

## ARTICLE

## UV-Protective Plastic Cover Changes the Microclimate of the Canopy-Rhizosphere of Peanuts: Daily UV-B Attenuation, Thermal Trapping, and Crop Yield Component Responses

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### ABSTRACT

Ultraviolet-B (UV-B) exposure and microclimate shifts can affect pod set and seed filling in peanut, yet field evidence comparing UV-blocking versus conventional plastic shading within integrated cultivation packages remains limited, especially for linked canopy–rhizosphere responses and plot yield. Six technology packages (A–F)—a farmer baseline package or the Balitkabi recommendation (Indonesian Legume and Tuber Crops Research Institute, Malang), combined with no shade, conventional plastic, or UV-blocking plastic—were arranged in a randomized block design (hereinafter referred to as RBD) with 6 treatments  $\times$  4 blocks. Microclimate was recorded at 14, 21, 28, 35, and 42 days after planting (hereinafter referred to as DAP), including UV-B irradiance ( $\mu\text{W cm}^{-2}$ ), PPFD ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), and relative humidity (%) at 08:00, 12:00, and 16:00, plus air and rhizosphere temperature ( $^{\circ}\text{C}$ ) at 05:00 and 13:00. UV-B peaked at midday and treatment separation was clearest at 12:00; at 42 DAP, unshaded A–B reached 6,727.5–6,592.5  $\mu\text{W cm}^{-2}$ , while UV-blocking shade reduced UV-B to 3,967.75  $\mu\text{W cm}^{-2}$  (package D). Shaded plots were warmer at 13:00 than unshaded plots (14 DAP: 34.05–34.90 vs 31.02–31.32  $^{\circ}\text{C}$ ), indicating thermal trapping, whereas humidity was mainly time-driven and not significantly different among packages. Package F had the highest yield components (total pods 20.18  $\text{plant}^{-1}$ ; filled pods 17.70  $\text{plant}^{-1}$ ; seeds 29.15  $\text{plant}^{-1}$ ), but plot yield (filled-pod and dry-seed weight per plot) was not significant at LSD 5%. These results suggest optimizing shade configuration/ventilation to limit midday heat

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accumulation and improving water–stand uniformity during reproductive filling to convert microclimate gains into yield.

**Keywords:** *Arachis hypogaea*; UV-B Radiation; UV-Blocking Film; Canopy–Rhizosphere Microclimate; Protected Cultivation; Technology Packages

## 1. Introduction

Peanuts (*Arachis hypogaea* L.) are a food and industrial commodity whose productivity is highly sensitive to the quality of the growing environment, especially during the pod formation and seed filling phases, which depend on the balance between photosynthesis (source) and yield formation capacity (sink). In cultivation practices, daily radiation fluctuations, extreme air temperatures, and changes in soil water availability often cause yield instability, making technological interventions that modify the microclimate relevant to reducing production risks. Physiologically, changes in the radiation energy received by the canopy will shift the rates of photosynthesis, transpiration, biomass formation, and ultimately yield components. While changes in temperature and humidity around the canopy and root zone will affect the plant's water balance and nutrient absorption efficiency<sup>[1–5]</sup>.

In the context of radiation, UV-B is an important spectrum because it plays a dual role: at certain doses, it can trigger acclimation responses and the strengthening of protective metabolites, but at high exposures, it can cause oxidative stress, protein/DNA damage, and a decline in plant physiological performance. Here, 'protection' refers specifically to photosensitive plastic shading films used as overhead covers—namely, conventional polyethylene (regular plastic) and UV-blocking (UV-protective) plastic—designed to modify UV-B transmission and the canopy energy balance, rather than pest control or chemical protection<sup>[6–8]</sup>. The UV-B response mechanism is primarily mediated by the UVR8 photoreceptor, which activates regulatory pathways (including interactions with COP1/HY5) to regulate the expression of genes related to protection and morphological adaptation. A number of modern molecular studies show that UVR8 is not just a "sensor," but a central controller that determines whether plants move toward acclimation or stress susceptibility, depending on dose, light context, and other microclimate conditions<sup>[9–11]</sup>.

Therefore, photo-selective film/plastic-based shading technology (UV plastic or regular plastic) is a theoretically sound approach: it does not simply "reduce light," but rather changes the quality of the spectrum (including UV-B transmission) while modifying the microclimate of the canopy. However, changes in the spectrum often result in changes in temperature (the "heat trap" effect), changes in vapor pressure deficit, and humidity dynamics—which then interact with plant physiological processes<sup>[12–14]</sup>. The literature on protected agriculture shows that light manipulation with photosensitive covers can affect microclimate stability, shift canopy growth strategies, and alter yields through the combined effects of radiation, thermal, and water<sup>[15,16]</sup>. Recent evidence confirms that "light manipulation" needs to be read as a system (spectrum + energy + microclimate), not as a single factor<sup>[17–19]</sup>.

On the other hand, crop response is determined not only by the canopy, but also by rhizosphere conditions. Changes in radiation and temperature above the surface will affect soil temperature, soil moisture, and evapotranspiration rates, which ultimately alter the root environment. In field systems, cover films/plastics and accompanying cultivation practices can shift heat and water flow patterns in beds (through shading, reflection, and changes in air flow), so that rhizosphere response can become a "mechanistic link" between microclimate modification and productivity. The modern mulch/film literature also shows that differences in film materials/characteristics can have agronomic consequences that are not always linear to yield—especially when microclimate effects are not large enough to overcome field variation<sup>[20–24]</sup>.

Based on this framework, this study tested six peanut cultivation technology packages (A–F) that combined cultivation practices (e.g., fertilizer input, ridging, and management components) with different shading systems (no shade, regular plastic roof, and UV plastic roof). The main contribution of this study is to present a coherent evidence chain: (i) quantification of UV-B exposure and light intensity at sever-

al ages and daily time windows, (ii) verification of microclimate consequences in the canopy (temperature–humidity), (iii) tracing rhizosphere responses (root zone temperature–humidity), and (iv) testing the ultimate implications for yield components and productivity. In this way, the research results do not stop at "differences in numbers," but reinforce a mechanistic reading of how shade-based technology packages affect process pathways (radiation → canopy/rhizosphere microclimate → yield components)<sup>[5,10,25–27]</sup>.

