



From sun to shade: Cultivar-specific plasticity of robusta coffee in diverse light environments

 **Veera Klaipuk**^{1,3}

 **Poonpipope Kasemsap**¹

 **Prasart Kermanee**²

 **Patchareeya Boonkorkaew**^{1,*}

¹ Department of Horticulture, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand

² Department of Botany, Faculty of Science, Kasetsart University, Bangkok 10900, Thailand

³ Horticultural Research Institute, Department of Agriculture, Ministry of Agriculture and Cooperatives, Bangkok 10900, Thailand



* Corresponding author: agrpyb@ku.ac.th

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Abstract

Background and Objective: Coffee production faces increasing challenges from climate variability, particularly light availability, while the adaptability of robusta coffee to shaded environments remains insufficiently understood compared to arabica. This study evaluated phenotypic plasticity in five robusta coffee cultivars across contrasting light conditions using morpho-anatomical, physiological, and biochemical traits, with the Relative Distance Plasticity Index (RDPI) used to quantify trait responsiveness and identify adaptive strategies.

Methodology: One-year-old plants of five robusta coffee cultivars, namely Chumphon 2 (CH2), Chumphon 4 (CH4), R2017–1 (R–1), R2017–2 (R–2), and a local Thai variety (LO), were grown under three shading levels (0%, 50%, and 80%) in a factorial design (shade × cultivar) with five replicates, where individual plants served as experimental units. Morphological, anatomical, physiological, photochemical, and pigment traits were measured, and phenotypic plasticity was quantified using RDPI. Data were analyzed by two-way ANOVA followed by Duncan's multiple range test ($P < 0.05$) in RStudio (v. 2022.02.3) using the “Agricolae” and “Plasticity” packages.

Main Results: Physiological/biochemical traits exhibited greater plasticity (RDPI = 0.16–0.25) than morpho-anatomical traits (0.10–0.13). Among cultivars, CH2 showed the highest plasticity (0.25), followed by LO (0.21), R–2 (0.20), and R–1 (0.19), whereas CH4 exhibited the lowest

responsiveness (0.16). Shading significantly modified structural traits, increasing specific leaf area and reducing leaf thickness, palisade thickness, and stomatal density ($P < 0.05$). Physiological responses were significantly affected ($P < 0.05$), with increased photochemical efficiency (F_v/F_m) and chlorophyll content, alongside reductions in dark respiration (R_d) and light compensation point (LCP).

Conclusions: Phenotypic plasticity in robusta coffee was trait-specific and cultivar-dependent. Cultivars with higher RDPI values, particularly R-2 and CH2, exhibited broader responsiveness across light environments, whereas CH4 showed comparatively limited plasticity. These findings support the use of quantitative plasticity indices to guide cultivar selection in diversified coffee production systems.

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INTRODUCTION

Coffee cultivation is a vital agricultural activity in tropical regions, contributing significantly to the economy and livelihoods of millions of farmers. However, coffee production faces growing challenges from climate change, habitat degradation, and fluctuating environmental conditions, particularly changes in light availability. These factors have heightened the need to develop sustainable cultivation systems that optimize productivity while conserving resources and maintaining ecosystem services (Jha *et al.*, 2014).

Robusta coffee (*Coffea canephora*), known for its tolerance to high temperatures and disease resistance, is traditionally cultivated in open-field systems under full sunlight. While this approach maximizes yield in optimal conditions, it often comes at the cost of soil degradation, biodiversity loss, and increased vulnerability to environmental stressors (DaMatta *et al.*, 2007). In contrast, shade-grown systems, such as agroforestry, offer numerous ecological benefits, including improved soil quality,

enhanced biodiversity, and a stable microclimate that buffers extreme weather conditions (Jha *et al.*, 2014). Such systems have also been associated with improved coffee quality and reduced vulnerability to pests and diseases (Perfecto *et al.*, 1996). Despite the growing interest in shade-grown systems, much of the existing research has focused on arabica coffee (*Coffea arabica*), which is inherently more shade-tolerant than robusta. Studies on the adaptability of robusta coffee to shaded environments remain limited. Robusta coffee is generally considered a shade-facultative species, capable of tolerating moderate shading but requiring further investigation to understand its phenotypic plasticity under varying light conditions (Matos *et al.*, 2009).

Phenotypic plasticity, defined as the capacity of a genotype to modify its morphology, anatomy, physiology, and biochemical traits in response to environmental variation, plays a central role in determining the adaptability of coffee cultivars to contrasting light conditions (Gratani, 2014). In coffee and other shade-adaptable tropical species, traits

such as specific leaf area, leaf thickness, chlorophyll concentration, and photosynthetic capacity are particularly responsive to light gradients, enabling plants to optimize carbon gain under both high and low irradiance (Valladares *et al.*, 2005; Niinemets, 2007). Understanding the coordinated adjustment of these traits under different shading regimes is therefore essential for selecting cultivars suitable for either open-field monoculture systems or agroforestry-based shaded cultivation.

To quantify the magnitude of phenotypic plasticity across light environments, the Relative Distance Plasticity Index (RDPI) was employed. RDPI provides a standardized measure of trait plasticity by calculating the relative difference in a given trait between environmental conditions, scaled between 0 (no plasticity) and 1 (maximum plasticity) (Valladares *et al.*, 2006). Unlike simple comparisons of mean trait values, RDPI integrates the degree of proportional change across treatments, allowing direct comparison among traits with different units and scales. This index has been widely applied in ecophysiological studies to assess adaptive strategies in response to light heterogeneity, particularly in forest and agroforestry systems (Valladares *et al.*, 2006; Gratani, 2014). Therefore, RDPI serves as an effective tool for identifying which morphological and anatomical traits contribute most strongly to light acclimation in robusta coffee cultivars.

This study tests the hypothesis that phenotypic plasticity differs significantly among five commercially cultivated robusta coffee cultivars when exposed to contrasting light environments, namely full sunlight (0% shading), moderate shade (50%), and deep shade (80%). We hypothesize that morphoanatomical traits associated with light interception, including specific leaf area, leaf area, and palisade thickness, exhibit greater plastic responses under shaded conditions than under full sunlight. Furthermore, we propose that physiological and biochemical traits

related to photosynthetic performance, such as chlorophyll content and light-use efficiency, display cultivar-specific responses across light gradients. We also hypothesize that cultivars characterized by higher RDPI values in key adaptive traits demonstrate greater suitability for shaded or agroforestry-based production systems, whereas cultivars with lower plasticity maintain more stable performance under full-sun conditions. By testing these hypotheses, this study aims to elucidate cultivar-specific adaptive strategies that optimize productivity while supporting ecological sustainability across diverse coffee cultivation systems.

