Research Article

Estimation of radiation interception and intercepted photosynthetically active radiation in soybean using smartphone images[1]

Diecson Ruy Orsolin da Silva[2], Fernanda Trentin[3], Claudir José Basso[2], Gizelli Moiano de Paula[2]

ABSTRACT

The acquisition of parameters such as canopy cover, leaf area index, radiation interception, and intercepted photosynthetically active radiation (iPAR) in crops such as soybean often relies on methods that are costly and time-consuming. This study aimed to identify the most suitable smartphone-based image acquisition method for estimating the percentage of radiation interception, iPAR, and radiation-use efficiency in soybean crop. The images were collected using a smartphone positioned at different heights, angles, and orientations relative to the canopy, including nadir (vertical), upward-facing, and video-based acquisitions. The images and videos were analyzed using the Canopeo application to obtain the fractional green canopy cover (FGCC). The video-based and smartphone camera images acquired at distances of 0.8 and 1.0 m from the crop canopy, respectively, were the most effective approaches for estimating radiation interception and iPAR through FGCC.

KEYWORDS: *Glycine max*, radiation-use efficiency, fractional green canopy cover.

RESUMO

Estimativa de interceptação de radiação e radiação fotossinteticamente ativa interceptada na cultura da soja usando imagens de *smartphone*

A obtenção de parâmetros como cobertura de dossel, índice de área foliar, interceptação de radiação e radiação fotossinteticamente ativa interceptada (iPAR) em culturas como a soja geralmente envolve métodos caros e demorados. Objetivou-se identificar o melhor método de captura de imagens via *smartphone* para estimar a porcentagem de interceptação de radiação, iPAR e eficiência de uso da radiação na cultura da soja. As imagens foram obtidas utilizando-se *smartphone* posicionado em diferentes alturas, ângulos e orientações em relação ao dossel, incluindo capturas verticais, ascendentes e por vídeo. As imagens e vídeos foram analisados no aplicativo Canopeo, para obtenção da cobertura de dossel verde fracionada (CDVF). As imagens por vídeo e câmera de celular, a distâncias de 0,8 e 1,0 m do dossel da cultura, respectivamente, destacaram-se como as mais eficazes na estimativa da interceptação de radiação e iPAR por meio da CDVF.

PALAVRAS-CHAVE: *Glycine max*, eficiência de uso de radiação, cobertura de dossel verde fracionada.

INTRODUCTION

Soybean [*Glycine max* (L.) Merril] is one of the main commodities of Brazilian agribusiness, with the country consolidating its position as the world's largest producer and exporter, with a national production that has exceeded an average of 110 million tons over the past ten years (Conab 2023).

Technologies applied to soybean cultivation are essential for achieving a high yield, including tools that enable yield prediction, monitoring, and the assessment of crop development, such as the determination of canopy cover (Schmitz & Kandel 2021).

The analysis of soybean canopy cover contributes to a more precise approach to the implementation of several management practices throughout the crop cycle. These include adjustments in seeding density, fertilization strategies, biomass estimation, and phytosanitary applications (Avolio et al. 2018, Heinonen & Mattila 2021). In addition, canopy cover assessment enables the estimation of other important parameters, such as the percentage of radiation interception, intercepted photosynthetically

[1] Received: Sep. 11, 2025. Accepted: Dec. 19, 2025. Published: Jan. 21, 2026. DOI: 10.1590/1983-40632026v5683915.
[2] Universidade Federal de Santa Maria, Departamento de Ciências Agronômicas e Ambientais, Frederico Westphalen, RS, Brazil.
E-mail/ORCID: diecsonros@gmail.com/0000-0002-0354-7744; claudirbasso@gmail.com/0000-0002-3013-5702; gizellidepaula@gmail.com/0000-0003-4644-4005.
[3] Universidade Federal de Pelotas, Departamento de Fitossanidade, Capão do Leão, RS, Brazil.
E-mail/ORCID: fernandatrentin@gmail.com/0000-0003-3623-3634.
Editor: Luis Carlos Cunha Junior/Data Availability Statement: Research data are only made available by authors upon request.

active radiation (iPAR), and leaf area index (Tenreiro et al. 2021). These variables are essential because variations in soybean canopy cover substantially affect the plant's ability to convert solar radiation into photoassimilates, directly influencing crop growth and development (Quijano & Morandi 2023).

Currently, several methods are available for evaluating plant canopy cover, which can be classified as destructive or non-destructive. These approaches differ in terms of practicality, accuracy, implementation, and operational costs (Shu et al. 2023). Destructive methods, such as the leaf disk method, are more time-consuming for data collection and require the removal of plants from the field for analysis. Moreover, they demand a considerable number of samples to ensure representativeness, and to adequately capture spatial heterogeneity in the assessments (Gonçalves et al. 2020).

In contrast, techniques based on remote sensing or devices that measure the normalized difference vegetation index, which are increasingly adopted in agriculture, represent a more efficient and rapid option for in-field data acquisition and processing. Nevertheless, these approaches also present limitations, including higher costs associated with data acquisition and the need for specialized training to ensure a proper use and interpretation (Lykhovyd et al. 2022).

