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Performance of Different Bunch Cover Materials to Improve Quality of Cavendish Banana Cultivated during Winter and Summer in Thailand

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Abstract: Performance of different cover materials on improving Cavendish banana quality was examined during winter and summer. The banana bunch was covered with a thin nonwoven innermost layer, followed by cover materials arranged from inner to outer as follows. (1) Control (commercial cover), paper/polystyrene sheet (PS)/non-perforated blue polyethylene (NPPE), (2) nonwoven (NW)/NPPE, (3) waterproof nonwoven (WPNW), (4) aluminum foil (ALF), and (5) WPNW + ALF. For the summer trial, control without PS layer was applied. Material properties including thickness, light transmissivity and heat energy (Q_x) were evaluated. Results showed that Q_x values transferred through PS sheet, NW, WPNW and ALF were not significantly different. ALF exhibited the lowest light transmissivity, associated with the highest fruit lightness (L^*) and lowest fruit weight. For the winter trial, all cover materials exhibited chilling injury on fruit caused by temperatures below 10 °C. For the summer trial, five treatments prevented sunburn defect. Under field air temperature of 47.5 °C, ALF exhibited the lowest temperature (31.6 °C). All cover materials reduced hand and fruit sizes, whereas WPNW resulted in an increase in total soluble solids and prevented fading of the green peel color. Results suggested that WPNW, with reduced layers as environmentally friendly and reusable materials, had potential as a cover material to improve the quality of Cavendish banana.

Keywords: banana bunch covering; chilling injury; cover material; sunburn

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1. Introduction

Cavendish banana (*Musa acuminata* (AAA group) "Kluai Hom Khieo") is grown commercially in subtropical areas of Thailand, especially in Chiang Rai. Severe temperature changes as either extreme drop below 13 °C or increase above 36 °C cause physiological disorders of banana in the field associated with quality defects such as chilling injury (CI) or sunburn (SB), respectively [1,2]. CI and SB symptoms tended to increase fruit maturity but to reduce total soluble solids or sugar content, which is an indicator of fruit flavor. In addition, both symptoms caused physiological disorder such as dull grey peel color, pulp browning and fingertip burning [3,4], which affect the visual appearance of fruits and fail to meet quality requirements for export. Information from a farm manager (personal interview) revealed that CI and SB symptoms in Cavendish banana grown resulted in annual field losses of around 5 to 20%.

Recently, application of banana cover materials during the preharvest stage has received increasing interest to investigate the ability to mitigate damage associated with physiological disorders arising from seasonal temperature changes, insect and pest infestation, as well as to create a microclimate for fruit development [1,5–7]. In most tropical and subtropical banana growing countries, cover materials of polyethylene (PE) film are extensively applied to prevent peel damage and insect attack, as well as to improve visual appearance [2,8,9]. PE covers showed no effect on fruit size of Cavendish banana [10,11]. A plethora of authors has reported the use of non-perforated polyethylene (NPPE) during winter and summer to mitigate CI and SB effects on banana bunch, respectively [1–3,12]. Recently, the use of nonwoven (NW: polypropylene (PP)-based spun-bond fabrics) and aluminum foil (ALF) as cover materials for longan and Cavendish banana was shown to reduce fruit cracking due to low temperature and drought stresses in cross-winter off-season and SB, respectively [13,14].

CI symptoms of field banana were reported in Australia [1], Brazil [14] and Thailand [15,16]. However, few reports exist on the application of NW cover materials in Cavendish banana to reduce CI in winter. The use of nonwoven, double paper and PE on banana "Nanica" did not prevent CI [14]. Recent studies conducted on Cavendish banana indicated that application of NW and ALF reduced CI and SB during early and late winter, respectively [4,15]. In Thailand, few studies have investigated the use of cover materials in Cavendish banana or other fruit varieties to control or reduce CI caused by cool temperature fluctuation in winter. A nonwoven prototype with insulation performance comparable to polystyrene (PS) sheet showed success as a commercial cover, preventing cool temperature fluctuation [15]. Use of polystyrene sheet (PS) material for Cavendish banana cover during winter adversely affected SB defect on the top and middle hands of the banana bunch due to heat accumulation inside the multilayered cover [4]. Also, ALF has been used for material cover of lady finger bananas in commercial practice to protect peel damage and SB in Thailand [16].

In Chiang Rai Province, the commercial practice to reduce CI during winter consists of multiple layering as a commercial cover of NPPE, paper and thin PS sheet on banana bunches. This practice has raised concerns regarding the environmental aspects of disposal of these nonreusable and nonrecyclable materials. Reducing the number of layers of cover material to protect the fruit against temperature extremes would be environmentally friendly. Therefore, here, the effects of NW, waterproof nonwoven (WPNW) and ALF as cover materials, compared with commercial cover, to reduce CI, prevent SB, and reduce the disposal of nonreusable and nonrecyclable materials in Cavendish banana during winter and summer months in Thailand were investigated.

