

## EFFECT OF SHADING NET COLOR ON HARVEST AGE AND FRUIT QUALITY OF MD2 PINEAPPLE (*ANANAS COMOSUS* L. Merr.)

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<https://doi.org/10.55251/jmbfs.13911>

### ARTICLE INFO

Received 4. 2. 2026  
Revised 9. 3. 2026  
Accepted 25. 3. 2026  
Published 1. 4. 2026

Regular article



### ABSTRACT

Global fresh pineapple market is dominated by MD2 cultivar due to superior sweetness, golden yellow flesh color, lower acidity, and longer shelf life compared with earlier cultivars. Despite the advantages, sunburn causes significant surface damage and yield loss. Therefore, this research aimed to evaluate the effectiveness of colored shading net application as a preharvest treatment to modify the fruit microclimate and reduce sunburn incidence. The experiment was arranged in a completely randomized design with seven treatments. These included a control without cover, recycled paper bagging, and five shading nets of different colors, namely black, white, red, green, and blue. Treatments were applied at 78 days after forcing, and evaluations were made when fruits were at the 10–20% stage of maturity or shell color 2 (SC2). The parameters included the extent of sunburn, age at harvest, physical characteristics (weight, length, diameter, and length of the crown), and attributes of fruits, color of the flesh, firmness, total soluble solids (<sup>o</sup>Brix), titratable acidity, and vitamin C levels. The results showed that all protective treatments significantly reduced sunburn compared with the control. Blue and green shading nets provided the most effective protection against sunburn (up to 96.5%) and increased vitamin C content by 17–23% compared to the control, directly enhancing the visual appearance and nutritional value of the fruit. By minimizing physiological damage and preserving antioxidant content, these treatments contribute to improved postharvest quality, greater storage stability, and higher market acceptance. Meanwhile, the black shading net increased fruit size by 33.06% without reducing <sup>o</sup>Brix or acidity, showing that sweetness and flavor balance were maintained with yield improvement. Collectively, these results report the significant role of green, blue, and black shading nets in improving overall food quality and postharvest performance, while offering a simpler and more efficient preharvest alternative to bagging for export-grade MD2 fruit production.

**Keywords:** Industry, light intensity, physicochemical, preharvest, postharvest losses

### INTRODUCTION

The MD2 cultivar accounts for 80% of the global fresh pineapple trade due to superior quality attributes, including enhanced sweetness, golden-yellow flesh color, lower acidity, and extended shelf life compared with earlier cultivars (Hossain, 2016; Nordin et al., 2023). In tropical regions such as Indonesia, high solar radiation constitutes a major production constraint since the concept increases the risk of sunburn development on the fruit. This physiological disorder compromises visual quality through peel damage and disruption of epidermal tissue integrity, reducing market value and consumer acceptance (Hossain, 2016). Continuously improved preharvest environmental modification technologies include shading nets, which are indoor protective covering materials. These nets are considered important for optimization because of the capacity to reduce solar radiation and fruit surface temperature, minimizing sunburn without altering physical or chemical properties of fruit (Syazwani et al., 2013; Siti Rashima et al., 2019). The shading nets have been demonstrated to cut down sunburn in apple, pear, and citrus fruits (Kalcsits et al., 2017; Goodwin et al., 2017; Mupambi et al., 2019), along with the fact that the operands decrease the incoming solar radiation, making a lower fruit surface temperature and a better canopy microclimate possible. Further investigation is needed in terms of the effect on the physical and chemical parameters of MD2 pineapple fruit.

Preharvest microclimate management using protective shading nets has been reported to effectively reduce sunburn incidence in MD2 pineapple to nearly zero under 50% shading intensity (Santos et al., 2021). The application of 50% shading nets in 'Smooth Cayenne' pineapple increased fruit mass and total yield by 22–39% and 22–40% compared with newspaper bagging, while mitigating sunburn (Santos et al., 2021). Shading nets reduce excessive solar radiation, protect the fruit peel from ultraviolet-induced damage, and improve postharvest quality attributes, including total soluble solids reaching 16–19 <sup>o</sup>Brix and enhanced fruit weight (Ao et al., 2025). Therefore, the fruit exhibits superior aesthetic quality

directly associated with extended shelf life and improved postharvest marketability (Santos et al., 2021).