Therefore, this study tested six integrated cultivation technology packages (A–F) combining farmer and Balitkabi recommendations with either conventional plastic or UV-blocking plastic overhead shade. We hypothesized that UV-blocking plastic would (i) reduce canopy UV-B most strongly at midday, (ii) increase daytime canopy air temperature via thermal trapping, and (iii) induce stage-dependent changes in rhizosphere temperature and moisture, with downstream effects on pod formation and seed filling. The study further evaluated whether improvements in yield components translate into significant plot-scale productivity under field conditions.

## 2. Materials and Methods

### 2.1. Study Site, Plant Material, and Field Management

The field experiment was conducted during the main cropping season under rainfed conditions at a smallholder experimental field in Indonesia, representing a tropical monsoonal agroecosystem typical of upland peanut cultivation. The site is characterized by warm air temperature, seasonal rainfall distribution, and well-drained agricultural soil commonly used for legume production. Daily rainfall and ambient air temperature throughout the experimental period were obtained from the nearest meteorological station to provide an environmental context for canopy–rhizosphere microclimate dynamics.

Prior to planting, composite topsoil samples (0–20 cm depth) were collected and analyzed to determine key physicochemical properties, including soil texture, pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and bulk density, using standard soil laboratory procedures. These soil attributes are essential determinants of rhizosphere thermal–moisture regulation and strongly influence crop physiological processes,

resource uptake, and yield formation<sup>[28,29]</sup>.

Peanut (*Arachis hypogaea* L.) seeds derived from locally adapted cultivation material were established following regionally relevant agronomic practices and institutional cultivation recommendations. Field management components—including land preparation, planting density, fertilization strategy, weed control, and pest management—were implemented according to the specifications of each cultivation technology package to ensure treatment consistency, agronomic realism, and reproducibility of yield responses under field conditions.

### 2.2. Experimental Design and Treatment

This study was a field experiment designed using a randomized block design (RBD) with one treatment factor in the form of peanut cultivation technology packages (A–F). ARG was chosen to control for field variation between groups (blocks) so that the differences that emerged better reflected the treatment effects<sup>[30,31]</sup>. Each treatment was replicated four times, giving 24 experimental plots.

Technology packages were defined as follows: (A) farmer's standard practice (baseline, including 0.5 t ha<sup>-1</sup> farmyard manure) without shade; (B) recommended package from the Indonesian Legume and Tuber Crops Research Institute (Balitkabi), Malang, Indonesia, without shade; (C) farmer's baseline with increased manure rate (2 t ha<sup>-1</sup>) plus conventional plastic shade; (D) farmer's baseline with increased manure rate (2 t ha<sup>-1</sup>) plus UV-blocking plastic shade; (E) Balitkabi recommended package plus hilling at 21 DAP and conventional plastic shade; and (F) Balitkabi recommended package plus hilling at 21 DAP and UV-blocking plastic shade.

The six technology packages tested were:

A = farmer technology package (without shade).

B = recommended technology package from Balitkabi Malang (without shade).

C = farmer technology package + manure + regular plastic roofing.

D = farmer technology package + manure + UV plastic roofing.

E = Balitkabi technology package + mulching + regular plastic roofing.

F = Balitkabi technology package + mulching + UV plastic roofing.

Each treatment was repeated four times (four blocks), resulting in 24 experimental units. The size of the experimental unit is 2.5 m × 2.5 m; the distance between blocks is 100 cm, and the distance between plots is 50 cm. Planting distance and cultivation components follow the technology package specifications in **Table 1**.

**Table 1.** Peanut Cultivation Technology Package.

Treatment	Technology Package					
	A	B	C	D	E	F
Land preparation	Basic tillage; hoed without fine leveling	Well-prepared; finely leveled	Basic tillage; hoed without fine leveling	Basic tillage; hoed without fine leveling	Well-prepared; finely leveled	Well-prepared; finely leveled
Seeds per planting hole	2	1	2	2	1	1
Plant spacing (cm)	30 × 20	40 × 20	30 × 20	30 × 20	40 × 20	40 × 20
Fertilization	Farmyard manure 0.5 t ha <sup>-1</sup> ; SP-36 50 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>	Farmyard manure 2 t ha <sup>-1</sup> ; SP-36 60 kg ha <sup>-1</sup> ; KCl 60 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>	Farmyard manure 2 t ha <sup>-1</sup> ; SP-36 50 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>	Farmyard manure 2 t ha <sup>-1</sup> ; SP-36 50 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>	Farmyard manure 2 t ha <sup>-1</sup> ; SP-36 60 kg ha <sup>-1</sup> ; KCl 60 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>	Farmyard manure 2 t ha <sup>-1</sup> ; SP-36 60 kg ha <sup>-1</sup> ; KCl 60 kg ha <sup>-1</sup> ; NPK Phonska 100 kg ha <sup>-1</sup>
Pest and disease management	Chemical control (pesticides)	Integrated pest management (IPM)	Chemical control (pesticides)	Chemical control (pesticides)	Integrated pest management (IPM)	Integrated pest management (IPM)
Weed management	Occasional (as needed)	According to weed growth stages	Occasional (as needed)	Occasional (as needed)	According to weed growth stages	According to weed growth stages
Hilling (earthing-up)	–	–	–	–	21 DAP	21 DAP
Roof cover	No cover	No cover	Conventional plastic cover	UV-blocking plastic cover	Conventional plastic cover	UV-blocking plastic cover

### 2.3. Shade Implementation and Field Documentation

Plastic shade treatments were installed according to the predefined cultivation technology packages described in **Table 1**. Unshaded conditions were applied in packages A and B, conventional plastic shade covers in packages C and E, and UV-blocking plastic shade covers in packages D and F. All shade structures were constructed using uniform support frames and installed at comparable height and orientation to ensure consistent light interception and

airflow across shaded plots. This standardization allowed treatment effects to be attributed specifically to differences in plastic spectral properties rather than structural variation.