The free mobile application Canopeo, developed by the Oklahoma State University, Stillwater, OK, USA, provides a simple and rapid approach for measuring fractional green canopy cover (FGCC). Canopeo is based on the digital analysis of images acquired using cameras or smartphones, classifying pixels according to threshold values of red, green, and blue (RGB) ratios, which allows the discrimination of green vegetation from other scene elements such as soil, crop residue, and shadows (Patrignani & Ochsner 2015). FGCC is calculated as the proportion of pixels classified as vegetation relative to the total number of pixels in the analyzed image.

Since its development, Canopeo has been applied to a range of agricultural crops, including wheat, maize, sorghum, pastures, sugarcane and soybean, showing strong correlations with traditional methods used to estimate canopy cover, leaf area index, and radiation interception (Patrignani & Ochsner 2015, Tenreiro et al. 2021, Shu et al. 2023). As an example, in sugarcane, light interception determined using a linear quantum sensor showed a positive and significant correlation (r = 0.764) with canopy cover, indicating high reliability of the application, particularly during the early and intermediate stages of crop development (Kumar et al 2023).

In addition to using the integrated smartphone camera for image analysis with Canopeo, an alternative approach involves the use of attachable lenses, commonly referred to as fisheye lenses. These lenses are widely used in forest canopy assessments and provide a wide field of view, enabling panoramic image acquisition from a single position and thereby increasing the representativeness of the evaluations (Chianucci 2016, Smith & Ramsay 2018). The incorporation of fisheye lenses has allowed smartphone-based photographs to capture greater details of forest canopy openings, proving crucial for monitoring seasonal changes in vegetation dynamics (Smith & Ramsay 2018). However, their application in annual crops still requires validation due to differences in canopy structure, height, and light distribution.

Based on the conceptual relationship between canopy structural attributes and intercepted radiation, the hypothesis of this study is that image acquisition and processing methods using Canopeo have estimation power comparable to that of traditional destructive methods for radiation interception, iPAR, and radiation-use efficiency. Therefore, it aimed to identify the most suitable image acquisition method using a smartphone camera to estimate the percentage of radiation interception, intercepted photosynthetically active radiation (iPAR), and radiation-use efficiency in soybean.

MATERIAL AND METHODS

The study was conducted at the experimental area of the Universidade Federal de Santa Maria, in Frederico Westphalen, Rio Grande do Sul state, Brazil, during the 2021/2022 growing season. The site is characterized by clayey soil (Embrapa 2013), and environmental conditions [incident radiation, intercepted photosynthetically active radiation (iPAR), temperature, and rainfall] were obtained from an automatic meteorological station located at approximately 400 m from the experimental area (Figure 1).

The BMX Lótus IPRO soybean cultivar, characterized by an indeterminate growth habit

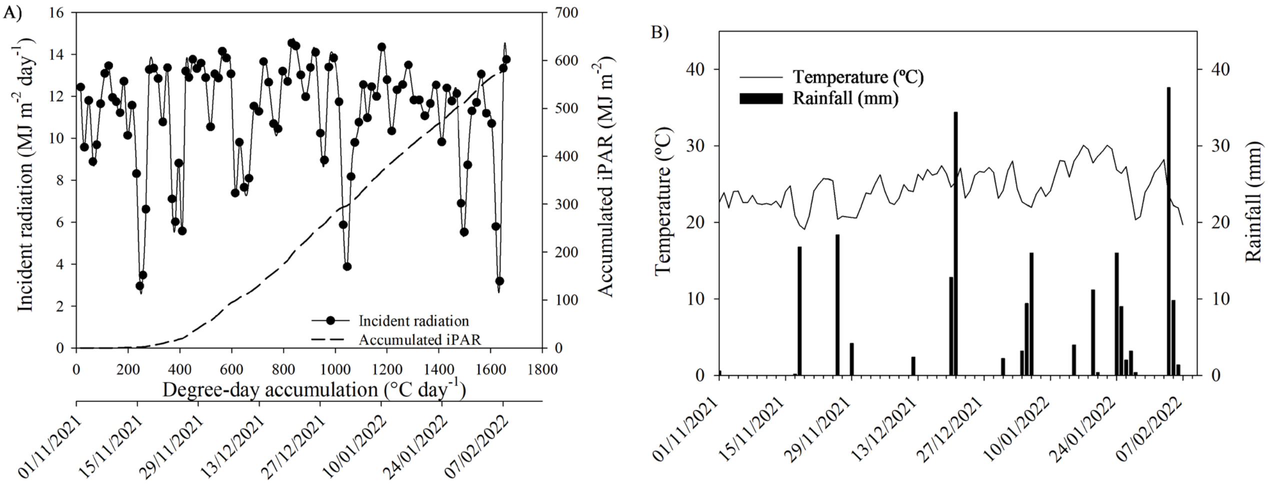

Figure 1. Incident radiation and accumulated intercepted photosynthetically active radiation (accumulated iPAR) as a function of accumulated growing degree-days (A), and mean daily air temperature and daily rainfall (B) recorded in Frederico Westphalen, Rio Grande do Sul state, Brazil, during the 2021/2022 growing season.