2. Materials and Methods

2.1. Plant Materials and Experimental Design

Two trials were conducted (winter and summer), using 30 uniform 9-month-old Cavendish banana plants (*Musa acuminata* (AAA group) "Kluai Hom Khieo") for each trial in Chiang Rai Province (19°49′14.0″ N 100°10′56.5″ E). A randomized complete block design (RCBD) was carried out with six replications per treatment. Cover material arrangement of each treatment, as well as a period of bunch covering to harvesting in the winter and summer productions are summarized in Table 1. Material covers with size 80 × 180 cm were allocated for five treatments approximate 3 weeks after inflorescence emergence (AIE) in both seasons (Figure 1). NW was coated with a slurry of 2.5% wt. zinc oxide (for UV protection) and WPNW was NW further coated with 0.5% wt. fluoroethylene-based water-repellent agent. WPNW + ALF signifies that the right half and left half of the cover material were ALF and WPNW, respectively.

In our previous study, control with a PS layer exhibited SB on banana hands, particularly the top hand, due to heat accumulation in the field at 50.2 °C (maximum temperature) [4]. In this study, the control without PS layer in the summer trial was designed to prevent SB on banana peel.

Table 1. Five cover material treatments.

Treatment (Typical Color)	Layer	Cover Materials (from Inner to Outer Layers)				Covering to Harvesting Dates
Control	3 or 4	TNW	Paper	PS *	NPPE	
NW (White)	3	TNW	NW	NPPE	-	1 trial (winter) (22 December 2017 to 17 March 2018) 2 trial (summer) (19 February 2018 to 28 April 2018)
WPNW (White)	2	TNW	WPNW	-	-	
ALF (White)	2	TNW	ALF	-	-	
WPNW + ALF (White + White)	2	TNW	WPNW + ALF	-	-	

Remarks: Thin nonwoven (TNW); Polystyrene sheet (PS); Non-perforated blue polyethylene (NPPE); Nonwoven (NW); Water-proof nonwoven (WPNW); Aluminum foil (ALF); None (-). * The control with PS layer as a thermal insulation material was applied only in the winter trial.

Control NW WPNW ALF WPNW + ALF

Figure 1. Five treatments of banana bunch covers.

2.2. Banana Harvesting and Ripening

Banana bunches were harvested on 17 March 2018 (12 weeks after inflorescent emergence (AIE)) and on 28 April 2018 (10 weeks AIE). Harvesting time was determined by the control size of three-quarters maturity index (the company standardization for Chinese export). The middle hand of each bunch (the 3rd hand) was selected as representative for quality evaluation. Evaluation of fruit quality was carried out at mature green and ripening stages. The selected banana hands were cleaned with chlorinated water (150 mg L^{-1}) followed by treatment with ethephon (750 mg L^{-1}) and subsequently stored at 18 °C with 70% RH for 5 days to accelerate the ripening process.

2.3. Evaluation of Cover Material Properties

Thickness, light transmission, and heat energy (Q_x) transmission of cover materials were evaluated with five replicates. Thickness was measured using a digital thickness gauge (547–400, Mitutoyo, Kawasaki, Japan). A polystyrene foam box (75 × 38 × 38.5 cm) with two chambers was used to evaluate the rate at which heat energy Q_x passed through different materials, following an adapted Harvey's method [1]. Temperature monitoring was carried out using a temperature data logger (Tinytag Talk 2: TK-4014-PK Gemini Data Loggers, West Sussex, UK) to measure temperature change in each chamber for up to 3 h until the temperature became constant. Heat energy transmission (Q_x) was reported in unit of $J\ s^{-1}$.

Light transmission through cover material samples of size 10 × 10 cm was examined, using light source intensity of 2.78×10^5 lux, adapted from the method of Lima et al. [3]. The transmitted light was measured by a light meter (Tenmars TM-204, Taipei, Taiwan) and recorded as percentage of transparency (%).

2.4. Field Temperature Monitoring

Air temperature was monitored both inside and outside the bunch covers at intervals of 20 min, using a temperature data logger (Tinytag Talk 2:TK-4023-PK, Gemini Data Loggers, West Sussex, UK). Data analysis of temperature was calculated based on average, medium, maximum, and minimum temperatures and plotted as a box-plot graph. Heatmap chart represents mean maximum temperature inside the bunch cover and ambient temperature during covering; red-to-blue gradient showed high and low mean maximum temperature, respectively. The heatmap chart was implemented by Python 3.6.9, including packages Seaborn 0.11.1, Pandas 1.1.5 and Matplotlib 3.2.2.

2.5. Evaluation of Hand and Fruit Quality

Fruit physical qualities (size and color) were evaluated at mature green stage. Hand weight and fruit weight were measured using a digital weight scale (PB4001-S, Mettler Toledo, Zurich, Switzerland). Peel color of eight selected fruits from each hand was measured by a CIE-lab color colorimeter (MiniScan EZ-45/0, HunterLab, Reston, WV, USA) and reported based on CIE-Lab (L^* and H°).