MATERIALS AND METHODS

Plant Material and Experimental Setup

Five cultivars of *Coffea canephora* Pierre ex A. Froehner (robusta coffee) were evaluated: Chumphon 2 (CH2), a progeny of the Congolese group; Chumphon 4 (CH4), a progeny of the Guinean and Congolese groups; R2017–1 (R–1) and R2017–2 (R–2), both progeny of the local Thai variety; and the local Thai variety (LO). CH2 and CH4 were developed by the Plant Breeding Program (PBP) of the Department of Agriculture (DOA) of Thailand, while R–1 and R–2 were developed by the PBP of Quality Coffee Products Co., Ltd. The local Thai variety was included in the study due to its widespread use by producers.

Twelve-month-old coffee plantlets from each cultivar, with approximately eight pairs of fully expanded leaves, were transplanted into 16-liter plastic baskets (26 cm high × 36 cm in diameter) filled with a growing medium composed of soil, well-decomposed cow dung, and rice husk in a ratio of 6:1:2 (v/v). Following transplantation, the plantlets were acclimatized in an area with filtered natural sunlight under 50% shading black nylon nets for 40 days to facilitate recovery and adjustment. Healthy plants of uniform height and width were selected for the subsequent experimental treatments. All cultivation conditions, including

pot size, growing medium composition, irrigation, fertilization, and field management practices, were kept uniform across treatments; light intensity was the only experimental variable.

Throughout the experiment, chemical top-dressing fertilization was conducted using NPK 16–16–16 fertilizer, applied at a rate of 2 grams per basket per session. Manual weeding was performed to control unwanted plants, and daily watering ensured the growing medium was maintained at field capacity. Environmental parameters, including air temperature and relative humidity, were recorded every 30 min using a data logger (EasyLog EL-USB, Lascar Electronics Ltd., PA, USA).

Study Location and Environmental Conditions

The experiment was conducted from January 2020 to May 2021 at the agricultural field of Kasetsart University in Bangkok, Thailand, located at 13° 85' N latitude and 100° 56' E longitude, at an elevation of 1 m. The site experiences a tropical savanna climate (Aw) according to the Köppen classification (Phumkokrux, 2021). The region has an annual average precipitation of 1,500 mm and an average day length of approximately 12 h. During the study period, the average maximum and minimum temperatures were 33.9°C and 25.0°C, respectively, with an average air temperature of $29.5 \pm 2.4^\circ\text{C}$. Relative humidity averaged 71.5%.

Light Treatments and Experimental Design

Three light treatments were established: full sunlight (T1, 0% shading), moderate shade (T2, 50% shading), and deep shade (T3, 80% shading). The 50% and 80% shade levels were generated using black nylon shade nets installed over nursery structures (4 × 9 × 3 m). The shading percentages were initially determined based on manufacturer specifications and subsequently verified by measuring photosynthetic photon flux density (PPFD) using line

quantum sensors (LI-191, LI-COR Biosciences, USA) connected to data loggers (LI-1400, LI-COR Biosciences, USA). PPFD measurements were recorded at canopy level under each treatment to confirm light reduction relative to full sun conditions. The average maximum PPFD was approximately $1,200 \mu\text{mol m}^{-2}\text{s}^{-1}$ under full sunlight (T1), $550 \mu\text{mol m}^{-2} \text{s}^{-1}$ under 50% shade (T2), and $210 \mu\text{mol m}^{-2} \text{s}^{-1}$ under 80% shade (T3). To maintain consistent light conditions throughout the experimental period, shade nets were securely fixed and regularly inspected for damage or displacement. Nursery structures were oriented perpendicular to the daily solar path to prevent cross-shading effects between treatments. Environmental parameters, including air temperature and relative humidity, were continuously monitored, and day length followed the natural photoperiod of the region, averaging approximately $12 \pm 0.5 \text{ h}$ (06:00–18:00).

After the 40-day acclimatization period, plants were transferred to the respective light treatments and maintained under full sun (0%), 50% shade, or 80% shade conditions for 12 months prior to data collection. The experiment was conducted from January 2020 to May 2021 at the agricultural field of Kasetsart University, Bangkok, Thailand. All morphological, anatomical, physiological, and biochemical measurements were performed in May 2021 after continuous exposure to the designated light regimes.

Plants were distributed in a completely randomized design, with five replicate plants per treatment per cultivar. Each experimental plot consisted of a single plant with one orthotropic stem per pot. This design ensured that individual plant responses could be accurately measured under each light treatment, providing robust data for analyzing the effects of varying light intensities on growth and physiological parameters.

Morphological Traits

At the end of the experiment in May 2021, various morphological traits were recorded, including plant height, stem circumference, the number of plagiotropic branches, and canopy diameter. Plant height was measured from the ground to the apex (cm), while stem circumference was determined 5 cm above the ground (cm). The number of branches was counted manually, and canopy diameter was calculated as the average of the east-west and north-south diameters (cm). Specific leaf area (SLA, $\text{m}^2 \text{g}^{-1}$) was calculated by measuring the dry mass of leaf discs of a known area.

Leaf Anatomical Characterization

Mid-laminar leaf fragments, excluding the central vein, were collected from ten blades per treatment for histological analysis. Freehand sections were stained with Safranin-O to evaluate histological features, including stomatal density on the abaxial epidermis. Histomorphometric analysis was conducted using digital imaging software (DinoCapture 2.0) and a digital eyepiece camera (DinoEye AM4023, AnMo Electronics Corporation, Taiwan) connected to a microscope (BH2, Olympus Corporation, Japan). Measurements of total leaf thickness, palisade and spongy parenchyma thickness, and adaxial and abaxial epidermis thickness were conducted using ImageJ software. Randomly selected regions of 10 micrographs were analyzed, totaling 50 measurements per treatment per cultivar.

Gas Exchange and Chlorophyll Fluorescence Analysis

In May 2021, gas exchange measurements were conducted on five fully expanded leaves per cultivar, at least 60 days after emergence, during clear-sky conditions between 08:00 and 13:00. Measurements included: net photosynthesis (A, $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$), stomatal conductance (g_s , $\text{mol H}_2\text{O m}^{-2} \text{s}^{-1}$),

and transpiration rate (E, $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$) using an open-flow infrared gas analyzer (LI-6400, Li-Cor Inc., NE, USA). Conditions included a flow rate of $500 \text{ cm}^3 \text{min}^{-1}$, a CO_2 concentration of $400 \mu\text{mol mol}^{-1}$, and irradiance of $1,000 \mu\text{mol m}^{-2} \text{s}^{-1}$. Water-use efficiency (WUE) was calculated as the ratio of net photosynthesis (A) to transpiration rate (E), representing instantaneous leaf-level water-use efficiency (Lambers *et al.*, 2008).