The application of shading nets at the preharvest stage enhances the preservation of MD2 pineapple by reducing physiological weight loss to below 5% and improving sugar and ascorbic acid content (Ao et al., 2025). The use has been reported to reduce sunburn incidence in apples, with up to 92% of fruit remaining undamaged, which is analogous to the benefits observed in pineapple to mitigate heat stress and improve overall quality (Kalcsits et al., 2018). This supports compliance with global export standards, where sunburn-free MD2 pineapples account for 50–55% of the market, strengthening product competitiveness (Ao et al., 2025). Furthermore, loss reductions of up to 50% achieved at relatively low cost contribute to the sustainability of the pineapple industry (Kalcsits et al., 2018).

### MATERIAL AND METHODS

This research was conducted between August and October 2025 at the Research and Development Postharvest Laboratory of PT. Great Giant Pineapple (PG4), East Lampung, Lampung province, Indonesia. The material used was MD2 cultivar at 78 days after forcing (DAF), corresponding to the swelling stage. The experiment was arranged in a Completely Randomized Design (CRD) with seven treatments: an uncovered control, bagging using recycled brown paper routinely applied at PT Great Giant Pineapple, and five shading net colors (black, white, red, green, and blue) with a density of 40 mesh and a size of 2 × 2 m under uniform field conditions (24 plants per shaded unit). Each treatment was replicated five times. Treatment allocation was performed through complete randomization using the RAND() function in Microsoft Excel. The treatment list was randomized and sorted based on randomly generated numbers, and the obtained sequence was used to assign treatments to the numbered experimental units before application.

Observations were conducted on the first day of harvest. Each replication consisted of six fruit samples, leading to a total of 210 fruits harvested at shell color stage 2 (SC2) in accordance with the export standards of the company. The variables observed included sunburn severity, assessed visually based on the level of peel damage; harvest age, calculated from forcing until fruits reached SC2; flesh color, expressed as the proportion of yellow flesh length relative to total fruit length; fruit weight measured using a digital balance; total soluble solids (°Brix) measured with a refractometer; titratable acidity determined by titration with 0.1 N NaOH and expressed as percentage of citric acid; vitamin C content analyzed using the 2,6-dichlorophenolindophenol titrimetric method (AOAC, 1967); and fruit firmness measured to characterize flesh and core texture. The data were analyzed using analysis of variance (ANOVA) at a 95% confidence level, followed by Tukey's honestly significant difference (HSD) test at  $\alpha = 0.05$  using Minitab 22 statistical software.

**RESULTS AND DISCUSSION**

The results (Table 1) of the empirical research confirmed that all analyzed variables indicated the considerable impact of colored shading nets on MD2 cultivar quality and performance. The protective treatments resulted in a lower incidence of sunburn compared to the uncovered control, with green and blue

shading nets proving most effective, corresponding to reduced fruit surface temperature and decreased light intensity (Table 2). The shift of microclimate conditions lessened skin damage caused by sunburn and influenced the date of harvest since some shading net treatments often delayed the acquisition of shell color 2 (SC2) in comparison to the control. The results are similar to those in apples and citrus, where the application of shading nets helped avoid sunburn, while affecting fruit ripening rate. This caused the change in harvest time compared to the non-shaded control treatments (Iglesias & Alegre, 2006; Middleton & McWaters, 2002; Cronje et al., 2020).