Field implementation and crop development under each treatment were documented photographically throughout the growing period to provide visual verification of treatment structure and crop response<sup>[32–34]</sup>. The field experimental setup and shade installation are illustrated in **Figure 1**.



**Figure 1.** Documentation of shade treatment in the peanut field experiment: (a) Experimental bed preparation before planting; (b) Installation of plastic shade structures over treatment plots; (c) Peanut crop growth under shade treatment conditions.

Note: Treatment codes A–F correspond to the cultivation technology packages defined in Table 1. Specifically, A and B = unshaded control plots; C and E = conventional plastic shade cover; D and F = UV-blocking plastic shade cover. These codes indicate experimental treatment plots in the field, rather than additional sub-figure panels.

## 2.4. Observation of Microclimate Canopy and Rhizosphere

Microclimate observations were conducted at five observation periods, namely 14, 21, 28, 35, and 42 days after planting. The variables observed included:

1. UV-B radiation at 8:00 a.m., 12:00 p.m., and 4:00 p.m. (Western Indonesian Time, hereinafter referred to as WIB).
2. Light intensity at 8:00 a.m., 12:00 p.m., and 4:00 p.m. WIB.
3. Air humidity at 8:00 a.m., 12:00 p.m., and 4:00 p.m. WIB.
4. Air temperature at 5:00 a.m. and 1:00 p.m. WIB.
5. Rhizosphere temperature at 5:00 a.m. and 1:00 p.m. WIB.
6. Rhizosphere moisture at 8:00 a.m., 12:00 p.m., and 4:00 p.m.

Measurements were taken consistently at the same time to ensure comparability between treatments. Methodologically, meteorological/microclimate observations need to pay attention to measurement consistency, direct sensor exposure, and standardization principles so that data over time can be validly compared [35–37].

## 2.5. Output and Productivity Components

To evaluate generative performance, the following yield components were observed: number of pods per plant (total pods, filled pods, empty pods), seed characteristics per plant (number of seeds, seed weight per plant, weight of 100 seeds), and plot-scale productivity in the form of weight of filled pods per plot and weight of dry seeds per plot. Definitions and recording procedures followed field agronomic measurement practices in a block experimental design [31,38,39].

## 2.6. Data Analysis

The data were analyzed using analysis of variance (ANOVA) according to the RBD model:

$$Y_{ij} = \mu + T_i + B_j + \varepsilon_{ij}$$

with  $Y_{ij}$  = observation values for treatment  $i$  in block  $j$ ;  $\mu$  = general average;  $T_i$  = treatment effect;  $B_j$  = block effect;  $\varepsilon_{ij}$

= experimental error. If ANOVA shows a significant effect, the mean differences are further tested using LSD at the 5% (0.05) level. The use of ANOVA-RBD and LSD mean separation tests is a standard procedure in agricultural experiments to distinguish treatment effects when the design and assumptions are met [30,31,40–42].

## 3. Results

### 3.1. Microclimate Shifts under UV vs. Non-UV Cover: Diurnal Patterns and Seasonal Consistency

Microclimate was monitored at five growth stages (14, 21, 28, 35, and 42 DAP) and three diurnal windows (08:00, 12:00, and 16:00) to measure differences in UV-B exposure driven by treatment. **Figure 2** summarizes the midday (12:00) UV-B trajectory across treatments (A–F). Where available, complementary microclimate indicators (e.g., light intensity/PAR, air temperature, and relative humidity, including rhizosphere conditions) are reported in **Table 2**.

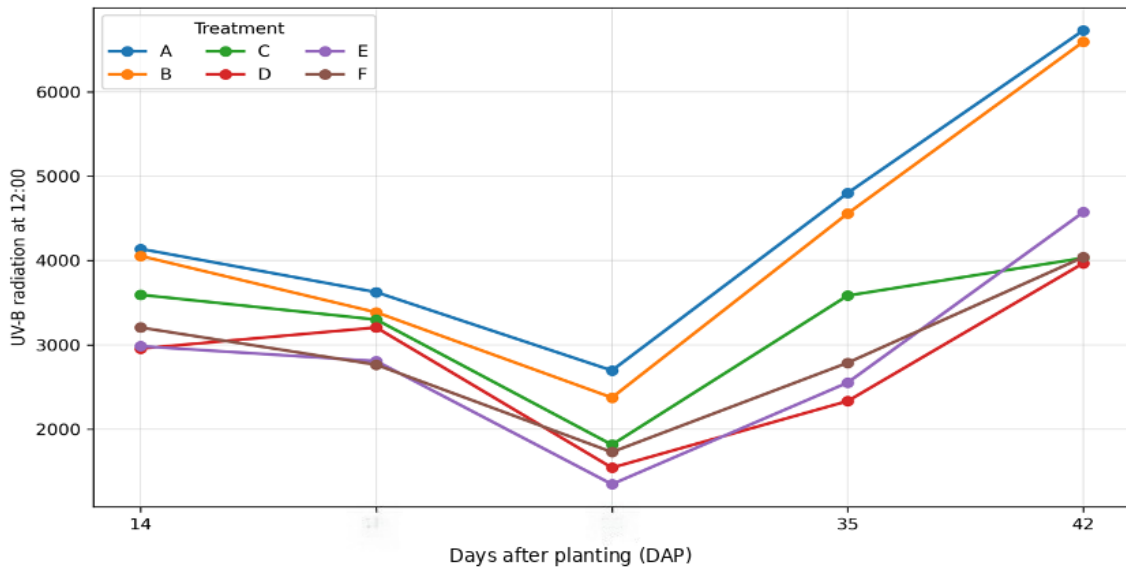
Throughout the observation dates, UV-B showed pronounced diurnal variation—highest at 12:00 and lower at 16:00 (**Supplementary Materials Table S1**)—indicating that time is the dominant driver of UV-B exposure. The contrast becomes even clearer in the next stage; for example, at 42 DAP (12:00), UV-B ranged from 3,967.75 to 6,727.5, whereas at 14 DAP (4:00 PM) the values were substantially lower (18.25–31.0), supporting the interpretation that treatment differences are most diagnostic in mid-day conditions.