2.6. Total Soluble Solids (TSS) and Total Acidity Determinations

Four fruits in each hand at the ripening stage were sampled and determined for total soluble solids (TSS) using a digital pocket refractometer (PAL-11, Atago, Tokyo, Japan). For total acidity (%TA) determination, samples (5 mL) of diluted pulp (mixture of pulp and water at 1:9 (w/v) ratio), were titrated against 0.1 N NaOH in the presence of phenolphthalein (as indicator). TA was calculated from Equation (1):

$$\text{Total acidity (\%)} = (\text{Volume of NaOH} \times \text{N} \times \text{meq. wt. malic acid})/(\text{Volume of juice sample}) \times 100 \quad (1)$$

2.7. Dry Matter Content and Pulp-to-Peel Ratio Assessment

Dry matter assessment and pulp-to-peel ratio at the mature green stage were conducted, following the method of Amin et al. [17] with slight modifications. Pulp-to-peel ratio at the mature green stage was determined on three banana fingers sampling from the middle of each hand. The peel was carefully separated from the pulp and weighed. The weight ratio was then calculated.

2.8. Chilling Injury and Sunburn Assessment

Chilling injury (CI) in banana fruit at mature green stage, based on intensity of surface browning, was scored from 1 to 5 following the method of Nguyen et al. with some adaptations [18] and Lima et al. [4,14,19], and rated as follows: score 1 = no CI, score 2 = mild CI, score 3 = moderate CI, score 4 = severe CI, and score 5 = very severe CI.

The method of determination of browning index due to CI was modified from Supapvanich et al. [20] and Ding and Ling [21]. Absorbance of extract was measured at 420 nm using a UV/VIS spectrophotometer in a microplate reader (Type 1510 + 24 VDC/4A, Multiskan GO, Thermo Scientific™, Vantaa, Finland).

Sunburn (SB) damage was observed by blackening or browning on peel as well as fruit cracking (Figure 2). Class I SB was determined by a slight defect area not exceeding 5% of total surface area [22]. The percentage of sunburn was calculated by counting the number of SB hands per treatment.

Figure 2. Sunburn (SB) symptoms from field heat injury.

2.9. Statistical Analysis

Data analysis for material and fruit properties except for the CI score among five treatments was compared by mean at the 5% probability level by Tukey's HSD post hoc test using SPSS version 20 (IBM, Armonk, NY, USA). For the CI score, Steel–Dwass test was conducted using BellCurve for Excel version 3.20 (Social Survey Research Information, Tokyo, Japan). The significance level for all tests was set at 0.05.

3. Results

3.1. Evaluation of Cover Material Properties

Light transmissivity of TNW was the highest (59.32%), whereas ALF was the lowest. WPNW, NW and PS exhibited comparable light transmissivity in a range of 29.74% to 41.31%. Heat energy (Q_x) penetrating through PS sheet was the highest (8.77×10^{-6} J s^{-1}), indicating high heat insulation, whereas heat transmission through NPPE (6.8×10^{-6} J s^{-1}) and TNW (7.0×10^{-6} J s^{-1}) was significantly low (Table 2).

Table 2. Thickness, light transmissivity and heat energy (Q_x) of materials.

Material Cover	Thickness (mm)	Light Transmissivity (%)	Heat Energy ($Q_x \times 10^{-6}$) (J s^{-1})
TNW	0.055 ± 0.001 c	59.32 ± 0.03 a	6.71 ± 0.03 b
Paper	0.047 ± 0.001 c	4.07 ± 0.01 f	8.51 ± 0.03 a
PS	0.253 ± 0.000 b	31.78 ± 0.04 d	8.77 ± 0.07 a
NPPE	0.027 ± 0.001 d	56.03 ± 0.02 b	6.85 ± 0.06 b
NW	0.262 ± 0.001 b	41.31 ± 0.04 c	8.37 ± 0.02 a
WPNW	0.310 ± 0.002 a	29.74 ± 0.03 e	7.97 ± 0.05 a
ALF	0.061 ± 0.001 c	0.00 ± 0.00 g	8.58 ± 0.13 a

Note: Different letters indicate significant differences at $p < 0.05$. Values are mean ± S.E. from five replicates.