Light-response curves (A/PAR) were constructed by exposing fully expanded leaves to incremental light intensities ranging from 0 to $2,000 \mu\text{mol m}^{-2} \text{s}^{-1}$ under controlled CO_2 concentration ($400 \mu\text{mol mol}^{-1}$). The data were fitted to a non-rectangular hyperbola model (Thornley and Johnson, 1990) to estimate apparent quantum yield (α), convexity factor (θ), dark respiration rate (R_d), and light compensation point (LCP). The apparent quantum yield (α) was derived from the initial linear portion of the A/PAR curve ($0\text{--}100 \mu\text{mol m}^{-2} \text{s}^{-1}$).

Chlorophyll fluorescence parameters, including the maximum quantum yield of PSII (Fv/Fm), were measured using a Handy PEA chlorophyll fluorimeter (Hansatech Instruments Ltd., UK). Prior to measurement, leaves were dark-adapted for 30 min using leaf clips to ensure complete relaxation of PSII reaction centers. Fluorescence measurements were conducted immediately after the dark-adaptation period under ambient field conditions.

Chlorophyll Content Determination

Chlorophyll (chl) and carotenoid (car) contents were extracted from fresh 1 cm^2 leaf discs using N, N-dimethylformamide (DMF) following Hughes and Smith (2007). Absorbances at 647, 664, and 480 nm were recorded using a UV-visible spectrophotometer (GeneQuant 1300, GE Healthcare, Sweden). Chlorophyll concentrations were calculated based on Porra *et al.* (1989) and carotenoid content using Wellburn (1994).

Data Analysis and Plasticity Index

The experiment was conducted as a two-factor factorial design (shade × cultivar) arranged in a completely randomized design (CRD). Statistical analyses were performed using RStudio v. 2022.02.3 (RStudio Team, 2022). Trait data were analyzed using two-way analysis of variance (ANOVA) to evaluate the effects of shade, cultivar, and their interaction. When significant effects were detected, mean comparisons were performed using Duncan's multiple range test with the "Agricolae" package (Mendiburu, 2006) at $P < 0.05$.

Phenotypic plasticity was quantified using RDPI following Valladares *et al.* (2006), calculated with the "Plasticity" package (Ameztegui, 2017). RDPI values were computed for each trait and cultivar across shading treatments and were subsequently analyzed using ANOVA to test for differences among cultivars.

RESULTS AND DISCUSSION

This study examined how five robusta coffee cultivars (CH2, CH4, LO, R-1, and R-2) respond to contrasting light environments, ranging from full sunlight to deep shade. When considered collectively, the results indicate that phenotypic plasticity in robusta coffee is not expressed uniformly, but varies according to both cultivar identity and trait category (Table 1).

A consistent pattern observed across all cultivars was the structural adjustment associated with shade conditions, particularly an increase in specific leaf area and a reduction in both total leaf thickness and palisade mesophyll thickness. These responses are widely recognized as mechanisms that enhance light interception and improve internal light distribution under reduced irradiance (Niinemets, 2007; Valladares and Niinemets, 2008). Despite these common structural adjustments, the magnitude and coordination of trait responses differed among cultivars, indicating distinct acclimation strategies.

In CH2 and R-2, structural changes were closely accompanied by shifts in physiological processes, particularly gas exchange and respiration-related parameters. Increases in SLA and modifications in mesophyll organization, particularly changes in palisade mesophyll thickness (Tables 2–3), occurred alongside changes in gas exchange parameters, including stomatal conductance (g_s) and transpiration rate (E) (Table 4), suggesting a coordinated adjustment between structure and function (Niinemets, 2007; Valladares and Niinemets, 2008). In CH2, the reduction in respiration-related parameters, including dark respiration (R_d) and light compensation point (LCP) (Table 4), further indicates a rebalancing of carbon use under shaded conditions, consistent with previous findings in coffee and other C3 species (Fahl *et al.*, 1994; Morais *et al.*, 2003; DaMatta *et al.*, 2007).

In contrast to CH2 and R-2, LO and R-1 exhibited more selective and less coordinated responses. In LO, variation was most evident in canopy structure and anatomical traits, including changes in canopy diameter (Table 2) and palisade thickness (Table 3), together with increases in chlorophyll b and carotenoids (Table 5), consistent with pigment-based acclimation under shaded conditions (DaMatta *et al.*, 2007; Lichtenthaler and Babani, 2022). R-1, in contrast, showed a tendency toward leaf expansion and pigment accumulation (Tables 2 and 5) while maintaining relatively stable photochemical efficiency (F_v/F_m) and water-use efficiency (Table 4), a pattern commonly observed in shade-acclimated coffee plants (DaMatta *et al.*, 2007). These responses indicate that both cultivars rely on targeted adjustments in light capture and pigment composition rather than coordinated changes across multiple functional systems, consistent with trait-specific plasticity reported in previous studies (Valladares *et al.*, 2007; Gratani, 2014).

Table 1 Proportion of explained variance by shade and cultivar factors and their interaction (two-way ANOVA), and relative distance plasticity index (RDPI) of morpho-anatomical and physiological/biochemical traits in five cultivars of robusta coffee (Chumphon 2 [CH2], Chumphon 4 [CH4], local variety [LO], R2017–1 [R–1], and R2017–2 [R–2]) grown under full sun, 50% shading net, and 80% shading net

