/ij/). SPAD value was measured on the largest leaves of each plant using a chlorophyll meter (SPAD-502; Konica Minolta, Inc., Tokyo, Japan).

RGR was calculated from dry weights of the shoots and leaf areas using a software written in Microsoft® Excel (Hunt et al. 2002). There were three RGR periods, i.e., on 21-28, 28-35, and 35-42 DAS. To investigate the relationships between RGR and environmental data, average daytime air temperature and daily average solar radiation were calculated on the basis of three RGR periods.

Table 2. Photosynthetic photon flux (PPF) under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

Treatment	PPF (µmol m^{-2} s^{-1})
US	1,113
PS-1	762
PS-2	1,073
NT	1,471

All treatments were measured on June 20, 2019 at around 12:00 pm.

4. Component analysis

Ascorbic acid (AsA) and nitrate contents were measured to evaluate spinach qualities. Four samples from each treatment were harvested at the last stage for measuring AsA content (July 24). Each spinach sample was finely chopped and mixed. A mixed sample (10 g) was suspended in 100 ml of 5% metaphosphoric acid and homogenized in a blender for 1 min. The solution was filtered, and AsA content was determined using a reflection spectrophotometer (RQ-flex with the AsA test 25-450 mg L^{-1}; MERCK, Darmstadt, Germany).

Five spinach samples from each treatment were harvested at the last stage on July 24, 2019, to measure the nitrate content. Each spinach sample was finely chopped and mixed. A distilled water solution (200 ml) containing the mixed sample (5 g) was homogenized in a blender for 1 min. The solution was filtered, and nitrate content was analyzed using a reflection spectrophotometer (RQ-flex with the Nitrate test 5-225 mg L^{-1}; MERCK, Germany).

5. Statistical analysis

Statistical analyses for morphological and component assessment were performed using Dunnett's tests ($P< 0.01$, $P< 0.05$), with the US treatment set as a control for the comparison of each treatment, especially for the comparison of the effect on a different shading profile between the US and photoselective shading treatments. In the morphological analysis, 30 samples were analyzed from each treatment, except SPAD measurements under the US treatment at 21 DAS, which were conducted on 29 plants.

Results

According to the spectroradiometer data collected on June 20, 2019, the US treatment uniformly reduced the transmittance of all spectra in comparison with the NT treatment (Table 1; Fig. 2). The transmittance level of B and FR regions was similar under the PS-1 and PS-2 treatments. Compared with the NT treatment, the PS-1 treatment primarily reduced the transmittance of R to 43%, resulting in the lowest R/FR ratio, whereas the PS-2 treatment mainly reduced the transmittance of FR to 59%, resulting in the highest R/FR ratio. The NIR transmittance rates differed among all the shading treatments. The PS-2 treatment had the lowest transmittance of NIR, and the difference between the PS-2 and US treatments was approximately 20%. On June 20, 2019, the PPF under the shading treatments ranged from 761.5 to 1,113 μmol m^{-2} s^{-1}, whereas the highest value of 1,471 μmol m^{-2} s^{-1} was measured under the NT treatment (Table 2).

Average temperatures of air were similar under all treatments (Table 3). In contrast, the average temperatures of soil and leaf were slightly lower under the shading treatments than under the NT treatment. The maximum differences in temperatures of daytime soil and leaf between the NT and shading treatments were 1.4°C and 0.7°C, respectively (Table 3).

The fresh weight and leaf area values under the NT treatment were the highest among all treatments until 35 DAS (Table 4), but not during the last sampling period. In addition, the standard deviations of fresh weight and leaf area under the NT treatment were the highest among all the treatments. The RGR of the NT treatment gradually decreased, unlike those of the shading treatments (Fig. 3A). The transition in temperature of daytime air under all shading treatments was similar (Fig. 3B), with the highest values obtained under the NT treatment (Fig. 3C). At 42 DAS of the PS-1 and PS-2 treatments, fresh weight and leaf area was 40.2% and 52%, and 51.5% and 47.3% higher, respectively, compared with those under the US treatment (Table 4). This trend was similar to that of the leaf length and dry weight. There were no significant differences in the AsA and nitrate contents between the US and other treatments (Fig. 4).