and maturity group 6.1, was sown following black oat (*Avena strigosa*) cultivation. Desiccation was performed at 7 days prior to sowing, using glyphosate combined with 2,4-D. Row spacing was 0.45 m, and plant density was 211,111 plants ha^{-1}. An NPK fertilizer was applied at a rate of 250 kg ha^{-1}, using the 02-23-23 formulation. Phytosanitary treatments were carried out periodically to prevent damage to plant growth and development.

A randomized complete block design was used, with four replications. Experimental plots measured 2.25 × 5.0 m. Different image acquisition methods and normalized difference vegetation index readings were applied between the vegetative emergence and early reproductive stages (VE to R5), with evaluations conducted at regular intervals of approximately 10 days throughout the crop cycle. Data collection began on Nov. 13, 2021, and continued until Feb. 7, 2022, covering the vegetative and early reproductive stages of soybean development.

The image acquisition methods consisted of: nadir (top-down) image capture using the smartphone camera positioned at 1 m above the plant canopy (T1); nadir image capture using a fisheye lens attached to the smartphone at heights of 1 m and 0.43 m above the canopy (T2 and T3, respectively); upward-facing image capture with the smartphone camera positioned on the soil surface (T4) and with the fisheye lens attached (T5); and video recording at a speed of 1 m s^{-1} with the smartphone positioned at 0.80 m above the crop canopy (T6). Nadir photographs were taken by an operator with arms extended or using a selfie stick, at predetermined distances from the canopy, maintaining the camera as parallel to the soil surface as possible, without any prior preparation of the area for image acquisition (Figure 2). Upward-facing photographs were obtained by positioning the smartphone between crop rows using a selfie stick.

Prior to image acquisition, weeds were manually removed from the plots to avoid interference. Normalized difference vegetation index readings were obtained using a GreenSeeker sensor, positioned statically and parallel to the canopy at a distance of 0.90 m, with the sensor centered over the crop row. All image acquisitions were performed in the same plot for each evaluation period.

Images and videos were captured using a Motorola Moto G8 Power smartphone camera between 10:00 and 12:00 a.m., under clear-sky conditions. Camera focus and brightness were set to automatic mode. Images were saved in jpeg format, with resolution of 4,128 × 3,096 pixels (12 MP), and videos were recorded in Full HD (1,920 × 1,080 pixels; 2 MP), with a 16:9 aspect ratio. The field of view for images and videos was 61 × 48 º, corresponding to a capture area of 0.90 × 1.2 m. The fisheye lens provided a field of view of 116 × 90 º, with a capture area similar to that of the standard lens at a height of 0.43 m above the canopy, and an area of 2.0 × 3.2 m (6.4 m²) at a height of 1.0 m above the canopy. The fisheye lens was attached to the smartphone using a clip aligned with the camera lens, allowing the generation of circular or