From the perspective of physical quality, shading nets had fruit weight, diameter, and length reaching or exceeding export standards, while crown size was unchanged in all the treatments. Fruit chemical quality was retained well, as evidenced by Brix values, which were not statistically different between the treatments and were above the minimum standards. Titratable acidity and vitamin C content had positive responses to some specific net colors, specifically green and blue, where flavor was more balanced and nutritional value was improved. For sunburn control, colored shading nets and bagging are the most effective and are responsible for maintaining and improving the physical and chemical quality, as well as the uniformity, of MD2 cultivar. This leads to an increase in the percentage of fruits for export markets.

**Table 1** Effects of shading net colors on fruit quality and harvest age of MD2 cultivar. The values represent the averages, and different letters in the same row suggest statistically significant differences according to Tukey's test ( $\alpha = 0.05$ ).

Variable	Control	Bagging	Black shading net	White shading net	Red shading net	Green shading net	Blue shading net
<b>Sunburn in MD2 Cultivar</b>							
Sunburn (Level)	2.00 a	0.23 b	0.50 b	0.60 b	0.23 b	0.07 b	0.07 b
<b>Harvest Age (SC1 and SC2)</b>							
SC 1 (DAF)	135.13 b	135.5 ab	136.4 a	136.16 ab	136.13 ab	135.83 ab	136 ab
Harvest age (SC2) (DAF)	140.8 b	140.63 b	142.33 a	142.66 a	142.67 a	141.93 ab	142.1 ab
<b>Fruit Physical Quality (Fruit Weight, Diameter, Length, and Crown)</b>							
Fruit weight (g)	929.6 c	1141.5 abc	1236.9 a	1058.3 abc	1163.1 ab	978.8 bc	1098.4 abc
Fruit diameter (cm)	10.28 b	11.08 a	11.02 a	10.47 ab	10.77 ab	10.30 b	10.69 ab
Fruit length (cm)	12.79 c	15.05 a	14.81 ab	13.84 abc	14.25 abc	13.27 bc	13.64 abc
Crown length (cm)	11.59 a	11.07 a	11.45 a	11.44 a	12.69 a	11.27 a	12.54 a
<b>The Texture (Flesh and Core Firmness) and Flesh Color of Fruit</b>							
Fruit flesh firmness (N)	5.57 a	4.95 a	3.80 b	3.26 b	3.71 b	3.26 b	3.69 b
Core firmness (N)	39.23 a	39.17 a	33.21 ab	30.76 b	33.14 ab	30.74 b	31.73 b
Flesh Color (%)	0.94 ab	0.97 a	0.84 c	0.85 bc	0.89 abc	0.87 bc	0.90 abc

**Table 2** Effects of shading net colors on fruit chemical quality of MD2 cultivar. The values represent the averages, and different letters in the same row suggest statistically significant differences according to Tukey's test ( $\alpha = 0.05$ ).

Variable	Control	Bagging	Black shading net	White shading net	Red shading net	Green shading net	Blue shading net
<b>Fruit Chemical Quality (°Brix, Titratable Acidity, and Vitamin C)</b>							
Brix (%)	14.63 a	14.54 a	14.36 a	13.64 a	14.03 a	14.54 a	14.11 a
Acidity (%)	0.48 ab	0.44 b	0.48 ab	0.56 a	0.53 ab	0.56 a	0.53 ab
Vitamin C (mg/l)	421.2 ab	337.3 ab	342.5 ab	458.5 ab	405.2 ab	509.8 a	495.8 ab

The evaluation of sunburn in MD2 cultivar is carried out according to the criteria by Santos et al. (2020), where damages are classified into four levels (Figure 1), according to the intensity of a color change and the affected fruit surface area. Level 0 is for fruit with no sunburn symptoms, which is the normal green peel color. Level I has a slightly yellow color that is limited to one area only. Level II is characterized by yellowing that is spreading, accompanied by some browning, with one side of the fruit exhibiting a more intense coloration. In contrast, Level III presents extensive yellow-brown discoloration covering more than half of the fruit, with increased damage to the epidermal tissue. Level IV is described as the most severe condition, which consists of necrotic areas that are dark brown to black and structural damage, such as cortex cracking, causing the fruit to be unfit for fresh-market quality. The use of this type of classification enables uniform determination of sunburn severity and shows the difference between commercially tolerable and serious damage.