Traits	Factor			R ²	RDPI				
	Shade (S)	Cultivar (CV)	S x CV		CH2	CH4	LO	R-1	R-2
Morpho-anatomical									
Specific leaf area	<0.001	0.063	0.028	80.3	0.15 ^{ab}	0.17 ^a	0.10 ^c	0.10 ^c	0.12 ^{bc}
Single leaf area	<0.001	0.002	0.246	57.9	0.23 ^{ab}	0.12 ^c	0.20 ^{bc}	0.26 ^{ab}	0.31 ^a
Branch number	0.537	<0.001	0.123	68.1	0.11 ^b	0.11 ^b	0.26 ^a	0.12 ^b	0.13 ^b
Stem height	0.915	<0.001	0.694	79.5	0.05 ^b	0.04 ^b	0.10 ^a	0.13 ^a	0.12 ^a
Stem circumference	<0.001	<0.001	0.005	67.3	0.05 ^c	0.11 ^{ab}	0.14 ^a	0.07 ^{bc}	0.08 ^{bc}
Canopy diameter	0.004	0.034	0.067	45.9	0.03 ^b	0.08 ^a	0.10 ^a	0.10 ^a	0.09 ^a
Total leaf thickness	<0.001	0.016	0.301	60.0	0.05 ^{bc}	0.05 ^{bc}	0.07 ^{ab}	0.04 ^c	0.08 ^a
Palisade thickness	<0.001	0.025	0.256	68.9	0.15 ^{ab}	0.18 ^a	0.14 ^{ab}	0.13 ^b	0.18 ^a
Spongy thickness	<0.001	0.004	0.751	44.8	0.07	0.06	0.07	0.07	0.08
Upper epidermis thick-ness	0.001	0.815	0.008	49.3	0.04 ^b	0.05 ^b	0.09 ^a	0.10 ^a	0.09 ^a
Lower epidermis thick-ness	<0.001	0.003	0.399	53.1	0.05 ^c	0.09 ^b	0.09 ^{bc}	0.11 ^{ab}	0.13 ^a
Stomatal density	<0.001	0.162	0.426	69.1	0.18 ^b	0.29 ^a	0.18 ^b	0.16 ^b	0.18 ^b
Stomatal size	0.407	<0.001	0.117	55.7	0.01 ^c	0.02 ^{bc}	0.03 ^b	0.04 ^a	0.03 ^{ab}
Palisade-to-spongy paren-chyma ratio	<0.001	<0.001	0.315	62.9	0.14 ^{ab}	0.17 ^a	0.11 ^b	0.12 ^b	0.13 ^{ab}
Mean					0.10	0.11	0.12	0.11	0.13
Physiological/biochemical									
Photosynthetic rates	0.021	0.580	0.407	28.8	0.20	0.18	0.23	0.27	0.27
Stomatal conductance	0.972	0.011	0.226	33.4	0.39 ^a	0.31 ^{ab}	0.27 ^b	0.32 ^{ab}	0.36 ^{ab}
Transpiration rate	0.639	0.026	0.353	28.6	0.39 ^a	0.31 ^{ab}	0.24 ^b	0.30 ^{ab}	0.35 ^a
Water use efficiency	0.164	0.057	0.726	27.5	0.37 ^a	0.20 ^b	0.17 ^b	0.13 ^b	0.21 ^b
Maximum quantum efficiency of PSII	<0.001	0.023	0.473	64.5	0.04 ^b	0.06 ^a	0.02 ^b	0.03 ^b	0.03 ^b
Apparent quantum yield	<0.001	0.035	<0.001	63.9	0.11 ^b	0.10 ^b	0.09 ^b	0.15 ^a	0.04 ^c
Convexity factor	0.014	<0.001	0.362	55.4	0.06 ^b	0.16 ^b	0.35 ^a	0.16 ^b	0.29 ^a
Dark respiration rate	<0.001	0.017	0.359	60.9	0.80 ^a	0.31 ^c	0.58 ^b	0.42 ^{bc}	0.43 ^{bc}
Light compensation point	<0.001	0.018	0.909	50.0	0.81 ^a	0.24 ^d	0.56 ^b	0.37 ^{cd}	0.45 ^{bc}
Chlorophylls a	<0.001	<0.001	0.175	71.7	0.09 ^b	0.08 ^b	0.09 ^b	0.14 ^a	0.10 ^b
Chlorophylls b	<0.001	0.011	0.622	50.1	0.15 ^b	0.14 ^b	0.18 ^{ab}	0.21 ^a	0.17 ^{ab}
Total chlorophyll	<0.001	0.002	0.493	59.1	0.11 ^b	0.10 ^b	0.10 ^b	0.16 ^a	0.11 ^b
Carotenoids	<0.001	<0.001	0.017	57.2	0.06 ^b	0.06 ^b	0.08 ^{ab}	0.11 ^a	0.07 ^b
Ratios of chlorophylls a/b	<0.001	0.116	0.557	62.1	0.07	0.08	0.08	0.09	0.09
Ratios of total chlorophyll// carotenoids	<0.001	0.177	0.565	72.0	0.07	0.08	0.07	0.06	0.07
Mean					0.25	0.16	0.21	0.19	0.20

Note: Means within the same row followed by different superscript letters (a, b, c, d) are significantly different ($P < 0.05$). Values represent the mean RDPI for each cultivar of robusta coffee.

Table 2 Leaf morphological traits of five robusta coffee cultivars (Chumphon 2 [CH2], Chumphon 4 [CH4], local variety [LO], R2017–1 [R–1], and R2017–2 [R–2]) under three shade treatments (T1: full sun, T2: 50% shade, and T3: 80% shade)