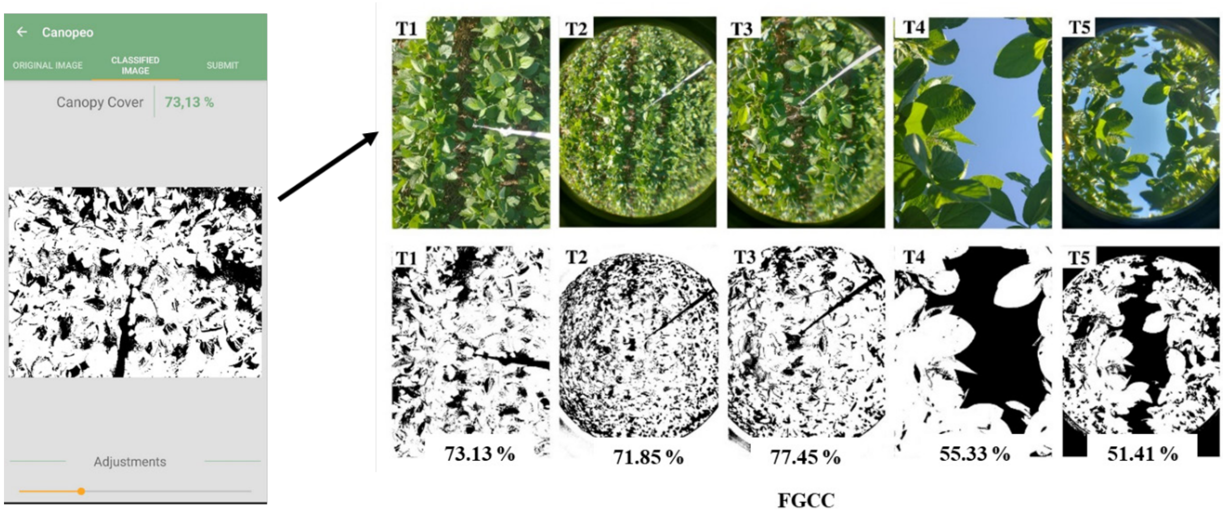

Figure 2. Images obtained and analyzed using the Canopeo application for fractional green canopy cover (FGCC) determination. Treatments: T1) nadir view, smartphone camera, height 1.0 m; T2) nadir view, fisheye lens, height 1.0 m; T3) nadir view, fisheye lens, height 0.43 m; T4) upward-facing view, smartphone camera; T5) upward-facing view, fisheye lens. At the same growth stage, the video-based method (T6, not shown) resulted in an FGCC of 80.7 %. Soybean at the V5 growth stage.

spherical images with greater distortion at the edges relative to the center.

Field-acquired images were analyzed using the Canopeo application (Oklahoma State University, Stillwater, OK, USA) to generate fractional green canopy cover (FGCC) values for soybean. The application classifies pixels based on predefined red/green and blue/green ratio thresholds, converting pixels identified as green vegetation to white and non-vegetated pixels to black. FGCC is calculated as the proportion of white pixels relative to the total image area. In this study, red/green and blue/green thresholds were set to 1.0 for all analyses (Figure 2), and FGCC values were used as indicators of crop canopy cover and radiation interception.

Following image acquisition, the soybean growth stage was determined, and the leaf area was measured within a 0.45-m^2 sampling area. The leaf disk method was used to determine the leaf area (m^2), and the leaf area index (LAI) was estimated as the ratio between the leaf area and the sampled ground area (0.45 m^2).

Calculated intercepted photosynthetically active radiation (iPAR_cal; MJ m^{-2}) was determined using the model proposed by Varlet-Grancher (1989): $iPAR_{cal} = 0.95 * (PARinc) * [1 - e^{(-k * LAI)}]$, where incident photosynthetically active radiation (PARinc; MJ m^{-2}) was obtained by assuming that 45 % of global solar radiation corresponds to PAR (Assis & Mendez 1989). The dimensionless light extinction coefficient (k) was assumed to be 0.5 for soybean (Pengelly et al. 1999). The leaf area index was included as previously described.

Two methods were used to estimate the percentage of intercepted radiation (iR%) by the crop. The first one (destructive method) was based on the ratio between iPARcal and PARinc, whereas the second method considered FGCC as equivalent to the percentage of intercepted radiation.

The percentage of intercepted radiation obtained by both methods at each evaluation period was fitted to a logistic model, as a function of accumulated growing degree-days: $iR(\%) = a/[1 + (x/x_o)^b]$, where *a* represents the maximum asymptote of iR(%); x_0 corresponds to the accumulated degree-days at which 50 % of the maximum iR(%) is reached; and *b* is the slope of the curve at x_0.

Using the logistic model, the percentage of intercepted radiation was calculated for each method on each day of the crop cycle. Accumulated intercepted radiation (MJ m^{-2}) was obtained by summing the daily product of the intercepted radiation fraction (calculated and estimated) and PARinc for each specific day. Subsequently, the radiation-use efficiency (g MJ^{-1}) was estimated by dividing the observed biomass at the R5 stage by the accumulated intercepted radiation for the different image-based methods, in comparison with the destructive method.

Pearson's correlation analyses and regression models were used to investigate the relationships between the intercepted radiation and the FGCC obtained with Canopeo. Data were analyzed separately for the vegetative stage, reproductive stage, and the complete crop cycle to assess whether image acquisition methods could capture variations across different stages of crop development. The model performance was evaluated using the coefficient of determination (R^2) and root mean square error. When the slope of the linear regression was not significant ($p < 0.05$), the regression line was forced through the origin ($x = 0$). Radiation-use efficiency data were subjected to analysis of variance (Anova), with image acquisition methods considered as the main factor. Mean radiation-use efficiency values were compared using the least significant difference test ($p \leq 0.05$). The Rbio and Sigmaplot 15 software packages were used for statistical analyses and graphical representations.

RESULTS AND DISCUSSION

The highest leaf area index, obtained using the destructive plant evaluation method, was observed at the R3 growth stage of soybean, followed by a subsequent decline in the later stages. This indicates that maximum interception of incident light energy by the crop occurs close to the full flowering stage (Figure 3) (Zanon et al. 2018).

Estimates of intercepted radiation derived from the destructive method and from fractional green canopy cover (FGCC) showed a strong positive correlation when evaluated during the vegetative phase of soybean (r = 0.88 to 0.98), or when the entire crop cycle was considered (r = 0.95 to 0.98) (Figure 4). In contrast, correlations during the reproductive phase were low and/or not statistically significant. The results obtained for the reproductive phase are consistent with findings reported for wheat, in which light interception estimated using FGCC derived from Canopeo was overestimated during early growth stages and underestimated during the reproductive phase, when compared with measurements obtained using a line quantum sensor (Helguera et al. 2022). It is important to emphasize that Canopeo itself does not perform regression analyses or model fitting; instead, it estimates FGCC through pixel-based image classification, separating green canopy pixels from background pixels (soil, crop residue) based on fixed color threshold ratios (red/green and blue/green). Therefore, all statistical analyses and model fitting presented in this study were performed externally using FGCC values generated by the application.