3.2. *Field Air Temperature Monitoring*

The average, maximum and minimum temperatures inside the five cover materials and ambient air temperatures measured during the trials are shown in Figure 3. Average air temperatures in the field recorded during the winter and summer trials were 22.1 °C and 25.0 °C, respectively. In the winter trial, the lowest air temperature was 10 °C (Figure 3A) (Table 3), with a dip below 13 °C 12 times (45 h 40 min) (data not shown). The control, NW and WPNW + ALF exhibited slightly higher temperature (10.5 °C) inside the cover materials than ALF and WPNW (9.0 °C) (Figure 3A). In the summer trial, the highest maximum temperature was observed inside WPNW + ALF (38.4 °C) when maximum temperature in the field was 47.5 °C (Figure 3B). However, sunburn (SB) was not observed in WPNW + ALF despite a value of higher than SB critical temperature (36 °C). However, in previous reports, SB was observed in a top hand of Cavendish banana bunch inside control treatment with or without PS sheet as a commercial cover under the maximum temperature in the field at approximate 50 °C [4,22]. A possible explanation for this result may be a lower level of maximum temperature in the field (47.5 °C). Maximum temperature of ALF was the lowest (31.6 °C), followed by the control (34.2 °C), NW (35.8 °C) and WPNW (36.5 °C). In the second trial, for temperature range (box plot size) measured inside the cover materials, ALF exhibited the smallest temperature fluctuation (4.1 °C), followed by the control (4.9 °C), NW (5.3 °C), WPNW (5.8 °C) and WPNW + ALF (6.2 °C) (Figure 3B). The heatmap graph is shown as a matrix of red-blue color tones. In the winter trial, WPNW and the control with PS (red color tone) presented higher maximum temperature levels than the other three bunch covers (blue color tone). In the summer trial, WPNW (light orange color tone) also exhibited the highest maximum temperature over the other four bunch covers (Figure 4).

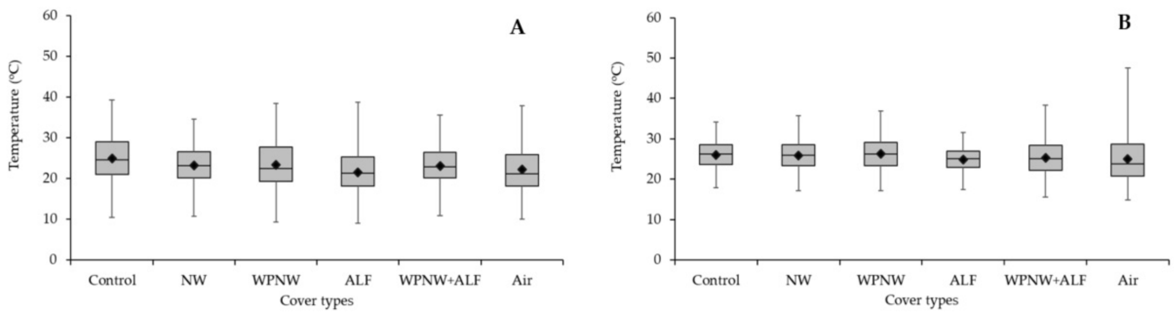

Figure 3. Box and whisker plots of temperatures inside cover materials and air temperature for the winter (**A**) and summer (**B**) trials. Boxes indicate the lower and upper quartile. The horizontal line in each box represents the median temperature. Average temperature for each treatment is indicated by ⧫. Vertical lines extending above and below each box represent minimum and maximum temperatures recorded.

Table 3. Physical properties at mature green and chemical properties at ripening stage of Cavendish banana.

Trial	Treatment	Hand Weight (g)	Finger Weight (g)	Finger Length (cm)	TSS (°Brix)	TA (%)	Lightness ($L*$)	Hue Angle (H°)
summer	Control	2874.6 ± 246.80 a	166.5 ± 14.11 a	19.8 ± 0.56 a	19.2 ± 0.91 a	0.39 ± 0.01 a	55.04 ± 0.35 ab	105.40 ± 0.45 bc
	NW	2735.1 ± 125.89 a	153.9 ± 5.61 a	19.9 ± 0.58 a	20.2 ± 0.79 a	0.35 ± 0.02 a	51.80 ± 0.39 c	107.53 ± 0.38 a
	WPNW	2561.3 ± 132.80 a	137.2 ± 8.75 a	18.8 ± 0.73 a	19.8 ± 0.65 a	0.41 ± 0.02 a	51.64 ± 0.85 c	107.51 ± 0.40 a
	ALF	2372.9 ± 143.90 a	131.0 ± 7.27 a	18.4 ± 0.49 a	21.3 ± 0.95 a	0.41 ± 0.02 a	55.62 ± 0.43 a	105.17 ± 0.41 c
	WPNW + ALF	2393.8 ± 194.30 a	142.2 ± 8.20 a	18.8 ± 0.63 a	21.0 ± 0.45 a	0.42 ± 0.01 a	53.35 ± 0.92 bc	106.71 ± 0.66 ab
winter	Control	3577.4 ± 145.23 A	205.4 ± 2.92 A	24.0 ± 0.46 A	19.3 ± 0.33 B	0.27 ± 0.00 A	58.58 ± 0.20 B	107.89 ± 0.25 AB
	NW	3359.6 ± 198.76 A	192.5 ± 8.49 AB	23.0 ± 0.40 A	18.7 ± 0.56 B	0.27 ± 0.00 A	57.07 ± 0.28 C	108.42 ± 0.42 A
	WPNW	3361.9 ± 101.06 A	184.4 ± 4.15 BC	23.0 ± 0.16 A	21.0 ± 0.00 A	0.27 ± 0.00 A	56.74 ± 0.25 C	107.69 ± 0.33 AB
	ALF	3115.3 ± 85.13 A	168.4 ± 2.10 C	22.7 ± 0.24 A	21.2 ± 0.48 A	0.31 ± 0.03 A	60.47 ± 0.29 A	106.02 ± 0.17 C
	WPNW + ALF	3144.9 ± 100.26 A	176.5 ± 6.07 BC	23.1 ± 0.42 A	20.7 ± 0.42 A	0.29 ± 0.02 A	58.40 ± 0.71 B	106.89 ± 0.49 B C