Figure 1. The criteria are the severity levels of sunburn on MD2 Pineapple. Damage Level: Level 1 - 1/3 of the fruit; Level 2 - 2/3 of the fruit; Level 3 - entire length of the fruit with sunburn; and Level 4 - scalding. Source: Author's own.

**Sunburn in MD2 Cultivar**

The results demonstrate that fruit exposed without protection experienced substantially greater sunburn severity than all shaded and bagged treatments, confirming that direct solar radiation is the primary determinant of peel injury in

MD2 pineapple. Relative to the control, all protective measures reduced sunburn by a large margin, indicating that even partial radiation interception produces a disproportionate biological benefit. This pattern reflects the radiation temperature interaction underlying sunburn development, where excessive energy load elevates fruit surface temperature beyond a critical physiological threshold, triggering cellular disruption. The clear statistical separation between the control and protected treatments supports the interpretation that unmoderated solar exposure exceeds the tolerance capacity of epidermal tissues.

From a mechanistic perspective, sunburn is closely associated with heat-induced oxidative stress. Excessive radiation increases reactive oxygen species (ROS) production, destabilizes membrane integrity, and improves pigment degradation, leading to a visible brown discoloration (Racsó & Schrader, 2012; Naschitz et al., 2015). Shading nets and bagging also reduce the total radiation load and improve the fruit microclimate, limiting thermal accumulation and suppressing ROS-mediated cellular damage (Goodwin et al., 2018). The marked reduction in peel injury under protective treatments supported previous results, where moderated radiation environments mitigate photothermal stress and preserve epidermal integrity (Shafawi et al., 2020). The absence of statistical differences among covered treatments suggests that additional spectral modifications yield diminishing returns in visible damage reduction after surface temperature is maintained below the injury threshold.

In practical terms, the strong suppression of sunburn under shading and bagging treatments substantially enhances the probability of meeting international export standards that require minimal surface defects (Codex Alimentarius Commission, 1993/1999). Conversely, fruit produced without protection would be more susceptible to downgrading due to increased visual damage. These findings underscore that radiation management is not merely a protective practice but a physiologically grounded strategy to maintain fruit quality under high-radiation tropical conditions. Collectively, the data reinforce the concept that regulating fruit microclimate is a critical intervention for stabilizing external quality and safeguarding commercial value.

#### Harvest Age (SC1 and SC2)

Harvest age is a critical indicator directly related to harvest scheduling, operational efficiency, and compliance with market quality standards. The results reported the difference in the time consumed to attain the SC1 and SC2 maturity stages in various treatments, where certain shading net treatments delay the maturity of the fruits in comparison to the control. Meanwhile, bagging had a relatively similar pattern to the control. The result suggests that preharvest microclimate modification is not just a sunburn control factor but has an effect on the rate of fruit maturation.

Pineapple maturity indices, based on shell color, reflect the ripening process from the base to the top of the fruit and are directly associated with changes in physical and chemical attributes (Rohazrin et al., 2016). Paull and Chen (2018) stated that the move from immature to a more advanced ripeness could happen in about ten days, but strongly depended on the environmental conditions. For MD2 cultivar, microclimate-modifying methods such as shading nets and bagging alter the peel color development and physicochemical changes during the ripening process. High-intensity colored shading nets reduce fruit metabolism and increase the time to reach SC2. In the absence of shading, SC1 and SC2 are reached faster (Sabtu et al., 2022). The basic results are that shading net treatments have the effect of the maturity progress being slower than the control.

Harvest age is a critical indicator for scheduling, operational efficiency, and compliance with market quality standards. These results show differences in time to reach shell color stages SC1 (30% yellowing from the base) and SC2 (50% yellowing) across treatments. Shading net treatments significantly delayed fruit maturity compared to the control, while bagging reported patterns similar to the control. These results indicate that pre-harvest microclimate modification, beyond sunburn prevention, affects fruit maturation rate through changes in light quality and intensity.