As canopy closure increases, mutual shading among leaves reduces the visibility of lower canopy layers, thereby affecting the ability of RGB-based image analysis methods to fully represent the three-dimensional structure of the canopy. Similarly, leaf senescence during the maturation process has a considerable influence on the fraction of intercepted photosynthetically active radiation, as the proportion of pixels classified as green decreases due to the fixed color threshold algorithms employed by Canopeo (Li et al. 2021). Consequently, the lower agreement between FGCC-based estimates and radiation interception during reproductive stages is primarily related to physical and methodological limitations, rather than to the image analysis mechanism of Canopeo itself.

Image acquisition methods using nadir views (T1) and video recordings (T6) stood out by providing the most accurate estimates of intercepted radiation (Figure 4). For both methods, the radiation interception estimation line passed through the y-intercept at zero, exhibited the highest coefficients of determination (R^2), and showed the lowest root mean square error, demonstrating the effectiveness of the fitted equations for predicting the percentage of intercepted radiation. These results support the hypothesis of a linear relationship between FGCC and radiation interception under conditions of uniform

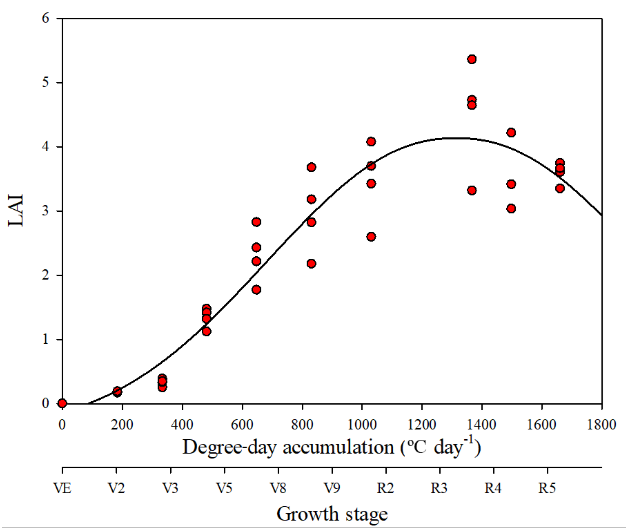

Figure 3. Temporal dynamics of soybean leaf area index (LAI) as a function of accumulated growing degree-days and developmental stage, during the 2021/2022 growing season. VE: vegetative emergence.