Note: Different letters in a column indicate significant differences at $p < 0.05$. Values are means ± SE from six replicates.

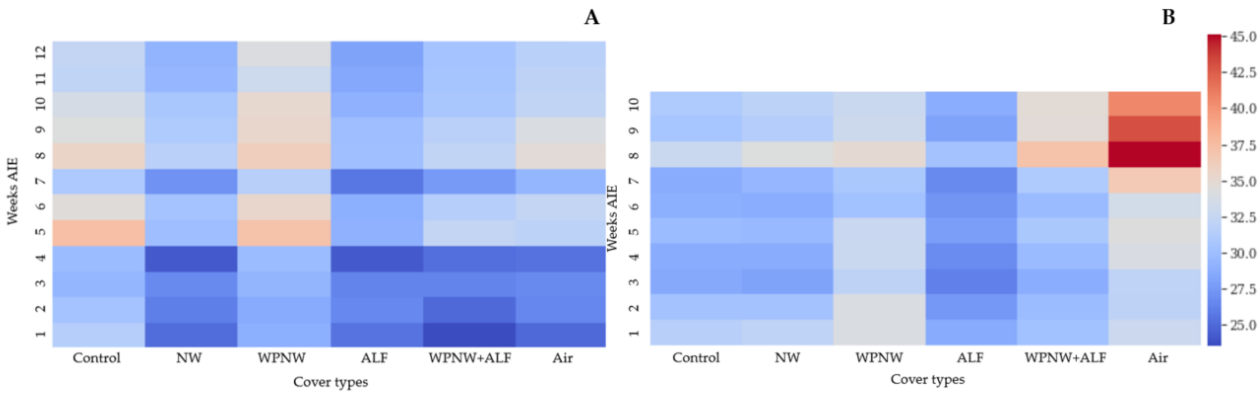

Figure 4. Heatmap chart of average maximum temperature during the weeks after inflorescence emergence (AIE) for the winter (12 weeks AIE) (**A**) and summer (10 weeks AIE) (**B**) trials. Red and blue colors represent high temperature and low temperature levels, respectively.

3.3. Evaluation of Hand and Fruit Quality

Hand weight and fruit size (fruit weight and length) obtained in the winter trial tended to be smaller than those obtained in the summer trial (summer) (Table 3). In the summer trial, the ALF cover resulted in the smallest finger weight compared with the other four treatments, while NW, WPNW and WPNW + ALF treatments showed no significant fruit weight differences. No significant difference in TSS content was observed among the five treatments in the winter trial; however, in the summer trial, ALF, WPNW and WPNW + ALF covers exhibited the highest TSS content. No significant difference was observed in TA content among the five treatments in both trials. For peel color at mature green stage, ALF treatment exhibited significantly higher *L** value and lower H° value compared with NW and WPNW (lowest *L** value and highest H° value) for both trials (Table 3).

3.4. Dry Matter Content and Pulp-to-Peel Ratio Assessment

To indicate banana fruit maturity, dry matter content and pulp-to-peel ratio were determined. In the winter trial, dry matter content was not significantly different among all five treatments (Figure 5). In the summer trial, ALF had the highest dry matter content among the treatments. The control, NW, WPNW and WPNW + ALF cover treatments showed no significant differences in dry matter contents (Figure 5B). For pulp-to-peel ratio, no significant differences were observed among all treatments in both trials (Figure 5).