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Specific leaf area (m ² kg ⁻¹)	CH2	17.7 ± 0.2 ^c	20.5 ± 0.3 ^b	27.8 ± 1.2 ^a	21.7	0.000
	CH4	17.9 ± 0.3 ^c	22.3 ± 0.7 ^b	30.0 ± 1.1 ^a	24.4	0.000
	LO	18.6 ± 1.1 ^b	20.1 ± 0.9 ^b	24.3 ± 0.4 ^a	20.8	0.004
	R–1	19.7 ± 0.8 ^c	22.4 ± 0.5 ^b	26.3 ± 0.9 ^a	22.6	0.000
	R–2	18.2 ± 0.3 ^b	22.9 ± 1.6 ^{ab}	25.0 ± 1.9 ^a	22.2	0.027
	Mean	18.5 ^c	21.6 ^b	26.7 ^a		
Single leaf area (cm ²)	CH2	56.2 ± 4.3 ^c	75.3 ± 1.0 ^b	108.8 ± 2.7 ^a	78.5 ^{BC}	0.000
	CH4	63.9 ± 5.7 ^b	80.6 ± 3.0 ^{ab}	91.2 ± 7.3 ^a	80.8 ^{ABC}	0.043
	LO	71.9 ± 9.5	110.9 ± 15.4	107.6 ± 13.0	98.6 ^A	0.136
	R–1	61.5 ± 11.4 ^b	110.9 ± 13.8 ^a	111.5 ± 16.2 ^a	93.5 ^{AB}	0.042
	R–2	45.6 ± 8.3 ^b	42.3 ± 7.9 ^b	94.7 ± 13.7 ^a	65.2 ^C	0.016
	Mean	59.6 ^c	88.1 ^b	102.5 ^a		
Branch number	CH2	41.75 ± 0.85 ^a	37.00 ± 2.07 ^{ab}	31.00 ± 2.81 ^b	36.2 ^A	0.020
	CH4	20.25 ± 2.17	20.50 ± 1.04	17.80 ± 1.93	19.4 ^C	0.515
	LO	16.80 ± 4.26	16.60 ± 3.63	18.20 ± 2.31	17.2 ^C	0.940
	R–1	20.25 ± 1.31	28.75 ± 3.09	23.33 ± 0.33	24.2 ^B	0.053
	R–2	19.00 ± 1.91	21.00 ± 0.91	23.80 ± 4.33	21.5 ^{BC}	0.562
	Mean	23.3	25.0	22.8		
Stem height (cm)	CH2	128.3 ± 2.7	135.4 ± 3.5	136.8 ± 8.0	133.9 ^A	0.558
	CH4	97.8 ± 4.0	99.8 ± 1.4	95.0 ± 4.4	97.3 ^C	0.666
	LO	124.8 ± 11.2	111.0 ± 10.3	118.4 ± 7.5	118.1 ^B	0.619
	R–1	66.6 ± 5.2	76.3 ± 6.5	67.2 ± 9.8	69.6 ^D	0.641
	R–2	64.0 ± 4.2	56.3 ± 0.5	70.6 ± 10.3	64.2 ^D	0.411
	Mean	96.2	98.2	97.6		
Stem circumference (cm)	CH2	6.96 ± 0.11	7.26 ± 0.32	6.44 ± 0.23	6.9 ^A	0.082
	CH4	7.07 ± 0.07 ^a	6.26 ± 0.40 ^a	4.97 ± 0.03 ^b	6.1 ^B	0.011
	LO	8.78 ± 0.90 ^a	6.15 ± 0.10 ^b	5.78 ± 0.24 ^b	7.0 ^A	0.006
	R–1	5.90 ± 0.10	5.73 ± 0.24	5.06 ± 0.26	5.5 ^B	0.075
	R–2	6.25 ± 0.41	6.18 ± 0.18	5.30 ± 0.23	5.9 ^B	0.064
	Mean	7.1 ^a	6.4 ^b	5.6 ^c		
Canopy diameter (cm)	CH2	102.8 ± 0.7	105.5 ± 4.6	107.1 ± 1.8	105.4 ^A	0.665
	CH4	98.3 ± 4.6	94.3 ± 2.1	88.2 ± 9.0	93.2 ^B	0.566
	LO	125.0 ± 7.6 ^a	112.9 ± 4.2 ^a	92.1 ± 4.1 ^b	111.3 ^A	0.008
	R–1	105.5 ± 5.8 ^{ab}	122.8 ± 8.9 ^a	90.4 ± 2.4 ^b	106.2 ^A	0.018
	R–2	106.6 ± 6.2	105.1 ± 6.3	100.7 ± 9.9	103.9 ^A	0.863
	Mean	108.6 ^a	108.3 ^a	95.6 ^b		

Note: For each parameter, means followed by different lowercase letters (a, b, c) in the same row indicate significant differences between shade treatments for each cultivar, whereas different uppercase letters (A, B, C, D) in the same column indicate significant differences between cultivars under the same shading treatment, based on Duncan's multiple range test ($P < 0.05$). Values are presented as mean ± standard error ($n = 5$).

CH4 displayed comparatively limited responsiveness across most traits. Although structural adjustments in leaf morphology, including increased SLA and reduced leaf thickness and palisade mesophyll thickness, were observed (Tables 2–3), physiological and pigment-related traits varied only slightly (Tables 4–5). A decline in Fv/Fm under deep shade (Table 4) indicates reduced photosynthetic efficiency under low irradiance. This pattern is consistent with a more conservative acclimation strategy, in which trait stability is maintained rather than actively adjusted (DaMatta *et al.*, 2007).

Across cultivars, not all traits responded equally to shading. Traits directly associated with light capture and carbon balance, including SLA, Rd, and

LCP, were generally more responsive to shading. Pigment-related traits, particularly chlorophyll b and carotenoids, also showed clear adjustments (Tables 2, 4, and 5), tended to be more responsive than traits such as stem circumference, stomatal density, or Fv/Fm, particularly in CH2, LO, and R–1 (Tables 2–4). This uneven response indicates that plasticity is expressed selectively, reflecting prioritization of key functional processes rather than uniform adjustment across all traits. Such patterns are consistent with ecophysiological theory, which suggests that plants optimize performance under heterogeneous environments through targeted allocation of resources (Valladares *et al.*, 2007; Gratani, 2014).

Table 3 Leaf anatomical traits of five robusta coffee cultivars (Chumphon 2 [CH2], Chumphon 4 [CH4], local variety [LO], R2017–1 [R–1], and R2017–2 [R–2]) under three shade treatments (T1: full sun, T2: 50% shade, and T3: 80% shade)

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Total leaf thickness (µm)	CH2	213.8 ± 5.2	190.5 ± 4.8	195.7 ± 8.7	200.0 ^B	0.061
	CH4	228.6 ± 8.7 ^a	197.1 ± 1.8 ^b	201.4 ± 2.9 ^b	209.4 ^{AB}	0.006
	LO	237.6 ± 9.4 ^a	203.9 ± 7.8 ^b	202.4 ± 6.0 ^b	214.6 ^A	0.013
	R–1	211.8 ± 5.3	202.7 ± 3.8	195.8 ± 4.9	203.5 ^{AB}	0.101
	R–2	225.8 ± 7.2 ^a	177.3 ± 3.6 ^b	189.1 ± 7.9 ^b	198.4 ^B	0.004
	Mean	223.2 ^a	195.3 ^b	196.9 ^b		
Palisade thickness (µm)	CH2	50.0 ± 0.4 ^a	45.6 ± 1.5 ^b	31.7 ± 0.8 ^c	42.1 ^A	0.000
	CH4	52.3 ± 3.3 ^a	40.8 ± 3.2 ^b	30.9 ± 1.8 ^c	40.5 ^{AB}	0.001
	LO	46.3 ± 1.8 ^a	38.1 ± 1.9 ^b	29.4 ± 0.8 ^c	38.5 ^{ABC}	0.000
	R–1	40.4 ± 4.2	39.8 ± 2.7	30.6 ± 2.5	36.7 ^{BC}	0.105
	R–2	45.9 ± 2.0 ^a	33.5 ± 1.1 ^b	29.4 ± 4.5 ^b	35.7 ^C	0.013
	Mean	46.5 ^a	39.8 ^b	30.4 ^c		
Spongy thickness (µm)	CH2	121.0 ± 4.6 ^a	102.7 ± 3.6 ^b	116.0 ± 5.7 ^{ab}	113.3 ^B	0.047
	CH4	131.0 ± 9.5	116.6 ± 5.5	120.2 ± 3.3	122.0 ^B	0.290
	LO	145.0 ± 8.8	128.1 ± 7.4	126.9 ± 5.5	133.3 ^A	0.193
	R–1	130.6 ± 6.8	122.6 ± 5.1	114.9 ± 5.7	122.7 ^B	0.212
	R–2	138.6 ± 2.2 ^a	112.2 ± 7.9 ^b	114.7 ± 0.2 ^b	120.9 ^B	0.030
	Mean	132.9 ^a	116.4 ^b	118.9 ^b		

Table 3 Cont.