Treatment rankings remained stable throughout all stages. Treatments A and B consistently produced higher UV-B levels, especially at 12:00, and often formed the top statistical group (letter “a/ab”). Conversely, treatments C–F reduced UV-B on most dates, with the most pronounced separation occurring at midday. For example, at 42 DAP (12:00), A reached 6,727.5a and B reached 6,592.5a, while C (4,030c), D (3,967.75c), and F (4,039c) were much lower; E was intermediate (4,572.5b). A similar separation is observed at 14 DAP (12:00), where A (4,137.75a) and B (4,054ab) exceed D (2,955.50d) and E (2,984d). Overall, these results confirm substantial differences in UV-B transmission among the treatments, with A–B maintaining higher UV-B exposure and C–F functioning as stronger UV-B

attenuators.

Collectively, the microclimate dataset indicates that treatment effects on UV-B are consistent across growth stages and are most discriminative at midday (12:00). This

stratification of UV-B exposure provides a robust physical basis for interpreting subsequent differences in plant growth, physiological responses, and yield components in the following Results subsections.



**Figure 2.** Midday UV-B radiation (12:00) across growth stages (14–42 DAP) under treatments A–F. Values are plotted from treatment means reported in **Supplementary Materials Table S1**; letter groupings and LSD (0.05) are reported in the supplementary table.

**Table 2.** Light intensity across all treatments (A–F) at three diurnal windows (08:00, 12:00, 16:00) at 14–42 DAP.

Treatment	Light Intensity														
	14 DAP			21 DAP			28 DAP			35 DAP			42 DAP		
	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00
A	298.75a	896.75a	9.50a	230.25a	495a	9.50a	321.50a	350a	10.50a	113.50a	535.50a	104.25a	119a	639.25a	12.75a
B	330a	912.25a	9.50a	212.50a	406a	8.50a	319a	358.75a	10.75a	115a	489.25a	103.75a	115.75a	636.25a	12.50a
C	223.50b	717.75b	7b	165.25b	368.50a	6.50b	232b	283a	7.25b	105.25a	444a	70b	70.75b	466bc	9b
D	232.50b	679.25b	7b	141.75b	377.75a	6.50b	221.75b	251.75a	7.25b	76b	404a	70.25b	72.25b	443.25c	8.75b
E	222.25b	731.75b	6.50b	163b	328a	6.75b	219.25b	251a	7.50b	74.50b	377.50a	74.75b	72.25b	471.75b	8.75b
F	233b	696.75b	6.75b	143.25b	377.50a	6.50b	214.25b	308a	7b	76.50b	436.50a	72.25b	75b	450.50bc	8.25b
LSD 0.05	35.67	62.68	0.65	42.78	109.39	0.67	20.21	91.18	0.65	12.24	160.99	8.29	8.36	27.05	0.87

Note: Light intensity values are reported across five growth stages (14–42 DAP) and three diurnal windows. Means followed by different letters within the same observation cell differ significantly at LSD (0.05).

### 3.2. Air Temperature and Humidity under Shade: The "Heat Trap" Effect and Humidity Stabilization

Microclimate observations at the canopy level were followed by evaluating air temperature (05:00 and 13:00 WIB) and air humidity (8:00 a.m., 12:00 p.m., and 4:00

p.m.) at five observation ages (14, 21, 28, 35, and 42 DAP). The aim was to explain how shade-based technology packages (UV plastic roofing or regular plastic) modify the growing environment compared to systems without shade. A summary of air temperature data is presented in **Table 3**, while air humidity is presented in **Table 4**.

**Table 3.** Average effect of six peanut cultivation technology packages on air temperature (°C) at 05:00 and 13:00.

Treatment	Air Temperature									
	14 DAP		21 DAP		28 DAP		35 DAP		42 DAP	
	05.00	13.00	05.00	13.00	05.00	13.00	05.00	13.00	05.00	13.00
A	24.62b	31.02b	24.62b	34.47b	24.90b	34.67b	23.70b	34.52b	23.05b	37.82b
B	24.50b	31.32b	24.40b	34.82b	24.80b	34.52b	23.70b	34.47b	23b	38.35ab
C	27.80a	34.05a	29.47a	37.20a	28.62a	37.02a	27.90a	37.67a	27.55a	38.95a
D	27.80a	34.65a	29.17a	37.32a	28.57a	37a	27.57a	37.37a	27.62a	39.07a
E	27.77a	34.90a	29.02a	37a	28.75a	36.92a	27.67a	36.85a	27.70a	39.45a
F	27.80a	34.62a	29.25a	37.12a	28.27a	36.87a	27.57a	37.27a	27.72a	39.10a
LSD 0.05	0.60	1.20	0.82	1.09	0.45	0.51	0.75	1.30	0.49	1.04

Note: A and B = no shade; C and E = regular plastic roof shade; D and F = UV plastic roof shade. Means followed by different letters within the same column differ significantly at  $p \leq 0.05$  based on the LSD test.

**Table 4.** Average effect of six peanut (*Arachis hypogaea* L.) cultivation technology packages on air humidity (%) at 08:00, 12:00, and 16:00.