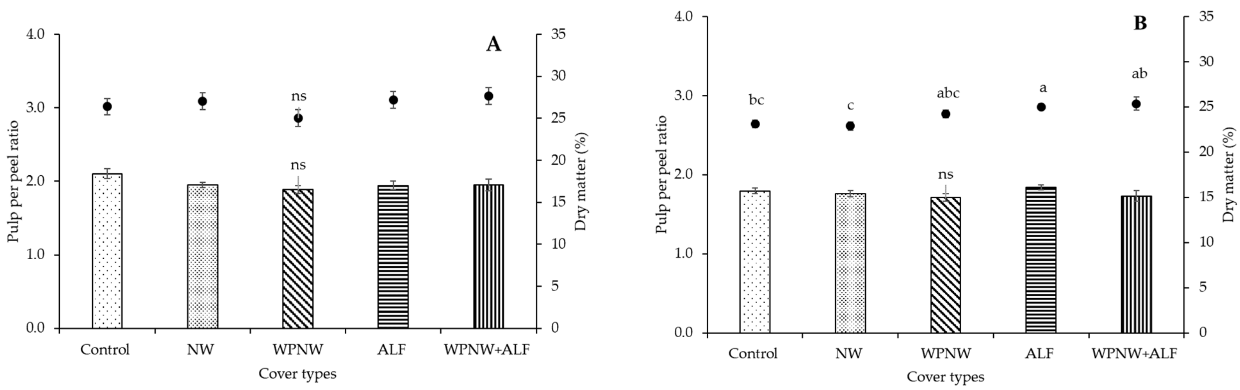

Figure 5. Pulp-to-peel ratio and dry matter of Cavendish banana fruit for mature green stage at the winter (**A**) and summer (**B**) trials. (Different letters indicate significant differences at $p < 0.05$).

3.5. Chilling Injury (CI) and Sunburn (SB) Assessment

Mild CI (score 2) was observed in all five treatments in the winter trial (Figures 6 and 7A), whereas no CI incidence (score 1) was observed in the summer trial (Figure 7B). CI was observed in all five treatments, increasing from score 2 to score 3 at the ripening stage (Figure 6B,C). However, no significant difference in browning index was shown among all five treatments in both trials (Figure 7). SB was not found in any of the five treatments in the summer trial (Figure 8) despite high maximum air temperature in the field (47.5 °C), even though the temperature of WPNW + ALF (38.4 °C) was above the critical temperature for SB (36 °C) (Figure 3B).

Figure 6. *Cont.*

Figure 6. Chilling injury (CI) on banana with peel at mature green stage (**A**), and with or without peel at ripening stage (**B**) and (**C**) (winter trial).

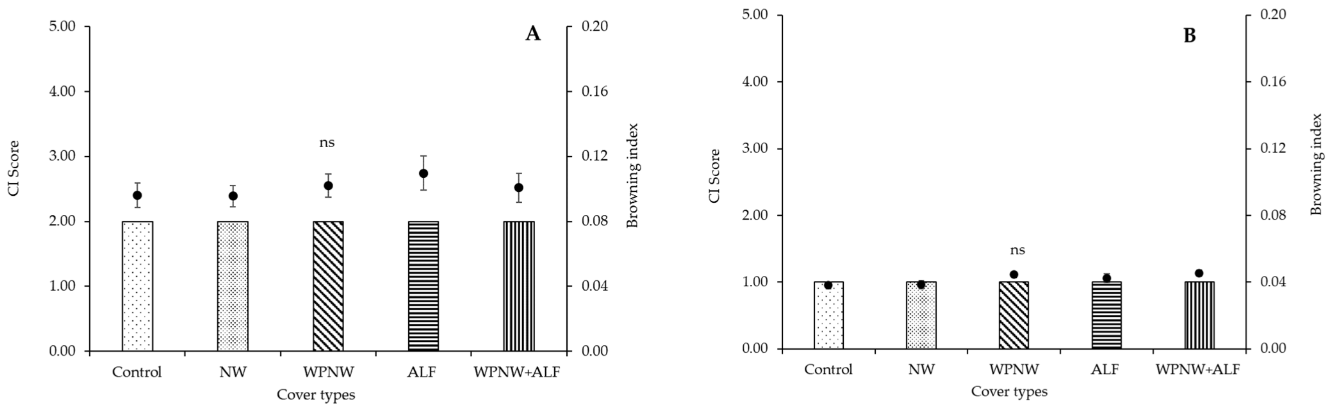

Figure 7. Chilling injury (CI) score and browning index of banana at mature green stage from the winter trial (**A**) and summer trial (**B**).

Figure 8. No sunburn (SB) incidence at mature green stage from the summer trial.

4. Discussion

Temperature affects fruit quality including weight, size, visual appearance, color and taste, leading to huge economic loss at the point of sale [23]. Overall average temperature levels inside the five treatments were 23.2 °C (winter trial) and 25.7 °C (summer trial) (Figure 3). Hand weight and fruit size (fruit weight and length) obtained in the winter trial (12 weeks AIE) were smaller than those obtained in the summer trial (10 weeks AIE) (Table 3). The winter trial (winter trial) conducted at a cooler temperature delayed harvesting time for 2 weeks AIE compared to the summer trial (summer trial). According to the Association of Southeast Asian Nations (ASEAN)standard for Cavendish banana fruit size [24], winter and summer production in this study were classified as size 2 (fruit length of 18–20 cm) and size 1 (fruit length of > 20 cm), respectively. One possible explanation for such a variation in fruit size was due to the radiation effect. Fruit length of "Prata" banana was found to be more related to solar radiation than to maximum and minimum temperatures [25]. In this study, shorter daylight during the winter trial caused smaller fruit size compared to the summer trial. Small fruit size observed during the winter trial was affected by temperature and light transmission factors, under low heat accumulation and photoassimilate levels.