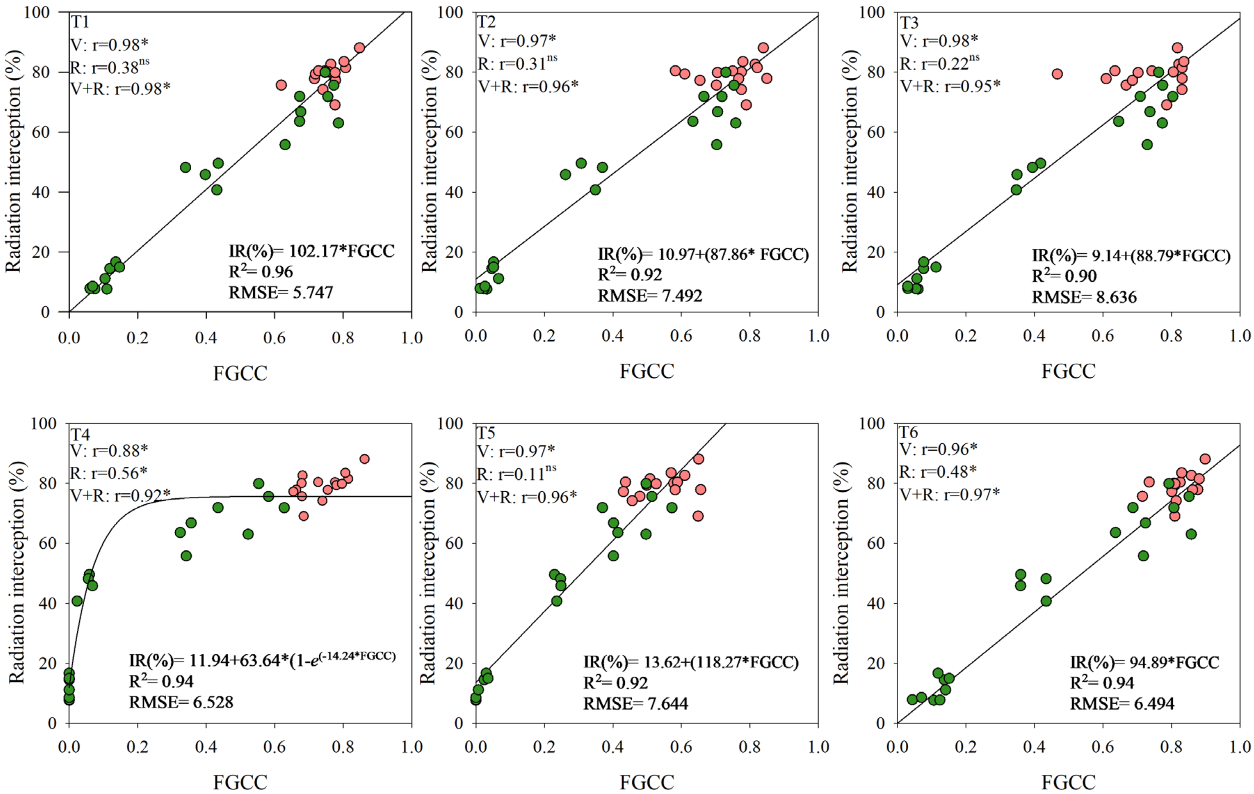

Figure 4. Relationship between the percentage of intercepted radiation estimated using the Varlet-Grancher (1989) model (destructive method) and fractional green canopy cover (FGCC). The blue line represents the 1:1 relationship. Data from the 2021/2022 growing season. Green (●) and red (●) points indicate observations collected during the vegetative (V) and reproductive (R) stages, respectively. r denotes the Pearson's correlation coefficient ($p \leq 0.05$). Treatments: T1) nadir view, smartphone camera, height 1.0 m; T2) nadir view, fisheye lens, height 1.0 m; T3) nadir view, fisheye lens, height 0.43 m; T4) upward-facing view, smartphone camera; T5) upward-facing view, fisheye lens; T6) video transect across the plot. IR: intercepted radiation; RMSE: root mean square error.

canopy development, as previously reported for soybean and other annual crops using destructive methods and optical sensors (Timlin et al. 2014, Shepherd et al. 2018).

These findings are highly encouraging, as smartphone-acquired imagery represents an accessible and cost-effective alternative to traditional approaches involving visual estimations, destructive procedures, or expensive equipment (Büchi et al. 2018, Arietta 2021).

Upward-facing images (T4 and T5) underestimated radiation interception during early vegetative stages of soybean, primarily due to the low plant height and limited canopy development at these stages (Timlin et al. 2014). Under such conditions, a substantial portion of the camera field of view positioned beneath the canopy did not capture vegetation. Consequently, the Canopeo color-threshold classification algorithm identified a lower proportion of pixels as green vegetation, resulting in reduced FGCC values and, therefore, underestimation of intercepted radiation. This effect arises from a physical and geometric limitation of the image acquisition method during early growth stages, rather than from an intrinsic failure of the application's algorithm. During reproductive stages, image quality is further reduced due to increased leaf shading, which generates very dark green tones that the application is unable to correctly interpret as green canopy area (Shepherd et al. 2018).

Images obtained using fisheye lenses (T2, T3, and T5) also exhibited a tendency to underestimate radiation interception, mainly due to intrinsic optical limitations associated with image distortion and reduced quality in peripheral regions, which appeared to be the most relevant factor in this study. Fisheye lenses provide an extremely wide field of view, resulting in reduced effective resolution at the image edges, often accompanied by lower brightness and sharpness, when compared with the central region (Bianchi et al. 2017). These characteristics compromise the accurate identification of green pixels by the Canopeo color classification algorithm. Another challenge associated with the use of fisheye lenses on smartphones relates to technical aspects, such as the lack of standardized mounting or attachment mechanisms, which may hinder proper alignment between the fisheye lens and the smartphone's integrated optics, leading, in some cases, to distorted estimates (Hederová et al. 2023). Furthermore, although fisheye lenses are more commonly and effectively applied in forest canopy assessments, their use in annual crops requires further investigation, considering variables such as crop type, vegetative characteristics, and the timing of evaluations.

It is noteworthy that the captured images and the collection of plant material represent different sampling areas. For example, the destructive method evaluated an area of approximately 0.45 m², whereas nadir (top-down) images covered an area of 1.08 m². In contrast, the fisheye lens captured areas ranging from 1.08 to 6.4 m², depending on the acquisition height. When using video, the sampled area may vary according to the plot size, resulting in a more spatially homogeneous representation of the canopy.

The use of the Canopeo application has been shown to be a viable alternative for determining leaf area index, canopy cover, and estimating radiation interception, among other variables, exhibiting excellent agreement with destructive methods or with measurements obtained using equipment such as a line quantum sensor. According to Shepherd et al. (2018), image-based approaches show strong correlations with linear quantum sensor measurements in soybean fields, in addition to offering advantages such as ease of data acquisition and handling in wheat crops, when compared with quantum sensors that require careful leveling and positioning in dense canopies (Helguera et al. 2022). Furthermore, image-based methods have the advantage of being applicable at any time of day and under low-light conditions (Purcell 2000). The Canopeo mobile application can also be considerably faster in quantifying FGCC than other commonly used software, processing images 20 to 130 times faster than SigmaScan Pro and 75 to 2,500 times faster than SamplePoint (Booth et al. 2006, Patrignani & Ochsner 2015).