Treatment	Air Humidity														
	14 DAP			21 DAP			28 DAP			35 DAP			42 DAP		
	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00
A	78ab	48.50a	98a	76.50a	56.25a	76.25a	69.50a	59.50a	87.25a	88.50a	58.25a	70.25a	95.25a	61a	91.25a
B	79.50a	48.75a	98a	73.75a	53.50a	76.75a	67.75a	58.25a	86.25a	86.75a	56.50a	72.25a	94.25a	61a	91.50a
C	76.25abc	48a	98.50a	74.50a	53.25a	76a	67.75a	59.25a	89a	86.75a	57.75a	72.25a	96.50a	61a	90.75a
D	73c	47.75a	98.50a	76.50a	57a	75.75a	70.75a	58a	88.50a	91.25a	59.50a	71.50a	96.75a	67.25a	91.75a
E	77.50ab	48.50a	97.75a	77a	56a	76.5a	70a	58.50a	86a	91a	57.75a	71a	94.50a	61.75a	91.75a
F	74.50bc	47.75a	98.50a	76.75a	56.25a	76.25a	70.25a	59.25a	88.25a	90a	59.50a	70.75a	96.50a	65.50a	91.5a
LSD 0.05	3.99	0.93	0.94	6.82	5.08	1.51	6.72	1.70	3.05	6.41	3.74	2.02	2.23	6.27	1.46

Note: A and B = no shade; C and E = regular plastic roof shade; D and F = UV plastic roof shade. Means followed by different letters within the same column indicate significant differences at  $p \leq 0.05$  according to the LSD test.

### 3.2.1. Air Temperature

Based on **Table 3**, six peanut cultivation technology packages showed a significant effect on air temperature at all observation ages (14–42 DAP) and at both observation times (05:00 and 13:00 WIB). Consistently, treatments without shade (A and B) had lower air temperatures than treatments with shade (C, D, E, F). This pattern was evident in both morning and afternoon observations, indicating that the presence of plastic shade altered the energy balance around the plant canopy. The difference was apparent from the early stages of growth. At 14 DAP at 05:00, the air temperature in A (24.62 °C) and B (24.50 °C) was lower than in C–F, which was in the range of 27.77–27.80 °C. At 14 DAP at 1:00 p.m., A (31.02 °C) and B (31.32 °C) were also lower than C–F (34.05–34.90 °C). The same trend persisted until the end of the observation; at 42 DAP at 5:00 a.m., A–B were around 23.00–23.05 °C, while C–F were around 27.55–27.72 °C, and at 42 DAP at

13:00, A (37.82 °C) and B (38.35 °C) were still lower than C–F (38.95–39.45 °C).

The increase in temperature under shade indicates the presence of a "heat trap" effect under plastic shade: radiation that penetrates the plastic is reflected back to the ground and plants, causing heat to be relatively trapped, resulting in higher temperatures under shade compared to open conditions. This pattern is in line with the principle of microclimate in shade structures/greenhouses, where the temperature in the protected space tends to increase during sunlight exposure.

Overall, the results in **Table 3** confirm that plastic shading (both UV plastic and regular plastic) consistently increases the air temperature around the canopy compared to no shading. Thus, in the next subsection, any differences in plant physiology/growth should be interpreted considering that treatments C–F took place under warmer thermal conditions.

### 3.2.2. Air Humidity

Unlike air temperature, **Table 4** shows that the six cultivation technology packages had no significant effect on air humidity at most ages and observation times. The range of air humidity between treatments was  $\pm 50\text{--}90\%$ , with a general trend: higher humidity in the morning (08.00) and afternoon (16.00), while values decreased at noon (12.00). This pattern is consistent with the inverse relationship between temperature and humidity, namely, when the temperature increases during the day, the relative humidity tends to decrease.

Although generally there was no significant difference, there was one important exception: at 08:00 DAP, air humidity showed a significant effect. At that time, the highest value was found in package B (79.50), followed by package A (78), while the lowest value was found in package D (73); the other treatments were in the middle range. This difference in early growth may occur due to initial conditions of humidity and morning evaporation, so that unshaded plots (A–B) may show higher air humidity than some shaded plots at certain measurement times.

Operationally, the insignificant differences in humidity between packages indicate that the shade system still allows for air exchange and mixing within and around the beds, resulting in relatively uniform humidity between treatments. In addition, as the plants grow, the increasingly

dense canopy can help maintain micro-humidity around the canopy, thereby reducing variations between treatments.

Thus, in the microclimate of the canopy, the technology package mainly differentiates the growing environment through increased air temperature (thermal effect of shade), while air humidity is relatively stable and is more influenced by the time of observation (morning, noon–afternoon) than by the type of shade. These findings provide an environmental basis for reading the next subsection of results, especially when linking plant responses to higher thermal conditions in shaded treatments.

### 3.3. Rhizosphere Dynamics under Shade: Rhizosphere Temperature and Rhizosphere Moisture

In addition to the canopy microclimate, environmental conditions in the root zone (rhizosphere) are important determinants of water availability and the efficiency of plant physiological processes. Therefore, observations were continued on rhizosphere temperature (05:00 and 13:00 WIB) and rhizosphere humidity (08:00, 12:00, 16:00 WIB) at five observation ages (14–42 DAP) to see how the shade technology package modified soil conditions around the roots. A summary of rhizosphere temperature is presented in **Table 5**, while rhizosphere moisture is presented in **Table 6**.

**Table 5.** Average effect of six peanut (*Arachis hypogaea* L.) cultivation technology packages on rhizosphere temperature (°C) at 05:00 and 13:00.

Treatment	Temperature Rhizosphere									
	14 DAP		21 DAP		28 DAP		35 DAP		42 DAP	
	05.00	13.00	05.00	13.00	05.00	13.00	05.00	13.00	05.00	13.00
A	27a	32ab	26.25bc	33.50a	25.25c	31.25ab	24b	31.25ab	23.50b	31b
B	26.50a	31.75ab	25.75c	33.75a	26bc	32a	24.25b	31.50a	23.75b	33a
C	26.50a	32ab	27ab	33a	26.25ab	31.25ab	25a	30cd	23.75b	29.25b
D	27a	31b	27.25a	33.50a	26bc	30.50b	25a	29.50d	24.75a	29.50b
E	26.75a	32.50a	27ab	33a	26.50ab	31ab	25a	30.25bcd	24.25ab	30b
F	27a	31.50ab	27ab	35.75a	27a	31.75a	25a	30.75abc	24.75a	30.25b
LSD 0.05	0.80	1.05	0.72	3.78	0.72	1.08	0.58	1.10	0.80	1.93

Note: A and B = no shade; C and E = regular plastic roof shade; D and F = UV plastic roof shade. Values represent the mean of replicates. Means followed by different letters within the same column indicate significant differences at  $p \leq 0.05$  according to the LSD test.