Table 3. Temperature of air, soil, and leaf under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

Treatment	Air (°C)[a]		Soil (°C)[b]		Leaf (°C)[c]
	Daytime[d]	Night-time	Daytime	Night-time	
US	26.4 ± 1.6	23.8 ± 1.1	28.0 ± 1.2	24.8 ± 0.9	28.6 ± 0.4
PS-1	26.5 ± 1.6	24.0 ± 1.1	27.9 ± 1.3	25.3 ± 1.1	28.7 ± 0.4
PS-2	26.5 ± 1.6	24.0 ± 1.1	28.3 ± 1.6	25.2 ± 1.0	28.6 ± 0.4
NT	26.6 ± 1.6	24.0 ± 1.1	29.3 ± 2.3	25.3 ± 1.0	29.3 ± 0.3

[a] Air (°C): average air temperature during the entire experimental period after transplanting (June 25-July 23, 2019)
[b] Soil (°C): average soil temperature during the six consecutive days before the last harvest (July 18-23, 2019)
[c] Leaf (°C): average leaf temperature measured using a thermal imaging camera (six times) on July 22, 2019
[d] Daytime: 5:00 am-7:00 pm
Data represent means ± SD.

Discussion

Air temperature was similar under all four treatments (Table 3; Fig. 3B) because the shading material covered only the top of rain shelters, and there was no ventilation obstruction on their sides. Consequently, it was difficult to detect air temperature differences among the treatments. However, the average soil and leaf temperatures under the US, PS-1, and PS-2 treatments tended to be lower than those under the NT treatment. Previous studies focused on thermal insulation by shading in the NIR region during the hot season in various crops (Fukuoka et al. 2009, Blanchard & Runkle 2010, Ishigami et al. 2013, Murakami et al. 2017). There was approximately 20% difference of NIR transmittance between the PS-2 and US treatments, but the differences in soil and leaf temperature were not detected (Tables 1 and 3). From the results, the difference of NIR transmittance in our experiment levels did not have a considerable influence on heat insulation between the shading treatments. In fact, Ishigami et al. (2013) demonstrated that the cooling tendency on leaf temperature under 6.2% transmittance level of NIR is relative to control in greenhouse in summer. It may make a difference between the US and photoselective shading treatments in our experiment in case of a substantial shading NIR. In contrast, there was a significant difference in leaf biomass between the shading treatments. The leaf biomass significantly increased in the PS-1 and PS-2 treatments during the latter period than that in the US treatment. In our experiment, the cooling effect between the shading treatments was similar according to soil and leaf temperature. Another factor except temperatures for the results may be affected leaf biomass. Only photoselective shading had a positive effect on leaf biomass, including fresh weight and leaf area, whereas the US treatment did not have any effect (Table 4). These results suggest that photoselective shading treatments affected leaf biomass.

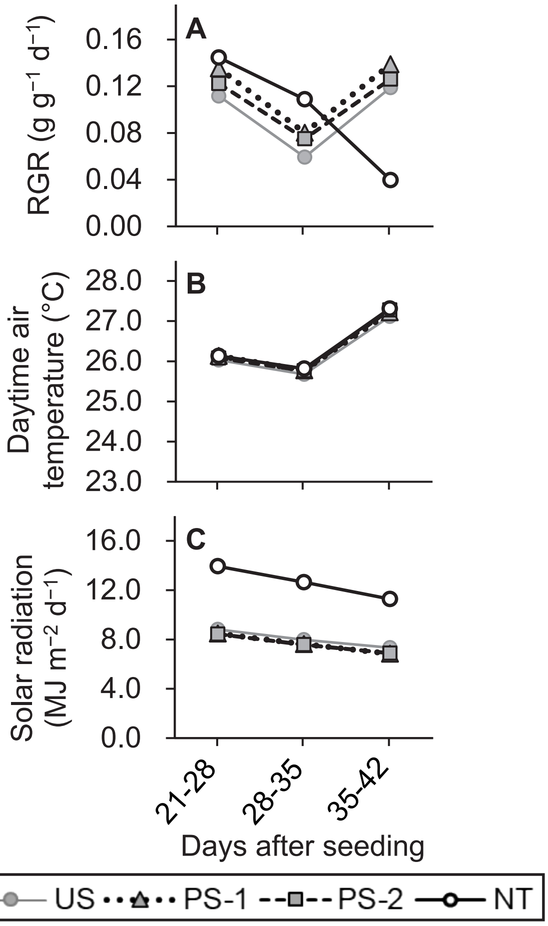

Fig. 3. Relative growth rate (RGR) (A), average daytime air temperature (B), and daily average solar radiation (C) under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

RGR was calculated from shoot dry weights and leaf areas taken from samples at 21, 28, 35, and 42 days after seeding (DAS). Daytime (5:00 am-7:00 pm) air temperature and solar radiation were the daily average of three periods (21-28, 28-35, and 35-42 DAS).