Image and video acquisition methods using nadir views exhibited the highest correlations for estimating soybean iPAR, with coefficients of determination ranging from 0.92 to 0.99 (Figure 5). Upward-facing images showed a greater proximity to the 1:1 line; however, the method T1 yielded the lowest root mean square error, when compared with the other image acquisition modalities. The use of fisheye lenses did not improve estimation accuracy relative to T1. Regarding the comparison between observed iPAR (destructive methods) and estimated iPAR (FGCC-based), all image acquisition methods exhibited high coefficients of determination during the vegetative stage of soybean; nevertheless, T1 and T6 again stood out as the most effective options (R^2 = 0.99). Image acquisition methods using upward-facing views were the least efficient for estimating iPAR, with Canopeo-based iPAR values being consistently underestimated.

Because radiation interception and iPAR in soybean are closely related to leaf area index and to the spatial arrangement of a given cultivar, upward-facing images likely resulted in lower iPAR estimates, because they captured fewer plants or represented canopy architecture less effectively. This limitation arises from the smaller capture angle when the smartphone is positioned at the soil surface. In addition, as crop development advances, increased shading and leaf overlap within the same plant further reduce canopy representativeness in images. Besides impairing photographic quality and image analysis, thereby reducing Canopeo-based iPAR estimates, more shaded leaf portions receive predominantly diffuse radiation, which also leads to divergence in photosynthetic rates (Nomura et al. 2021). This effect may not pose a limitation in more open canopies, such as forest ecosystems (Tanioka et al. 2020). In contrast, nadir-view images tend to capture leaves more representatively, in terms of both quantity and spatial distribution, as previously observed in digital photographs acquired at approximately 1.5 m above the soil surface in wheat fields, where the detection area was about 60 times larger than that of a line quantum sensor (Helguera et al. 2022).

Radiation-use efficiency estimated using image acquisition methods showed a positive correlation with the destructive leaf area index-based method, except for upward-facing images (T4 and T5), which significantly overestimated the radiation-