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Upper epidermis thickness (µm)	CH2	24.7 ± 0.1	22.7 ± 0.8	24.1 ± 1.0	23.74	0.302
	CH4	23.7 ± 1.3	24.1 ± 0.5	26.5 ± 0.9	24.93	0.110
	LO	27.3 ± 1.4 ^a	21.4 ± 0.5 ^b	24.4 ± 1.1 ^{ab}	24.60	0.015
	R-1	22.8 ± 0.6 ^b	22.9 ± 1.3 ^b	28.8 ± 1.0 ^a	25.34	0.004
	R-2	26.2 ± 1.4	21.7 ± 1.5	24.4 ± 1.5	24.14	0.174
	Mean	25.2 ^a	22.6 ^b	25.7 ^a		
Lower epidermis thickness (µm)	CH2	18.4 ± 0.6 ^b	18.8 ± 0.4 ^b	21.2 ± 0.2 ^a	19.2 ^B	0.011
	CH4	21.6 ± 1.3 ^{ab}	18.6 ± 0.5 ^b	23.8 ± 1.2 ^a	21.3 ^A	0.012
	LO	17.5 ± 0.7	15.7 ± 0.2	20.2 ± 2.0	18.2 ^B	0.168
	R-1	16.0 ± 0.8 ^b	17.4 ± 1.0 ^b	21.8 ± 2.0 ^a	18.1 ^B	0.004
	R-2	19.0 ± 2.8	14.7 ± 0.8	19.3 ± 1.2	18.0 ^B	0.259
	Mean	18.5 ^b	17.3 ^b	21.2 ^a		
Stomatal density (m/m ²)	CH2	283.9 ± 25.9 ^a	188.7 ± 0.3 ^b	175.4 ± 13.6 ^b	220.2	0.005
	CH4	278.5 ± 6.7 ^a	202.7 ± 11.5 ^b	109.1 ± 9.0 ^c	197.2	0.000
	LO	257.8 ± 26.7 ^a	199.3 ± 12.1 ^b	147.5 ± 7.1 ^b	205.4	0.006
	R-1	278.6 ± 15.0 ^a	194.5 ± 21.9 ^b	188.8 ± 14.3 ^b	222.5	0.004
	R-2	296.6 ± 40.0 ^a	221.0 ± 20.9 ^{ab}	180.9 ± 15.5 ^b	232.8	0.043
	Mean	278.4 ^a	201.8 ^b	162.3 ^c		
Stomatal size (µm)	CH2	0.021 ± 0.00 ^b	0.022 ± 0.00 ^a	0.022 ± 0.00 ^a	0.022 ^{BC}	0.033
	CH4	0.022 ± 0.00 ^b	0.022 ± 0.00 ^a	0.023 ± 0.00 ^a	0.023 ^A	0.296
	LO	0.022 ± 0.00	0.023 ± 0.00	0.022 ± 0.00	0.022 ^{AB}	0.436
	R-1	0.021 ± 0.00	0.020 ± 0.00	0.022 ± 0.00	0.021 ^{CD}	0.440
	R-2	0.021 ± 0.00 ^a	0.019 ± 0.00 ^b	0.021 ± 0.00 ^a	0.020 ^D	0.005
	Mean	0.022	0.022	0.022		
Palisade-to-spongy parenchyma ratio	CH2	0.41 ± 0.03 ^a	0.45 ± 0.02 ^a	0.30 ± 0.02 ^b	0.38 ^A	0.001
	CH4	0.41 ± 0.05 ^a	0.38 ± 0.01 ^a	0.26 ± 0.02 ^b	0.34 ^{AB}	0.010
	LO	0.32 ± 0.01 ^a	0.30 ± 0.02 ^{ab}	0.24 ± 0.01 ^b	0.28 ^C	0.039
	R-1	0.32 ± 0.04	0.33 ± 0.03	0.27 ± 0.01	0.31 ^{BC}	0.570
	R-2	0.34 ± 0.02	0.30 ± 0.02	0.25 ± 0.03	0.29 ^C	0.065
	Mean	0.36 ^a	0.35 ^a	0.26 ^b		

Note: For each parameter, means followed by different lowercase letters (a, b, c) in the same row indicate significant differences between shade treatments for each cultivar, whereas different uppercase letters (A, B, C, D) in the same column indicate significant differences between cultivars under the same shading treatment, based on Duncan's multiple range test ($P < 0.05$). Values are presented as mean ± standard error (n = 5).

Taken together, the cultivars can be viewed along a gradient of responsiveness. CH2 and R–2 exhibited broader and more coordinated adjustments, LO and R–1 showed intermediate and selective responses, while CH4 remained comparatively stable across light conditions. The RDPI (Table 1) provides a useful quantitative framework for comparing these differences, supporting trait-based evaluation of cultivar performance in line with previous studies in

coffee (DaMatta *et al.*, 2007; Matos *et al.*, 2009). From a practical perspective, the observed differences in coordinated versus selective trait responses suggest that cultivar selection should be aligned with the light environment of the production system. Cultivars exhibiting coordinated plasticity may be better suited to agroforestry systems with variable light, whereas more conservative types may perform more consistently under more uniform light conditions.

Table 4 Photosynthetic gas exchange, chlorophyll fluorescence, and associated light-response parameters in leaves of five robusta coffee cultivars (Chumphon 2 [CH2], Chumphon 4 [CH4], local variety [LO], R2017–1 [R–1], and R2017–2 [R–2]) under three shade treatments (T1: full sun, T2: 50% shade, and T3: 80% shade) during the measurement period (07:30–16:30)