Both the PS-1 and PS-2 treatments had similar transmittance levels of B and FR, which differed from those under the US treatment. PAR is involved in photosynthesis, which means that maintaining this radiation would be preferable. Both photoselective shading treatments maintained transmittance of B above 60% (Table 1). This result suggests that the shading levels of B under the PS-1 and PS-2 treatments were the allowable level to minimize growth losses. The PS-1 treatment did not substantially reduce the R/FR ratio, although R was photoselectively shaded. The PS-2 treatment resulted in the highest R/FR ratio among all treatments because of substantial FR shading, although the transmittance of R was lower than the NT treatment. FR reduction prevented shade avoidance responses, such as stem elongation and leaf area reduction (Smith & Whitelam 1997). In the present study, the leaf areas under both the photoselective shading treatments were significantly greater than those under the US treatment. Thus, the R/FR ratio range of 0.83-1.41 failed to induce shade avoidance responses in spinach plants during the hot season. These results suggest that the transmittance levels of R were different between the PS-1 and PS-2 treatments, but FR shading would prevent a substantial reduction in R/FR ratio.

The substantial decrease in RGR during the last harvesting period (Fig. 3A) and the substantial increase in the standard deviation of leaf biomass (Table 4) under the NT treatment indicated that plants under the NT treatment might be exposed to heat and high light stress compared with other treatments. In fact, the PPF on June 20, 2019; daytime soil temperature; and transition in solar

Table 4. Morphological analysis under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

Days after seeding	Treatment	Fresh weight (g)[a]	Leaf area (cm^2)[b]	Leaf number	Maximum leaf length (cm)[c]	Dry weight (g)[d]	SPAD
21	US (control)	2.0 ± 0.5	47.1 ± 12.1	8.7 ± 0.8	8.4 ± 0.9	0.19 ± 0.04	43.2 ± 4.0
	PS-1	1.6 ± 0.4NS	41.6 ± 10.1NS	8.5 ± 1.0NS	8.3 ± 0.7NS	0.15 ± 0.03 **	42.3 ± 3.0NS
	PS-2	2.2 ± 0.4**	51.9 ± 10.0NS	9.1 ± 0.7NS	8.9 ± 0.9NS	0.21 ± 0.04 NS	44.3 ± 4.4NS
	NT	2.1 ± 0.7NS	48.7 ± 15.1NS	8.9 ± 1.2NS	8.5 ± 0.9NS	0.19 ± 0.06 NS	42.0 ± 4.1NS
28	US (control)	3.7 ± 0.8	79.9 ± 19.8	13.2 ± 1.7	9.7 ± 1.2	0.41 ± 0.08	47.2 ± 4.6
	PS-1	4.0 ± 1.0NS	95.0 ± 21.9NS	12.9 ± 1.4NS	10.9 ± 1.1**	0.39 ± 0.11 NS	44.4 ± 3.7NS
	PS-2	4.5 ± 1.6NS	99.1 ± 37.0*	14.2 ± 2.6NS	10.3 ± 1.7NS	0.51 ± 0.18 *	50.9 ± 5.1*
	NT	5.0 ± 1.7**	96.4 ± 27.8*	12.9 ± 2.0NS	10.1 ± 1.3NS	0.51 ± 0.18 **	48.4 ± 4.1**
35	US (control)	5.2 ± 1.5	87.0 ± 21.8	15.7 ± 3.2	10.5 ± 1.1	0.63 ± 0.19	52.7 ± 4.8
	PS-1	5.7 ± 1.0NS	108.1 ± 18.3*	15.7 ± 2.4NS	11.8 ± 0.9**	0.67 ± 0.14 NS	48.0 ± 4.4**
	PS-2	6.8 ± 1.6*	123.6 ± 25.6**	17.1 ± 3.5NS	11.0 ± 1.1NS	0.83 ± 0.20 **	49.1 ± 4.3**
	NT	10.5 ± 3.9**	173.0 ± 59.0**	19.2 ± 4.4**	11.9 ± 1.9**	1.10 ± 0.36 **	48.9 ± 6.0**
42	US (control)	12.1 ± 2.9	217.3 ± 53.7	22.4 ± 3.6	12.8 ± 1.7	1.44 ± 0.37	53.2 ± 4.0
	PS-1	16.9 ± 4.4**	329.2 ± 85.2**	23.0 ± 4.9NS	16.2 ± 2.0**	1.78 ± 0.40 *	47.9 ± 3.5**
	PS-2	18.3 ± 5.8**	320.2 ± 93.6**	26.3 ± 7.2*	14.5 ± 1.7**	2.03 ± 0.58 **	49.6 ± 3.9**
	NT	13.6 ± 6.7NS	221.3 ± 103.8NS	22.8 ± 5.8NS	12.1 ± 2.3NS	1.49 ± 0.63 NS	51.3 ± 6.0NS

[a] Fresh weight (g): shoot fresh weight

[b] Leaf area (cm^2): total leaf area per plant

[c] Maximum leaf length (cm): the maximum leaf length, including leaf blade and petiole

[d] Dry weight (g): shoot dry weight

Data represent means ± SD (n = 29 or 30). Asterisks indicate statistically significant differences between the US treatment and each treatment according to Dunnett's test (** *P*< 0.01; * *P*< 0.05; ns, nonsignificant).