Colored shading nets filter specific wavelengths, modifying the light spectrum reaching the fruit. For example, blue or pearl nets (35-50% shading) transmit more photosynthetically active radiation (PAR, 400-700 nm) while attenuating excess ultraviolet (UV) and far-red light, which trigger stress responses (Shahak, 2008). In MD2 pineapples, high-intensity colored nets (e.g., gray or aluminet) lower the red:far-red ratio, slowing shell color development from green to yellow-orange. This spectral change delays SC1 and SC2 by 4-7 days compared to the control, as observed in this study and supported by Sabtu et al. (2022).

Light quality directly affects photosynthetic efficiency and stress reduction. Excessive direct sunlight causes photoinhibition and reactive oxygen species (ROS) accumulation, increasing maturity through increased ethylene biosynthesis. Shading nets also reduce photosynthetic stress by lowering light intensity and optimizing the blue:red light balance, enhancing chlorophyll stability and minimizing non-photochemical quenching (NPQ) (Urban et al., 2016). In pineapples, this moderates carbohydrate metabolism since shading reduces sucrose hydrolysis and starch degradation to maintain soluble solids content longer and delay the transition to SC2 (Paull and Chen, 2018). In contrast, bagging primarily blocks UV and limits gas exchange without strong spectral filtering, leading to maturation schedules similar to the control. Mechanistically, shading nets delay

maturity by downregulating fruit metabolism. Reduced light intensity lowers ATP and NADPH production, inhibiting key enzymes such as invertase and cell wall-modifying proteins essential for ripening (Rohazrin et al., 2016). This is consistent with the data, where shading treatments extend the immature to ripe phase (10 days under standard conditions) through altered auxin-ethylene interactions and delayed chlorophyll breakdown. Literature confirms that in similar crops, pearl nets increase maturation time by 20-30% through selective spectral photoprotection (Shahak et al., 2012). Therefore, targeted shading optimizes quality by synchronizing harvests for MD2 cultivars while enhancing shelf life. These modifications improve operational yields, balancing protection with precise maturation control.

#### Fruit Physical Quality (Fruit Weight, Diameter, Length, and Crown)

The results indicated that shading treatments, particularly black and red shading nets, significantly increased fruit weight compared with the control treatment. Under shaded conditions, the average fruit weight reached or approached the lower threshold required for export standards, whereas the control treatment produced noticeably lighter fruits. According to export quality requirements, MD2 pineapple must reach a minimum fruit size and weight to ensure adequate fruit proportion and structural integrity for packaging and long-distance transport (Syazwani et al., 2013). In addition, fruits produced under shading treatments generally achieved diameters that met or exceeded the minimum export standards, while fruits from the control treatment tended to have slightly smaller diameters. In this context, microclimate modification reduces environmental stress and improves translocation to the fruit (Araújo et al., 2022; Kishore et al., 2021). A greater proportion of fruit meets the expected export quality classes.

Practical standards require values in the range of 13–20 cm, with symmetrical length being critical for appearance and uniformity in export grading (Syazwani et al., 2013). The results suggested that bagging and black shading net treatments produced the longest fruit (approximately 14.8–15.1 cm), while the control treatment resulted in shorter fruit (approximately 12.8 cm). Consequently, shading treatments, particularly black and red, facilitated the development of more ideal and proportional fruit length for export markets. The UNECE FFV-49 standard requires crowns to be healthy, intact, and proportional, with a length of approximately 50–150% of the fruit length. In this research, red and blue shading nets produced crowns of approximately 12.5–12.7 cm on fruit measuring about 14–15 cm. Bagging resulted in crown lengths of approximately 11 cm on fruit of 15 cm long. These crown-to-fruit length ratios remained within the acceptable range for Extra Class and Class I under shading treatments (UNECE, 2012).