In the summer trial (summer), application of ALF significantly reduced banana fruit weight, with also a decrease in fruit length (Table 3), possibly as a result of lower heat accumulation. Maximum and average temperatures (31.6 °C and 24.9 °C) with the lowest temperature fluctuation were observed in ALF covering, and lower than the control (34.2 °C and 26.0 °C) (Figure 3B). The silver color inner ALF induced a lower average maximum temperature than the other four bunch covers (Figure 4). These observations agreed with previous reports that investigated application of ALF material on Cavendish banana during summer and winter [4,22]. Temperature rise within the cover material was partly caused by the increase in layering [6]. In the winter trial, WPNW (2 layers) and multilayer (4 layers) with PS sheet in the control treatment exhibited the highest maximum temperatures (Figures 3A and 4). However, no significant differences in hand weight were observed among the other four treatments (control, NW, WPNW, and WPNW + ALF). In the summer trial, the control (without PS layer) showed no significant difference in hand weight compared with the other four treatments (Table 3). With reduced layering, WPNW provided comparable or improved banana size and higher temperature compared to the control (commercial) (Figure 4 and Table 3). In terms of environmental aspect, WPNW performed reusability and was used in place of NPPE, paper and PS materials. This result demonstrated that reduction in layering of cover materials for Cavendish banana could be achieved. Bunch covering of thick black translucent polyethylene combined with white NW increased the temperature inside the cover, yielding a lower CI score in "Nanica" banana [19]. Further studies on insulation properties in black NW and WPNW covers for maintaining warm temperature and maximizing hand and fruit sizes are needed.

In terms of biochemical quality, WPNW, ALF and WPNW + ALF treatments significantly increased TSS content in banana fruits (summer trial) (Table 3). Such increase in TSS was attributed to lower heat accumulation during the summer trial (Figure 3B). Banana fruit produced under cool weather (low temperature) had higher TSS content than fruit produced under hot weather (high temperature) [4,26,27]. Low temperature induced starch degradation, leading to an increase in sugar during storage for "Nanicao" banana [28]. In our previous study, TSS content of Cavendish banana in ALF cover during late summer in Thailand (May to June) increased due to lower temperature (28 °C) compared with higher temperature (34 °C) in the control (perforated PE/paper/TNW) (15.7 vs. 14.7 °Brix) [7]. Similarly, a recent study reported that ALF and the control (NPPE/PS/paper/TNW) provided the highest and lowest TSS levels, respectively, in Cavendish banana during early summer in Thailand [4]. Interestingly, WPNW and WPNW + ALF treatments exhibited an increase in TSS content (summer trial). Similarly, PP-nonwoven increased TSS content compared to no cover in "Grand Naine" banana [29].

Many studies have investigated the effect of light intensity on fruit color and lightness under application of cover materials [3,4,19,22,30,31]. Here, ALF and the control significantly increased fruit color lightness (*L**) compared with the other three treatments (Table 3). Light penetration through paper (in the control) and aluminum (in ALF) was low, with radiation transmissivity of 0–4% compared with the other materials (29–56%) (Table 2). Lower light penetration through a material limits chlorophyll pigment formation during fruit growth and development [30]. This observation agreed with previous studies on other cover materials having low light penetration, for example, ALF on Cavendish banana [4,22,31], paper and polyethylene (PE) on "Prata" banana [3], and black PE on "Nanica" banana [19]. In previous studies, a reduction of *L** value on Cavendish banana [4,15], as well as an increase in hue angle (H°) value on banana "Nianca" [19], were observed in fruit covered with nonwoven material. However, an increase in lightness (*L**) value for banana fruit with AFL covering may not meet consumer acceptance (personal interview, data not shown), since the color of Cavendish banana changed from dark green to light green.