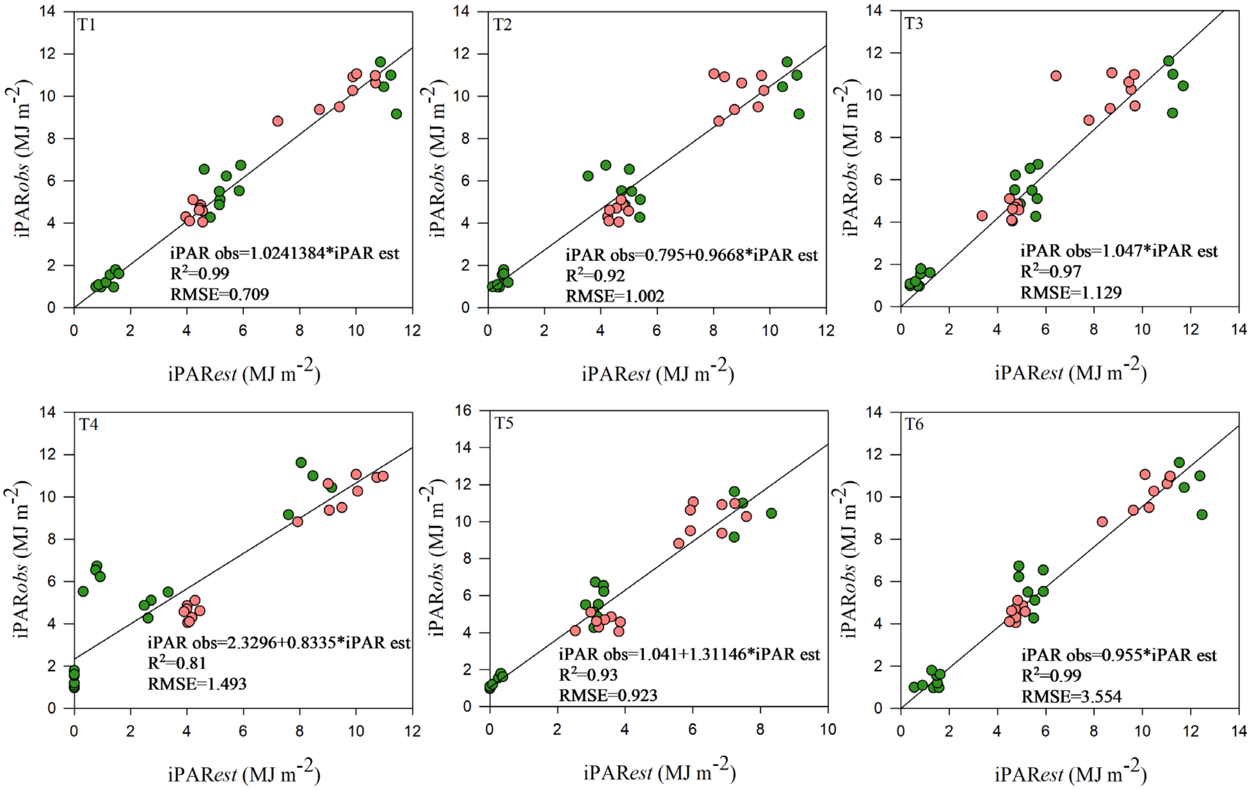

Figure 5. Relationship between the observed intercepted photosynthetically active radiation (iPAR), determined using the Varlet-Grancher (1989) model (destructive method), and iPAR estimated from fractional green canopy cover (FGCC) in soybean. The blue line represents the 1:1 relationship. Data from the 2021/2022 growing season. Green (●) and red (●) points indicate observations collected during the vegetative (V) and reproductive (R) stages, respectively. r denotes the Pearson's correlation coefficient ($p \leq 0.05$). Treatments: T1) nadir view, smartphone camera, height 1.0 m; T2) nadir view, fisheye lens, height 1.0 m; T3) nadir view, fisheye lens, height 0.43 m; T4) upward-facing view, smartphone camera; T5) upward-facing view, fisheye lens; T6) video transect across the plot. RMSE: root mean square error.

use efficiency relative to the destructive method (Figure 6). This overestimation can be partially attributed to the camera position beneath the plant canopy and to the use of fisheye lenses, which tend to distort the perceived size of leaves, thereby enlarging the apparent leaf area.

In agricultural research, accurate estimation of radiation-use efficiency is essential for understanding plant growth processes and optimizing crop production. Traditionally, this has been achieved through destructive methods involving direct measurement of crop growth parameters. However, these methods are time-consuming, labor-intensive, and often limited in practical applicability. Consequently, alternative approaches such as image-based techniques have increasingly been explored to estimate radiation-use efficiency.

The results presented here indicate a strong correlation between the destructive method and Canopeo-based image analysis for estimating radiation interception, iPAR, and radiation-use efficiency. While the leaf disk method involves multiple steps and tools, ranging from plant removal in the field to drying and weighing of plant material, image analysis using the Canopeo application is not only non-destructive, but also simpler to implement and freely available. At the same time, smartphones have become increasingly widespread and indispensable, with substantial advances in both software and optical hardware, enabling their use across a wide range of research applications (Arietta 2021). Supporting this perspective, Chung et al. (2017) evaluated biomass estimation in sorghum using the Canopeo application, in comparison with a destructive method, and reported significant results when plants were in the vegetative stage, particularly when comparing green color percentages, plant height, and node height.

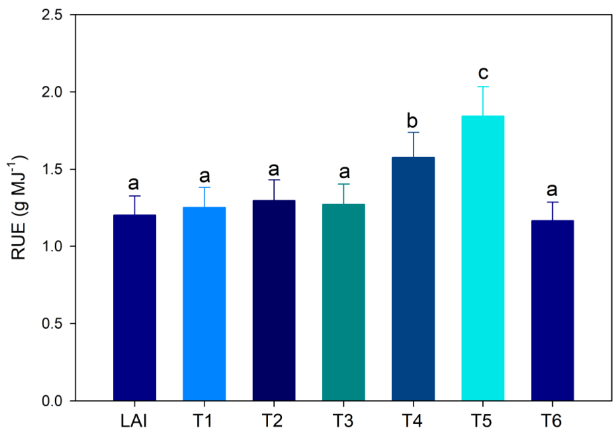

Figure 6. Radiation-use efficiency (RUE) in soybean estimated using the leaf area index (LAI)-based method and different image acquisition methods. Data from the 2021/2022 growing season. Means followed by the same letter do not differ significantly according to the least significant difference test ($p \leq 0.05$). Treatments: T1) nadir view, smartphone camera, height 1.0 m; T2) nadir view, fisheye lens, height 1.0 m; T3) nadir view, fisheye lens, height 0.43 m; T4) upward-facing view, smartphone camera; T5) upward-facing view, fisheye lens; T6) video transect across the plot.

The use of easy-to-apply tools with wide operational availability may be feasible, depending on the timing and objectives of the assessment, to rapidly obtain biophysical parameters in the field, thereby supporting both producers and researchers in crop monitoring and management.

CONCLUSIONS

1. Image acquisition techniques based on video and still photography, conducted at distances of 0.80 and 1.0 m above the crop canopy, respectively, proved to be the most effective methods for estimating radiation interception and intercepted photosynthetically active radiation (iPAR), using fractional green canopy cover (FGCC) derived from the Canopeo application. These approaches showed positive correlations with estimates obtained using the destructive analysis method;
2. Images acquired from an upward-facing perspective, with the smartphone camera positioned between soybean rows, underestimated both the percentage of intercepted radiation and soybean iPAR values, primarily because they captured a smaller leaf area.

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