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Net photosynthetic rates ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	CH2	5.76 ± 0.40^a	5.41 ± 0.58^a	3.20 ± 0.08^b	4.93	0.010
	CH4	6.78 ± 0.42	5.31 ± 0.84	3.99 ± 0.23	5.35	0.064
	LO	7.31 ± 0.80^a	6.24 ± 0.87^{ab}	4.01 ± 0.64^b	5.99	0.045
	R–1	5.91 ± 1.19	4.19 ± 0.78	4.38 ± 0.91	4.87	0.440
	R–2	4.42 ± 0.84	4.72 ± 1.43	5.54 ± 1.51	4.94	0.824
	Mean	6.06^a	5.23^{ab}	4.36^b		
Stomatal conductance ($\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$)	CH2	0.04 ± 0.02	0.02 ± 0.00	0.02 ± 0.00	0.03^B	0.368
	CH4	0.05 ± 0.02	0.03 ± 0.00	0.04 ± 0.01	0.04^{AB}	0.329
	LO	0.06 ± 0.01	0.07 ± 0.02	0.05 ± 0.01	0.06^A	0.473
	R–1	0.03 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.04^B	0.378
	R–2	0.02 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.04^B	0.246
	Mean	0.04	0.04	0.04		
Transpiration rate ($\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$)	CH2	1.05 ± 0.36	1.42 ± 0.60	0.50 ± 0.10	1.02^B	0.379
	CH4	1.57 ± 0.41	0.86 ± 0.14	1.06 ± 0.23	1.16^B	0.249
	LO	2.24 ± 0.27	1.93 ± 0.44	1.47 ± 0.16	1.88^A	0.248
	R–1	1.33 ± 0.35	1.10 ± 0.28	1.43 ± 0.35	1.30^{AB}	0.787
	R–2	0.83 ± 0.19	1.06 ± 0.40	1.49 ± 0.45	1.16^B	0.477
	Mean	1.42	1.31	1.22		
Water use efficiency ($\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$)	CH2	9.16 ± 3.65	5.30 ± 1.94	4.53 ± 0.80	6.33	0.383
	CH4	3.90 ± 0.41	4.11 ± 0.98	3.67 ± 0.31	3.89	0.893
	LO	3.40 ± 0.44	3.92 ± 0.90	2.92 ± 0.21	3.45	0.564
	R–1	3.72 ± 0.06^{ab}	4.16 ± 0.48^a	2.89 ± 0.05^b	3.58	0.046
	R–2	5.93 ± 1.28	4.96 ± 0.46	3.54 ± 0.13	4.81	0.152
	Mean	5.40	4.48	3.56		

Table 4 Cont.

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Maximum quantum efficiency of PSII	CH2	0.75 ± 0.02 ^b	0.81 ± 0.01 ^a	0.83 ± 0.00 ^a	0.80 ^{AB}	0.006
	CH4	0.69 ± 0.03 ^b	0.79 ± 0.01 ^{ab}	0.82 ± 0.01 ^a	0.77 ^B	0.002
	LO	0.78 ± 0.03	0.82 ± 0.00	0.83 ± 0.00	0.81 ^A	0.084
	R-1	0.75 ± 0.00 ^b	0.81 ± 0.01 ^a	0.81 ± 0.01 ^a	0.79 ^{AB}	0.001
	R-2	0.74 ± 0.03 ^b	0.80 ± 0.00 ^a	0.82 ± 0.00 ^a	0.79 ^{AB}	0.029
	Mean	0.74 ^b	0.80 ^a	0.82 ^a		
Apparent quantum yield (μmol CO ₂ μmol ⁻¹ photons)	CH2	0.052 ± 0.00 ^a	0.049 ± 0.00 ^a	0.038 ± 0.00 ^b	0.046 ^B	0.008
	CH4	0.052 ± 0.01	0.045 ± 0.00	0.040 ± 0.00	0.045 ^B	0.096
	LO	0.047 ± 0.00	0.041 ± 0.01	0.048 ± 0.00	0.046 ^B	0.326
	R-1	0.062 ± 0.00 ^a	0.038 ± 0.00 ^b	0.056 ± 0.00 ^a	0.052 ^A	0.002
	R-2	0.050 ± 0.00	0.049 ± 0.00	0.047 ± 0.00	0.049 ^{AB}	0.713
	Mean	0.052 ^a	0.045 ^b	0.046 ^b		
Convexity factor	CH2	0.82 ± 0.02	0.84 ± 0.04	0.93 ± 0.02	0.87 ^A	0.075
	CH4	0.65 ± 0.18	0.80 ± 0.05	0.68 ± 0.06	0.72 ^B	0.541
	LO	0.62 ± 0.04	0.50 ± 0.12	0.71 ± 0.06	0.47 ^C	0.223
	R-1	0.41 ± 0.15	0.38 ± 0.10	0.66 ± 0.02	0.62 ^B	0.269
	R-2	0.45 ± 0.15	0.60 ± 0.15	0.80 ± 0.04	0.63 ^B	0.096
	Mean	0.57 ^b	0.65 ^b	0.76 ^a		
Dark respiration rate (μmol CO ₂ m ⁻² s ⁻¹)	CH2	1.30 ± 0.17 ^a	0.85 ± 0.38 ^a	0.00 ± 0.00 ^b	0.77 ^B	0.018
	CH4	1.34 ± 0.36 ^a	1.06 ± 0.08 ^{ab}	0.54 ± 0.14 ^b	0.96 ^{AB}	0.040
	LO	1.28 ± 0.41 ^a	0.49 ± 0.05 ^{ab}	0.13 ± 0.03 ^b	0.65 ^B	0.035
	R-1	2.34 ± 0.11 ^a	0.87 ± 0.34 ^b	0.85 ± 0.13 ^b	1.36 ^A	0.004
	R-2	1.30 ± 0.22	0.86 ± 0.23	0.67 ± 0.29	0.93 ^{AB}	0.265
	Mean	1.47 ^a	0.85 ^b	0.43 ^c		
Light compensation point (μmol photons m ⁻² s ⁻¹)	CH2	22.75 ± 2.11 ^a	17.67 ± 7.99 ^a	0.00 ± 0.00 ^b	13.80 ^B	0.044
	CH4	28.87 ± 7.26	25.31 ± 1.54	15.71 ± 3.76	23.00 ^{AB}	0.107
	LO	29.50 ± 9.69 ^a	18.17 ± 4.01 ^{ab}	3.63 ± 1.46 ^b	17.10 ^B	0.044
	R-1	42.71 ± 3.99	27.39 ± 11.15	19.45 ± 3.63	28.81 ^A	0.099
	R-2	29.46 ± 6.09	19.33 ± 5.10	15.05 ± 6.80	20.92 ^{AB}	0.298
	Mean	30.10 ^a	21.39 ^b	10.97 ^c		

Note: For each parameter, means followed by different lowercase letters (a, b, c) in the same row indicate significant differences between shade treatments for each cultivar, whereas different uppercase letters (A, B, C) in the same column indicate significant differences between cultivars under the same shading treatment, based on Duncan's multiple range test ($P < 0.05$). Values are presented as mean ± standard error ($n = 5$).