#### The texture and flesh color of the fruit.

The firmness of the fruit was mainly higher in the control and bagging treatments of group A. The colored shading net treatments were categorized into group B, possessing lower firmness values. This result shows that shading nets increased flesh softness because of the fruit harvested at the same maturity stage. Light intensity affected photosynthesis and carbohydrate allocation, decreasing the strength of the cell wall and the tissue (Martínez-Conde et al., 2024; Ali et al., 2022). The control and bagging treatments yielded the highest values, while blue, white, and green shading nets decreased core firmness. The slightly softer texture can be viewed as a benefit, while the pineapples resist the stresses of handling and transport.

A minimum yellow flesh color of 50% is the main criterion for export eligibility. In contrast, flesh and core texture are required to be firm, without a specific numerical threshold to ensure the tolerance of harvesting and distribution processes (Syazwani et al., 2013). Bagging had the highest score in the flesh color rating. The shading net treatments were above 0.84, which represents visible to golden yellow flesh without internal browning symptoms. These values exceeded the yellow flesh minimum requirement of 50%, fulfilling the export quality criteria. The flesh color was stable in the golden yellow range for several weeks under the mature-green harvest and storage at 10 °C conditions. The logo that the flesh color achieved under shading net treatments was fully compliant with the minimum criteria needed for export markets (Syazwani et al., 2013).

#### Fruit Chemical Quality (°Brix, Titratable Acidity, and Vitamin C)

The total soluble solids (°Brix) of MD2 cultivar did not show a significant difference between the treatments, such as the control, bagging, and all shading net colors. All the treatments gave out values of °Brix that were higher than the minimum Codex standard and equal to or near the practical export standards for MD2 cultivar. The use of shading nets and bagging as preharvest protective technologies does not affect fruit sweetness. Therefore, the application of the methods is feasible since no reduction in sensory qualities occurs, which is a critical factor in consumer acceptance. Titratable acidity and Vitamin C content showed colored shading in net treatments more distinctly. White and green shading nets produced the highest acidity values, while bagging resulted in the lowest values, with all treatments remaining in the range accepted for export-quality MD2 cultivar. Acidity levels influence the perception of sweetness, with higher acidity enhancing the characteristic sweet taste of MD2 cultivar and balancing the flavor

profile, contributing to the desired sweet–acid taste (Medina & Garcia, 2005). In addition, vitamin C content had the best response to green and blue shading nets, which increased the content higher than other treatments. This outcome supports the result that light spectrum modification and shading nets can stimulate ascorbic acid synthesis and give different nutritional benefits (Syazwani et al., 2013; Siti Rashima et al., 2019).