**Table 6.** Average effect of six peanut (*Arachis hypogaea* L.) cultivation technology packages on rhizosphere moisture at 08:00, 12:00, and 16:00 WIB.

Treatment	Moisture Rhizosphere														
	14 DAP			21 DAP			28 DAP			35 DAP			42 DAP		
	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00	08.00	12.00	16.00
A	92.5a	78.75a	100a	81.25a	78.75a	100a	87.5a	81.25a	100a	100a	100a	100a	100a	100a	100a
B	95a	76.25a	100a	87.50a	72.50a	100a	87.50a	76.25a	100a	100a	100a	100a	100a	100a	100a
C	28.75b	25b	48.75b	56.25b	40.25b	51.25b	25b	21.25b	20c	81.25a	77.5a	80a	81.25a	77.50a	78.75a
D	41.25b	17.5b	38.75b	50b	50b	55b	26.25b	20b	23.75b	85a	71.25a	81.25a	82.50a	80a	80a
E	36.25b	18.75b	42.50b	40b	50b	50b	26.25b	20b	20c	97.50a	97.50a	100a	100a	100a	100a
F	20b	20b	58.75b	43.75b	47.50b	53.75b	26.25b	22.50b	21.25c	83.75a	80a	80a	82.50a	80a	80a
LSD 0.05	30.38	12.11	19.01	23.16	17.06	16.33	9.01	6.95	2.10	25.26	33.34	32.36	29.61	32.70	32.08

Note: A and B = no shade; C and E = plastic roof shade; D and F = UV plastic roof shade. Values represent the mean of replicates. Means followed by different letters within the same column indicate significant differences at  $p \leq 0.05$  according to the LSD test.

### 3.3.1. Rhizosphere Temperature

Based on **Table 5**, the effect of technology packages on rhizosphere temperature fluctuates according to plant age and observation time. In the early growth phase, several age-hour combinations showed no significant difference, which is logical because the plants were still small and the canopy had not yet covered the soil surface, so radiation reception on the bed surface was relatively homogeneous between treatments.

In general, at 14 days after sowing, the rhizosphere temperature ranged from 26.50 to 27.00 °C (at 5:00 a.m.) and 31.00 to 32.50 °C (at 1:00 p.m.) between treatments, showing relatively small differences. At mid-age (21–28 DAP), variations in rhizosphere temperature at 1:00 p.m. also tended to narrow in several treatments, indicating that the intensity of daytime radiation can equalize soil surface temperatures in both unshaded and shaded beds.

Towards the end of the observation period, there were indications of a decrease in rhizosphere temperature in several treatments, which was consistent with increased canopy cover. At 42 DAP at 05:00, the rhizosphere temperature ranged from 23.50 to 24.75 °C, and at 42 DAP at 13:00 it ranged from 29.25 to 33.00 °C. This variation is relevant because the rhizosphere is an environment that directly affects water and nutrient uptake; a decrease in soil temperature during the broad canopy phase may be related to a reduction in radiation reaching the soil surface due to the shading effect of the plant canopy.

Overall, rhizosphere temperature data show that

differences between technology packages do not always appear at every age-hour, but are influenced by canopy dynamics and daily radiation intensity. Therefore, the interpretation of growth results and yield components in the next subsection needs to consider that the effects of treatment on the root zone are situational, especially when the canopy begins to develop and changes the distribution of heat energy on the soil surface.

### 3.3.2. Rhizosphere Moisture

In contrast to rhizosphere temperature, **Table 6** shows that the technology package had a significant effect on rhizosphere moisture during most of the observation period. In general, treatments without shade (A and B) had higher rhizosphere moisture, while treatments with shade (C–F) showed lower moisture in the early to mid-observation phases. This pattern indicates that soil water conditions in the root zone are determined not only by shade, but also by rainfall distribution, capillarity, and differences in evaporation on the beds.

This contrast is very clear in the early phase. At 14 DAP at 08:00, rhizosphere moisture in A reached 92.5 and B 95, while C–F were much lower (e.g., F 20, C 28.75, E 36.25, D 41.25). The same pattern was seen at 14 DAP at 12:00, where A 78.75 and B 76.25 were still much higher than C 25, D 17.5, and E 18.75. At 28 DAP, the difference remains strong, especially at 4:00 p.m., where A–B reaches 100, while C–F is much lower (around 20–23.75).

However, towards the end of the observation period,

the differences between the treatments tended to decrease. At 35 and 42 days after planting, many rhizosphere moisture values increased sharply, and some treatments approached 80–100, indicating that soil moisture conditions were increasingly well maintained. This condition makes sense because in the broad canopy phase, the soil surface is more protected, so that evaporation is reduced and soil moisture is more stable, causing the differences between beds to become less contrasting.

In summary, the rhizosphere shows two main messages: (i) rhizosphere temperature is influenced by radiation–canopy interactions, so treatment differences are not always consistent at every age–hour; and (ii) rhizosphere moisture shows strong treatment separation, especially in the early to mid-phase, but tends to converge in the broad canopy phase (35–42 DAP). This combination of thermal conditions and soil water dynamics provides a strong environmental basis for interpreting differences in growth performance, physiology, and yield components in the next

subsection on yield.

### 3.4. Yield and Productivity Components: Pod Formation, Seed Characteristics, and Yield per Plot

The differences in canopy microclimate (Sub results 3.1–3.2) and rhizosphere dynamics (Sub result 3.3) were further evaluated for their implications on the generative performance of peanuts through yield and productivity components. The parameters analyzed include: (i) number of pods per plant (total pods, filled pods, and empty pods), (ii) seed characteristics per plant (number of seeds, seed weight, and weight of 100 seeds), and (iii) yield per plot (weight of filled pods per plot and weight of dry seeds per plot). A summary of the yield components is presented in **Tables 7** and **8**, while productivity per plot is presented in **Table 9**.