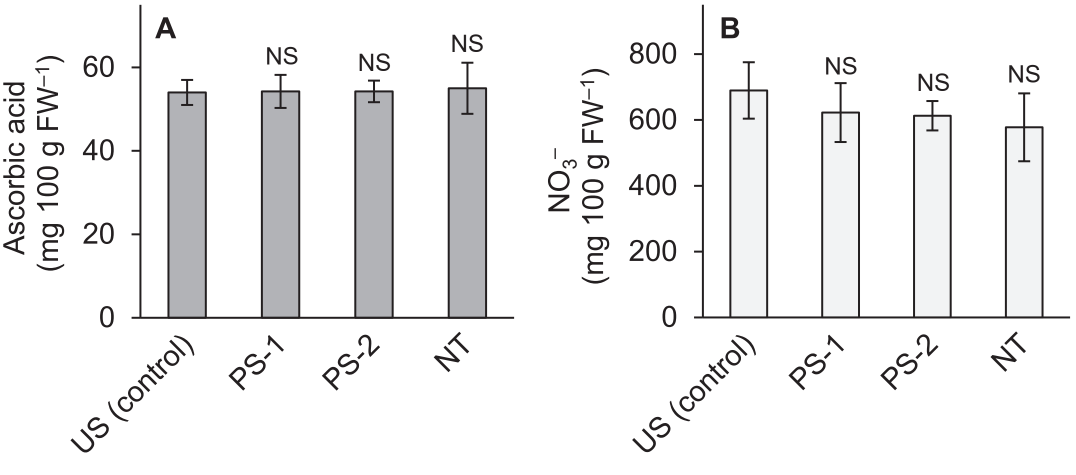

Fig. 4. Ascorbic acid (AsA) (A) and nitrate contents (B) under the uniform shading (US) treatment; photoselective shading treatment of mainly green, red, and near-infrared radiations (PS-1); photoselective shading treatment of mainly blue, far-red, and near-infrared radiations (PS-2); and nontreated (NT) treatment

Each column represents the mean. Error bars represent the standard deviation of the mean (AsA, n = 4; nitrate, n = 5). Statistical analysis was done using Dunnett's test between the US treatment and each treatment (ns, nonsignificant).

radiation under the NT treatment were the highest among all treatments (Tables 2 and 3 and Fig. 3C). Lefsrud et al. (2006) demonstrated that the light saturation point of spinach was 775 μmol m^{-2} s^{-1}. The PPF under the NT treatment was 1,471 μmol m^{-2} s^{-1} (Table 2), thereby exceeding the light saturation point by far. In contrast, based on the changes in the RGR, shading treatments prevented heat and high light stress in spinach compared with the NT treatment (Fig. 3A).

Nakamoto et al. (1998) indicated that the shading of spinach lowers the AsA content and increases the nitrate content. However, there were no significant differences in the AsA and nitrate contents among the treatments. Light intensities under all shading treatments were not markedly less than the light saturation point of spinach (775 μmol m^{-2} s^{-1}) described above (Table 2), suggesting that photosynthetic activity could progress under shading treatments. Therefore, the AsA and nitrate contents showed similar levels under all treatments.

Conclusion

The challenges of growth and cultivation of spinach at high temperatures can be practically alleviated using shading techniques. However, the reduction in light caused by shading can decrease the yield and nutritional composition of spinach. Our experiment was conducted during the hot season when spinach was subjected to high temperatures and excess light. Leaf biomass under the two photoselective shading treatments, PS-1 and PS-2, was higher than that under the US and NT treatments. The resemblances between the PS-1 and PS-2 treatments were the transmittance levels of B and FR. The AsA and nitrate contents were not reduced under any shading treatment. This is probably because the PPF in all shading treatments never decreased below the light saturation point of spinach. These results suggest that it is important to pay attention to the threshold value of shading. Our findings indicate that photoselective shading treatments positively affected spinach yield during the hot season compared with the US treatment when the light intensity is not decreased beyond the light saturation point of spinach. Therefore, we expect that the expansion of cultivation of spinach into the hot season will be possible using photoselective covering materials. To investigate two different photoselective shading conditions, NIR shading agent and photoselective shading materials were combined. There is abundant scope for further progress in adapting this method regarding the cost of materials or construction labor. Further studies should explore an optimal balance of transmitted solar spectrum from PAR to NIR, especially with a balance between the transmittance levels of B, R, and FR on the growth of spinach for creating the most effective shading materials.

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