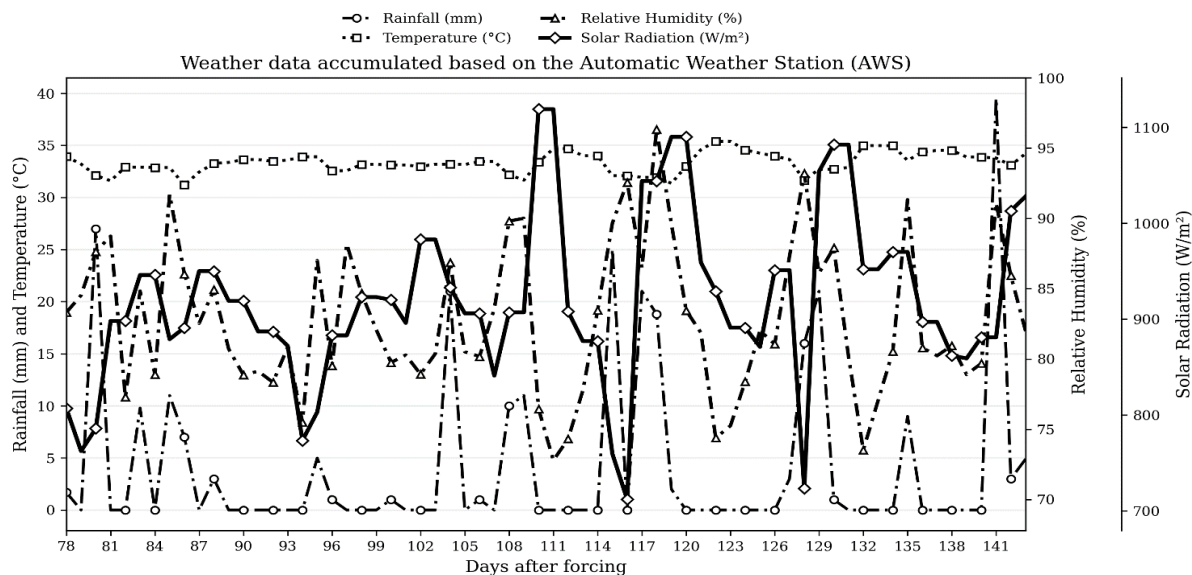
Mechanisms underlying increased vitamin C (ascorbic acid, AsA) synthesis in pineapple MD2 fruits under shading net treatments are primarily connected to modulated light absorption and photosynthetic activity, contrasting with increased maturation in full sunlight exposure (Hancock et al., 2019). High light intensity promotes AsA accumulation through enhanced photosynthesis, providing precursors and energy (ATP/NADPH). However, shading nets alter this by spectral filtering and intensity reduction, potentially optimizing synthesis amid delayed ripening (Ioannidi et al., 2019).

Light-Driven Biosynthesis Pathways: AsA biosynthesis follows the Smirnoff-Wheeler L-galactose pathway (GDP-D-mannose → L-galactose → L-galactono-1,4-lactone → AsA), dominant in fruits, with contributions from L-galacturonate (from pectin) and myo-inositol paths (Hancock et al., 2019). Light exposure upregulates genes such as GMP, GME, GGP, and GaLLDH through photoreceptor signaling (phytochromes/cryptochromes), increasing flux using photosynthate-derived substrates, including GDP-mannose (Chen et al., 2022). In shaded MD2 pineapples, colored nets (e.g., pearl/blue) transmit higher PAR diffusion while filtering UV/far-red, sustaining moderate photosynthesis without photoinhibition and supporting AsA pool maintenance during slowed SC1/SC2 progression (Bastias et al., 2017; Ioannidi et al., 2019).

**Microclimate Components**

Sunburn can be explained by cumulative radiation and heat stress, as reported by the Automatic Weather Station (AWS) during the period of 78–143 days after forcing (DAF). AWS data (Figure 2) showed environmental conditions characterized by low to moderate rainfall with frequent rainless days (mean 4.15 mm; range 0.0–39.5 mm). This increased atmospheric transparency and reduced cloud shielding against solar radiation. Furthermore, daily maximum air temperatures were relatively high (mean 33.35°C; range 31.19–35.39°C) and accompanied by relative humidity (mean 82.85%; range 72.78–96.33%). These conditions corresponded with very high levels of maximum solar radiation (mean 920.51 W m<sup>-2</sup>; range 711.9–1119.0 W m<sup>-2</sup>), increasing the radiation load on the fruit surface.

The combination of high solar radiation, elevated maximum temperatures, and reduced relative humidity during daytime hours increases the risk of sunburn by elevating the surface temperature, inducing photo-oxidative stress, and causing epidermal tissue damage in directly exposed fruit (Racskó & Schrader, 2012; Naschitz et al., 2015; Park et al., 2023). The microclimatic characteristics derived from AWS data provide strong field-based evidence that sunburn observed in the control treatment was triggered by repeated exposure to high radiation and heat stress in the observation period (Fischer et al., 2022).