**Table 7.** The effect of six peanut cultivation technology packages (A–F) on the number of pods per plant (total pods, filled pods, and empty pods).

Treatment	Total Pods (Plant Fruit <sup>-1</sup> )	Fruit Pods (Plant Fruit <sup>-1</sup> )	Empty Pod (Fruit of a Plant) <sup>-1</sup>
A	12.62 b	10.85 b	1.77 a
B	13.69 ab	12.10 ab	1.59 a
C	13.68 ab	12.05 ab	1.63 a
D	15.12 ab	12.70 ab	2.42 a
E	15.36 ab	14.20 ab	1.17 a
F	20.18 a	17.70 a	2.48 a
LSD 0.05	6.85	6.03	1.96

Note: A and B = no shade; C and E = regular plastic roof shade; D and F = UV plastic roof shade. Values are averages. Significant differences between treatments for each parameter were assessed using the LSD test at a 5% (0.05) level.

**Table 8.** The effect of 6 peanut cultivation technology packages (A–F) on the number of seeds per plant, seed weight per plant, and the weight of 100 seeds.

Treatment	Number of Seeds per Plant (Plant Grains <sup>-1</sup> )	Seed Weight per Plant (g Plant <sup>-1</sup> )	Weight of 100 Pieces (g)
A	18.90	6.64	43.94
B	21.00	7.76	35.30
C	20.60	7.61	41.65
D	22.45	9.05	42.48
E	23.85	9.96	39.12
F	29.15	9.72	38.68
LSD 0.05	11.90	4.64	6.47

Note: A and B = no shade; C and E = regular plastic roof shade; D and F = UV plastic roof shade. Values are averages; significant differences between treatments for each parameter were tested using LSD at a 5% (0.05) level.

**Table 9.** Peanut productivity in 6 technology packages (A–F): weight of filled pods per plot and weight of dry seeds per plot.

Treatment	Weight of Beans per Plot (g)	Dry Seed Weight per Plot (g)
A	294.05a	199.17a
B	212.60a	135.00a
C	364.92a	243.65a
D	346.12a	223.62a
E	199.85a	132.57a
F	249.75a	158.47a
LSD 0.05	230.00	159.06

Note: Values are means; numbers followed by different letters in the same column indicate significant differences in the LSD 0.05 test. All treatments received the same letter (a) for both columns because the differences between means did not exceed the LSD 0.05 value in each column.

### 3.4.1. Pod Formation per Plant

Based on **Table 7**, the technology package shows variations in the number of pods per plant, both for total pods and filled and empty pods. Pod formation per plant was analyzed through total pods, filled pods, and empty pods as indicators of yield formation efficiency. Filled pods represent successful formation and filling, while empty pods signal constraints on seed formation/filling under certain microclimate conditions.

Based on **Table 7**, the average total pods and pods filled tended to increase in certain packages, with the most obvious contrast between package F and package A. The difference between the mean of package F and package A exceeded the LSD value of 0.05 for both total pods (20.18 vs. 12.62) and filled pods (17.70 vs. 10.85), indicating a significant difference in both parameters. Conversely, the number of empty pods did not differ significantly between treatments (all mean differences did not exceed the LSD), so that the variation in yield components was mainly reflected in the increase in total pods and the fraction of filled pods, rather than in the reduction in empty pods.

### 3.4.2. Seed Characteristics per Plant

Furthermore, **Table 8** shows the differences in seed characteristics, which include the number of seeds per plant, seed weight per plant, and the weight of 100 seeds. The combination of these three parameters helps explain whether the difference in yield is mainly driven by an increase in the number of seeds (sink capacity), an increase in total seed weight per plant (yield accumulation), or a change in seed size reflected in the weight of 100 seeds. Interpretation of **Table 8** is important to clarify the mechanism of yield increase: whether it is due to a greater number of seeds, better seed filling, or both.

In seed characteristics (**Table 8**), the variation in

the average number of seeds per plant and seed weight per plant did not show a significant difference at the LSD 0.05 level because the difference between the means did not exceed the LSD value for each parameter. In contrast, the weight of 100 seeds showed more obvious variation; the package with the highest weight of 100 seeds (e.g., A) showed a greater value than the package with the lowest weight of 100 seeds (B), indicating that the difference in seed size/weight between packages was more prominent than the difference in the total number of seeds per plant.

The final impact of the technology package on productivity was evaluated based on the results per plot (**Table 9**). The parameters of pod weight per plot and dry seed weight per plot represent the most practically relevant crop yields, as they integrate environmental effects (UV-B, canopy temperature–humidity, and rhizosphere dynamics) with the generative growth response of plants. Therefore, **Table 9** is a key indicator for summarizing the most effective technology package for increasing crop yields at the plot scale.

In pod formation (**Table 7**), the most notable increase occurred in package F, especially in total pods and filled pods, while empty pods did not show consistent separation. In seed characteristics (**Table 8**), the variation in the number of seeds per plant and seed weight per plant tended not to exceed the LSD limit, while differences in seed size were more reflected in the weight of 100 seeds. However, when the results were integrated at the plot scale (**Table 9**), the mean weight of filled pods per plot and dry seed weight per plot did not differ significantly at the LSD level of 0.05. These findings indicate that changes in canopy microclimate and rhizosphere dynamics (Sub results 3.1–3.3) can affect certain yield components, but have not yet been converted into strong productivity separation at the plot level under the conditions of this experiment.

Across microclimate variables, treatment effects emerged primarily as consistent directional patterns rather than isolated numerical contrasts, where UV-blocking shade reduced midday UV-B exposure but simultaneously increased canopy thermal load, indicating coupled radiation attenuation and heat-trapping processes, while air humidity remained largely time-driven and weakly responsive to treatment. Lower rhizosphere moisture under shaded plots is therefore better explained by reduced rainfall interception and limited lateral water redistribution beneath plastic covers than by enhanced evapotranspiration, clarifying why open plots retained relatively higher soil moisture despite greater atmospheric exposure. Although several shaded packages improved reproductive yield components, plot-scale productivity remained statistically unchanged, revealing a source–sink or microclimate trade-off in which reduced UV stress may enhance pod initiation, but elevated canopy temperature and constrained soil moisture restrict assimilate accumulation during seed filling. Overall, these results indicate that microclimate modification alone is insufficient to ensure yield gain, and effective productivity improvement likely requires coordinated optimization of shade spectral properties, ventilation, and soil-water management during reproductive development.