Application of covers (3 week AIE) on fruit has a significant influence on fruit maturity during growth and development. Pulp-to-peel ratio and dry matter content were considered to be important parameters when determining fruit maturity for banana [7,32], avocado [33], durian [34] and kiwi fruit [35]. In this study, all five treatments (in both trials) did not significantly affect pulp-to-peel ratio (Figure 5). This result concurred with previous studies on different material covers, where perforated blue PE, NW, and ALF bunch cover materials did not significantly increase pulp-to-peel ratios of William, Jahaji and Cavendish banana, respectively [2,6,7]. A recent study conducted on Cavendish banana during the winter season also found that perforated blue PE and NW did not significantly affect pulp-to-peel ratio [4,15]. For dry matter content, there was a small difference between control and NW in the summer trial (Figure 5). This was related to low TSS content observed in both cover treatments (Table 3). WPNW, ALF and WPNW + ALF treatments provide the highest TSS and dry matter contents. The optimum temperature of banana fruit growth is 22 °C [29], whereas average temperatures in ALF and control covers (summer trial) were 24.9 °C and 26.1 °C, respectively (Figure 3). Fruit fill rate by dry matter accumulation decreased with increase in temperature [26]. The higher TSS and dry matter content observed in ALF cover may result from cooler temperature inside, promoting Cavendish fruit growth. Further study on starch accumulation and sugar conversion should be conducted to explain the effect of temperature inside bunch cover on starch and sugar level in Cavendish banana under cool and hot microclimates.

Limited studies have reported the effect of cover materials on the incidence of chilling injury (CI) and sunburn (SB) during winter in tropical and subtropical areas [1–4,15,19,22]. NPPE of 0.13 mm thickness was recommended to increase temperature inside bunch cover [29]. Recently, the use of black translucent PE (either 0.008 mm or 0.010 mm thickness) combined with NW (0.003 mm) exhibited mild CI in "Nanica banana [19]. In this study, material thickness ranged from 0.027 mm (NPPE) to 0.310 mm (WPNW). NPPE provided the lowest Q_x value (lowest thermal insulation property) compared to the other cover materials, except for TNW (Table 2). The PS layer (0.253 mm), despite its good thermal insulation (highest Q_x value), did not protect CI of banana in the winter trial. A recent report on CI of "Prata" banana in Brazil focused on employing different materials for CI protection. The use of NW (0.003 mm) and laminated NW (0.010 mm) as cover materials did not prevent CI on "Prata" banana peel [3]. Similarly, our results revealed that increasing material thickness (NPPE and NW), multilayer covering (2 to 4 layers), and combining different materials (WPNW + ALF) did not completely prevent CI in Cavendish banana in the winter trial.

CI incidence (score of 2) at the mature green stage was observed to increase (CI score of 3) at the ripening stage (Figures 6 and 7). CI remains a problem for Cavendish banana production in Chiang Rai, particularly during the coldest weather (November and December). The minimum air temperature recorded during the winter trial (10.0 °C) was below the CI temperature (13.0 °C) of banana (Figure 3A). The CI incidence depends on both temperature and exposure time. In this study, accumulated time for air temperature below 13 °C was 45 h (data not shown). In Brazil, "Prata" banana bunches covered with different materials and layers (NW, paper and blue PE) did not protect against CI incidence when the temperature fell below 5 °C for 5.25 h [13]. Most previous studies were conducted in the postharvest field. Mild symptoms of CI were evident in Cavendish banana after only 12 h of storage at 10 °C [36]. CI symptoms were evident on the peel of Cavendish banana stored under 5 °C for 24 h [1], while unripe Dwarf Cavendish banana exhibited CI symptoms equivalent to those after 7 days of storage at 8.8 °C, 60 h storage at 5.5 °C, and 36 h storage at 2.7 °C [37]. In addition, lower L^* and H° values observed in fruits from the winter trial occurred due to deterioration of chlorophyll and oxidative polymerization of phenols, causing CI symptoms [38], whereas bananas from the summer trial showed little or no CI (Figure 6). This result agreed with previous studies, where lower L^* and H° values were observed in bunches harvested in autumn–winter, compared to those harvested in winter–spring (CI indices were 3.38 and 2.13, respectively) [4,19].

Temperatures higher than the critical temperature range (35 °C to 38 °C) caused sunburn on the top hand of the bunch and affected fruit quality during growth and development [2,39,40]. In the summer trial, no SB defects were shown in all cover treatments (Figure 8). Maximum temperatures in all five treatments ranged from 31.6 °C to 38.4 °C (Figure 3B). These temperature levels were lower than those observed in our previous study in Cavendish banana (harvesting in early summer). High temperature inside the control treatment with PS layer at 39.4 °C under air temperature in the field of 50.2 °C caused SB on banana peel, particularly on the top and middle hands of the bunch [4].

5. Conclusions

Performances of different cover materials on protecting banana against losses from temperature variation were investigated. For the winter trial, all cover materials exhibited CI, caused by low temperature below 10 °C. For the summer trial, banana fruit of the control cover had the lowest TSS content and exhibited no SB incidence. Fruit grown under ALF cover exhibited the smallest hand size, highest L^* and lowest H° values due to low temperature and low light transmission. The lighter green color of Cavendish banana covered by ALF may not meet the demands of the consumer. Results suggested that waterproof nonwoven (WPNW) could be considered as a bunch cover material to increase the TSS and to prevent fading of the green color. Fewer layers in WPNW, as environmentally friendly and reusable materials, helped to reduce temperature fluctuation without fading of the green peel color.

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