**Figure 2** Weather data is collected over a specific period of time with the help of AWS

**Table 3** The average of the 18 field observations for each treatment was computed.

Treatment	Fruit surface temperature (°C)	Ambient temperature (°C)	Light intensity (lux)
Control	31.3	36.2	12571.1
Bagging	30.6	35.8	12263.3
Black shading net	28.1	36.2	11077.1
White shading net	28.3	34.7	12162.5
Red shading net	28.8	35.1	11397.9
Green shading net	28.0	34.9	11709.5
Blue shading net	27.8	35.1	11581.9

Field research supported the AWS-based explanation since the data reported a direct relationship between sunburn incidence and fruit surface temperature, solar light intensity, and ambient temperature in both control and experimental treatments. The control treatment had the highest exposure to light (12,571 lux at the peak) and fruit surface temperature (31.3°C). Bagging treatment possessed high fruit surface temperatures at 30.6°C. The opposite happened to all shading net treatments that resulted in fruit surface temperatures of 27.8–28.8 °C. The highest reductions were observed with the blue and green shading nets, which were the most effective in reducing incoming radiation and heat load on the fruit surface. Sunburn arises when the surface temperature is extremely high, causing the epidermal cells to overheat and stress. Therefore, shading is a major contributor to preventing the problem (Shahak et al., 2008; Stamps, 2008). The variability in fruit surface temperature and light intensity across the different treatments strongly

suggests that shading nets are efficient in decreasing fruit irradiance, stabilizing the microclimate around the fruit, and reducing the risk of extreme heating in the epidermal cells (Goodwin et al., 2016; Goodwin et al., 2018; Bastias & Corelli-Grappadelli, 2020; González et al., 2024).

**Practical Recommendations**

Colored shading nets prevent the occurrence of sunburn by decreasing the radiation intensity and fruit surface temperature. This has no negative impact on fruit quality since the physical and chemical quality of the fruit is preserved. The innovation prevents epidermal damage and helps to reach key quality parameters such as fruit weight, diameter, length, flesh color, and firmness required to satisfy the market. Shading nets are viewed as more operationally effective because a single system is

capable of protecting multiple plants simultaneously and is more favorable in the sunburn protection-internal quality attributes balance ( $^{\circ}$ Brix, titratable acidity, and vitamin C). Therefore, the strategy of using the right shade net color can be the beginning of dominant industry mass production, increasing the share of the MD2 pineapple fruit that reaches the export quality standards.

## CONCLUSION

In conclusion, the application of shading nets effectively reduced the incidence of sunburn in MD2 pineapple by regulating the fruit microclimate, particularly through reducing radiation exposure and lowering fruit surface temperature. All protective treatments significantly suppressed sunburn compared with the unprotected control, confirming that radiation management is the primary determinant of peel injury prevention. Although green and blue shading nets tended to exhibit lower sunburn levels, their effectiveness was statistically comparable to that of the other protective treatments, indicating that overall radiation interception rather than net color per se was the key factor underlying protection. Importantly, the use of shading nets and bagging did not adversely affect major physical and chemical quality attributes, including total soluble solids, titratable acidity, firmness, and vitamin C content, and all treatments remained within acceptable export-quality standards. Therefore, the appropriate implementation of shading systems represents a viable preharvest strategy to enhance external fruit quality while preserving internal quality characteristics. In total, the proper use of colored shading nets was a very viable preharvest strategy for large-scale industrial applications to elevate the level of fruit meeting quality standards for export markets.

**Acknowledgements:** The author expresses deepest gratitude to Mr. Ahmad Ziaurrahman, S.P., M.P., Mr. Cahyo Luqmantoro, S.P., and Ms. Indah Selviana Oktaviani, S.P. for their great motivation, help, and friendship in the research and development postharvest fresh pineapple laboratory of PT Great Giant Pineapple. Furthermore, the author also wishes to convey heartfelt thanks to the Fresh Pineapple Field Supervisors of PT Great Giant Pineapple, Mr. Suradi and Mr. Rahmat Triadi, along with all field technicians, for their cheerful support, technical assistance, and cooperation, which played a crucial role in the successful execution of field research activities.

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