## 4. Discussion

The present study demonstrates that UV-filtering plastic primarily restructures canopy energy balance and UV-B exposure dynamics rather than directly increasing plot-scale yield. Midday UV-B attenuation under UV-blocking shade was the most diagnostically distinct treatment response, confirming that spectral filtering modifies radiation signaling pathways associated with UVR8-mediated photomorphogenic regulation and stress acclimation<sup>[43,44]</sup>. Concurrently, the consistently higher midday air temperature observed beneath shaded treatments indicates partial thermal trapping, reflecting altered radiative and convective energy exchange within the canopy microenvironment<sup>[45]</sup>. These coupled radiation–temperature responses define the dominant physical mechanism through which shade treatments influenced crop development<sup>[24,46]</sup>.

Rhizosphere responses further suggest that microclimate modification propagated belowground through temperature–moisture redistribution, a process governed by soil heat flux and evaporative gradients rather than direct UV exposure<sup>[47,48]</sup>. Although shaded plots occasionally exhibited lower surface moisture, this pattern is mechanistically consistent with enhanced canopy interception and modified evaporation pathways rather than increased soil water loss per se. Such interactions align with environmental soil-physics theory in which canopy structure regulates subsurface thermal buffering and moisture retention, thereby indirectly shaping root-zone conditions and physiological stability during reproductive transition<sup>[49]</sup>.

Biologically, the divergence between significant improvements in yield components (e.g., higher pod and seed numbers in package F) and non-significant plot productivity indicates a classical source–sink limitation. Enhanced reproductive initiation under moderated UV-B and stabilized canopy temperature did not translate into greater final biomass allocation, implying constraints during seed filling such as assimilate supply, stand uniformity, or transient water limitation<sup>[43,50]</sup>. This distinction is critical: the treatments altered developmental partitioning without proportionally increasing whole-plot carbon gain, emphasizing that microclimate regulation alone is insufficient to secure yield enhancement<sup>[47,50]</sup>.

Taken together, the findings establish a clear ecological interpretation: UV-blocking shade functions as a microclimate regulator that reorganizes radiation signaling, canopy thermodynamics, and rhizosphere buffering, thereby strengthening early reproductive potential but not automatically increasing land-scale productivity<sup>[51,52]</sup>. The principal scientific contribution of this study is the identification of energy-balance restructuring—not yield amplification—as the primary outcome of UV-protective shading in open-field peanut systems. Translating these microclimate gains into significant yield will likely require integrative optimization of shade ventilation, water availability during seed filling, and spatial stand uniformity. Such integration positions protected or semi-protected cultivation as a potential adaptive strategy for stabilizing crop performance under increasing climatic variability, extending the relevance of these results beyond agronomy into broader agroecological resilience frameworks<sup>[51–53]</sup>.

## 5. Conclusions

The peanut cultivation technology package that combines different types of shade (no shade, regular plastic roof, and UV plastic roof) has been proven to systematically modify the microclimate throughout the 14–42 DAP phase. The unshaded treatment (A–B) maintained higher UV-B exposure, while the shaded treatments (C–F)—especially UV plastic—reduced UV-B transmission and created a warmer canopy environment (the "heat trap" effect). At the same time, relative air humidity was more stable between treatments and more controlled by observation time (morning–noon–afternoon), while rhizosphere dynamics showed patterns influenced by canopy development and water distribution: rhizosphere temperature did not always differ across age–time combinations, but rhizosphere moisture showed clearer separation in the early–middle phase and tended to converge as the canopy closed over the soil surface.

In terms of generative aspects, plant response is reflected more strongly in the yield per plant (number of pods and seed characteristics) than in the yield per plot. Certain technology packages (e.g., F) showed higher averages for total pods and filled pods, indicating an increase in yield formation and filling capacity at the plant level. However, productivity per plot (weight of filled pods and dry seed weight) did not differ significantly at the test level used, so the effectiveness of technology packages at the plot scale is still influenced by field variability and the magnitude of experimental error. Practically, these findings confirm that shade management plays a role as a powerful modifier of the growing environment, but to ensure productivity advantages at the plot level, other management components (population uniformity, water–nutrients, and control of limiting factors) need to be strengthened so that microclimate differences can be converted into consistent yields.

## Supplementary Materials

The supporting information can be downloaded at <https://journals.bilpubgroup.com/files/RE-13009-Supplementary-Materials.docx>.

## Author Contributions

Conceptualization, A.S. (Aman Suyadi) and O.D.H.; methodology, A.S. (Aman Suyadi) and O.D.H.; investigation, A.S. (Aman Suyadi), A.M.P. and A.S. (Anis Shofi-yani); data curation, A.S. (Aman Suyadi), A.M.P. and A.S. (Anis Shofi-yani); writing—original draft preparation, A.S. (Aman Suyadi); writing—review and editing, A.S. (Aman Suyadi), O.D.H., A.M.P. and A.S. (Anis Shofi-yani); visualization, A.S. (Aman Suyadi) and A.S. (Anis Shofi-yani); supervision, O.D.H.; validation, O.D.H.; project administration, A.S. (Aman Suyadi); resources, A.M.P.; formal analysis, A.S. (Aman Suyadi). All authors have read and agreed to the published version of the manuscript.

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## Institutional Review Board Statement

This study did not involve human participants or animals. Therefore, ethical approval from an Institutional Review Board or Ethics Committee was not required.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Supporting data are also provided in the **Supplementary Materials** accompanying this article.

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## Conflicts of Interest

The authors declare no conflict of interest.

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