Table 5 Leaf photosynthetic pigment contents of five robusta coffee cultivars (Chumphon 2 [CH2], Chumphon 4 [CH4], local variety [LO], R2017–1 [R–1], and R2017–2 [R–2]) under three shade treatments (T1: full sun, T2: 50% shade, and T3: 80% shade)

Parameters	Cultivars	Shade treatments			Mean	P-value
		T1	T2	T3		
Chlorophylls a (mg cm ⁻²)	CH2	6.68 ± 0.42 ^b	8.34 ± 0.35 ^a	8.55 ± 0.23 ^a	7.86 ^B	0.004
	CH4	6.52 ± 0.37 ^b	8.32 ± 0.14 ^a	8.22 ± 0.14 ^a	7.80 ^B	0.001
	LO	7.50 ± 0.02 ^b	9.40 ± 0.29 ^a	9.92 ± 0.35 ^a	9.07 ^A	0.001
	R–1	6.01 ± 0.33 ^b	7.31 ± 0.59 ^b	8.97 ± 0.39 ^a	7.32 ^B	0.002
	R–2	6.68 ± 0.37 ^b	8.83 ± 0.14 ^a	8.16 ± 0.44 ^a	7.81 ^B	0.010
	Mean	6.61 ^b	8.51 ^a	9.02 ^a		
Chlorophylls b (mg cm ⁻²)	CH2	2.15 ± 0.02 ^c	2.89 ± 0.15 ^b	3.47 ± 0.18 ^a	2.94 ^{AB}	0.001
	CH4	1.91 ± 0.05 ^b	2.80 ± 0.10 ^a	3.04 ± 0.13 ^a	2.62 ^{AB}	0.000
	LO	2.24 ± 0.06 ^c	3.22 ± 0.21 ^b	3.83 ± 0.24 ^a	3.03 ^A	0.001
	R–1	1.80 ± 0.17 ^c	2.56 ± 0.18 ^b	3.36 ± 0.28 ^a	2.51 ^B	0.001
	R–2	2.09 ± 0.21 ^b	3.18 ± 0.18 ^a	3.20 ± 0.31 ^a	2.82 ^{AB}	0.014
	Mean	2.03 ^c	2.92 ^b	4.42 ^a		
Total chlorophyll (mg cm ⁻²)	CH2	8.82 ± 0.53 ^b	11.23 ± 0.49 ^a	12.02 ± 0.39 ^a	10.69 ^B	0.001
	CH4	8.43 ± 0.42 ^b	11.11 ± 0.23 ^a	11.26 ± 0.27 ^a	10.42 ^B	0.000
	LO	9.79 ± 0.06 ^b	12.62 ± 0.48 ^a	13.47 ± 0.53 ^a	12.02 ^A	0.003
	R–1	7.81 ± 0.50 ^c	9.87 ± 0.77 ^b	12.33 ± 0.66 ^a	9.84 ^B	0.002
	R–2	8.77 ± 0.58 ^b	11.46 ± 0.71 ^a	11.36 ± 0.70 ^a	10.53 ^B	0.031
	Mean	8.64 ^c	11.25 ^b	12.06 ^a		
Carotenoids (mg cm ⁻²)	CH2	1.65 ± 0.09	1.86 ± 0.08	1.86 ± 0.05	1.79 ^{BC}	0.117
	CH4	1.57 ± 0.06 ^b	1.87 ± 0.03 ^a	1.76 ± 0.07 ^a	1.76 ^{BC}	0.007
	LO	1.77 ± 0.07 ^b	2.21 ± 0.03 ^a	2.16 ± 0.07 ^a	2.01 ^A	0.005
	R–1	1.41 ± 0.03 ^b	1.66 ± 0.12 ^b	1.98 ± 0.09 ^a	1.68 ^C	0.004
	R–2	1.73 ± 0.09	2.08 ± 0.06	1.81 ± 0.09	1.85 ^B	0.061
	Mean	1.64 ^b	1.91 ^a	1.91 ^a		
Ratios of chlorophylls a/b	CH2	3.14 ± 0.10 ^a	2.89 ± 0.05 ^b	2.55 ± 0.03 ^c	2.88 ^{AB}	0.000
	CH4	3.41 ± 0.11 ^a	2.99 ± 0.02 ^b	2.71 ± 0.08 ^c	3.04 ^A	0.002
	LO	3.25 ± 0.07 ^a	2.95 ± 0.14 ^a	2.53 ± 0.09 ^b	2.94 ^{AB}	0.005
	R–1	3.41 ± 0.15 ^a	2.85 ± 0.05 ^b	2.70 ± 0.13 ^b	3.02 ^A	0.005
	R–2	3.24 ± 0.14 ^a	2.61 ± 0.10 ^b	2.60 ± 0.16 ^b	2.82 ^B	0.013
	Mean	3.28 ^a	2.85 ^b	2.62 ^c		
chl/car	CH2	5.33 ± 0.08 ^c	6.08 ± 0.06 ^b	6.54 ± 0.05 ^a	5.92 ^{AB}	0.000
	CH4	5.43 ± 0.09 ^b	5.94 ± 0.15 ^b	6.88 ± 0.32 ^a	6.13 ^A	0.003
	LO	5.50 ± 0.24 ^b	5.88 ± 0.09 ^b	6.69 ± 0.28 ^a	6.02 ^{AB}	0.008
	R–1	5.36 ± 0.21 ^b	6.03 ± 0.02 ^a	6.22 ± 0.08 ^a	5.81 ^{AB}	0.008
	R–2	5.06 ± 0.10 ^c	5.87 ± 0.12 ^b	6.29 ± 0.12 ^a	5.74 ^B	0.000
	Mean	5.34 ^c	5.94 ^b	6.54 ^a		

Note: For each parameter, means followed by different lowercase letters (a, b, c) in the same row indicate significant differences between shade treatments for each cultivar, whereas different uppercase letters (A, B, C) in the same column indicate significant differences between cultivars under the same shading treatment, based on Duncan's multiple range test ($P < 0.05$). Values are presented as mean ± standard error ($n = 5$).

CONCLUSIONS

The results show that differences among robusta coffee cultivars under contrasting light conditions depend not only on how strongly they respond, but also on how different traits work together. Rather than responding uniformly, cultivars vary in their adjustment strategies. Some cultivars exhibit coordinated changes across multiple traits (structural and physiological), indicating high plasticity and a greater ability to perform under variable light conditions, such as in shaded or agroforestry systems, as observed in CH2 and R-2. Others rely on more selective adjustments, showing moderate plasticity, as seen in LO and R-1, while some cultivars display relatively stable trait expression with limited responsiveness, suggesting better suitability for more uniform light environments, as observed in CH4. These findings

indicate that adaptability in robusta coffee is determined by the balance between flexibility and stability of key functional traits. The RDPI proved useful for comparing differences in trait responsiveness among cultivars and provides a practical basis for evaluating their performance across environments. From an applied perspective, this trait-based understanding can support more appropriate cultivar selection, particularly in production systems where light availability is heterogeneous.

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