

Efficiency of photosynthetically active radiation interception associated with morphological traits in canola cultivars

Eficiencia de la interceptación de radiación fotosintéticamente activa asociada a caracteres morfológicos en cultivares de canola

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ABSTRACT

The interception of photosynthetically active radiation (PAR) is a key factor for biological productivity, and its magnitude depends on the availability of solar radiation, the stage of the plant development cycle, and the arrangement of plant structures. Given the arrangement of the vegetative and reproductive structures in different portions in the canola canopy, the objective of this study was to morphologically characterize canola cultivars and establish relationships with the stratification of the efficiency of PAR interception. Eight canola cultivars were evaluated in regards to PAR and plant morphological traits. Following the analysis of variance, treatment means were grouped, and the phenotypic correlation matrix between the traits was determined. We observed a strong relationship between the PAR interception efficiency of vegetative and reproductive structures with morphological traits. Plants with a higher number of branches have more siliques and greater efficiency of PAR interception, mainly through the reproductive structures. The characterization of morphological differences between canola cultivars in the PAR interception efficiency should be performed by measures stratified by vegetative and reproductive structures.

Keywords: *Brassica napus* L., cultivar characterization, ideotype, plant architecture, selection.

RESUMEN

La interceptación de radiación fotosintéticamente activa (ARF) es importante para la productividad biológica y su magnitud depende de la disponibilidad de radiación solar, la etapa del ciclo de desarrollo de la planta y la disposición de las estructuras de la planta. Dada la disposición de las estructuras vegetativas y reproductivas de la canola en diferentes porciones del perfil del dosel de las plantas, el objetivo del trabajo fue buscar la caracterización morfológica de cultivares de canola y establecer relaciones con la estratificación de la eficiencia de interceptación de la radiación fotosintéticamente activa. Se evaluaron ocho cultivares de canola, se midió la ARF y se evaluaron los caracteres morfológicos de la planta. Se realizaron análisis de varianza, agrupamiento de medias y se determinó la matriz de correlación fenotípica entre los caracteres. Se observó una alta relación entre la eficiencia de interceptación de la RFA de estructuras vegetativas y reproductivas con caracteres morfológicos. Las plantas con mayor número de ramas tienen más sílice y mayor eficiencia en la interceptación de la radiación fotosintéticamente activa, principalmente debido a las estructuras reproductivas. La caracterización de las diferencias morfológicas entre cultivares de canola en la eficiencia de interceptación de la RFA debe realizarse mediante medidas estratificadas por estructuras vegetativas y reproductivas.

Palabras clave: *Brassica napus* L., caracterización de cultivares, ideotipo, arquitectura vegetal, selección.

Introduction

Canola (*Brassica napus* L. subsp. *oleifera*) is an oilseed from the Brassicaceae family, with by-products used for human consumption and

energy purposes. In Brazil, the largest producing state is the Rio Grande do Sul, with a cultivated area of 33.1 thousand hectares, followed by the state of Paraná with 0.9 thousand hectares (Conab, 2020). Canola is grown during the autumn/winter

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period, being an economically viable and important option for crop rotation management. In succession with soybeans, there is no competition for the area during the different growing seasons, while the crop allows using the same machines and equipment at the farm level. In addition, the high oil seed content provides liquidity in the market and growing agricultural demand for the product (Pinto *et al.*, 2017).

Photosynthetically active radiation (PAR) is a meteorological element related to the plant's photosynthetic rate and directly influences crop growth and development. The use of PAR depends on the availability of incident solar radiation on the terrestrial surface, an interception by vegetative and reproductive structures, and plant morphological traits. The extinction of PAR in the canopy increases with denser vegetative and reproductive structures (Ruiz and Bertero, 2008).

The architecture of canola plants in the vegetative and reproductive subperiods determines the morphological structures exposed and intercepting the PAR. In the canola vegetative subperiod, the PAR interception occurs employing vegetative structures, mainly by the leaf area. Meanwhile, there is a high interception in the reproductive subperiod in the reproductive structures (flowers and siliques). This condition in the reproductive subperiod allows the stems, flowers, and siliques to perform photosynthesis (Fochesatto *et al.*, 2016). In addition, the process tends to compensate for losses in the photosynthetic capacity of the leaves and reduction of the leaf area index (LAI) due to their senescence and the shading caused by the reproductive structures (Nied *et al.*, 2014). Although Fochesatto *et al.* (2016) found that the reproductive structures perform 80% of the PAR interception, it is necessary to verify possible differences between genotypes and the contributions of the stems, flowers, and siliques in this process.

The accumulated interception of PAR and the total plant dry weight production throughout the cycle allow estimating the efficiency of PAR use by the crop. Thus, cultivars with different morphological traits can interfere with PAR extinction in the canopy, and PAR intercepted and absorbed by leaves, stems, flowers, and siliques. We can infer the productive crop potential from the relationship between the PAR interception and the production of plant dry weight. In this context, the study's objective was to morphologically characterize canola cultivars and

establish relationships with the stratification of the efficiency of PAR interception.

Material and Methods

Experiment location

The experiment was conducted in the 2017 agricultural year in the experimental area of the Department of Plant Science at the Federal University of Santa Maria (29°34'02.31S, 53°43'57.63W), with 117 m altitude. According to the Köppen climate classification, the region's climate is Cfa, humid subtropical, with hot summers and no dry season defined (Heldwein *et al.*, 2009). The soil is classified as red dystrophic arenic Ultisol (Santos *et al.*, 2006). The experiment location is characterized as an undulated plain with adequate soil drainage.

Experimental design, canola crop management and evaluated traits

The experiment was carried out in a randomized complete block design with four replicates. The experimental units were composed of five 3.5 m rows, spaced at 0.45 m, totaling 7.87 m². Eight canola cultivars were evaluated: 'Hyola 61', 'Hyola 50', 'Hyola 433', 'Hyola 571 CL', 'Hyola 575 CL', 'Diamond', 'ALHT B4' and 'ALHT M6.' These cultivars represent a large portion of the canola cultivars available for cultivation in southern Brazil.

The basic fertilization was performed mechanically in the furrow employing a 5-row planter, using the fertilizer dosage of 20 kg ha⁻¹ of N, 80 kg ha⁻¹ of P₂O₅, and 80 kg ha⁻¹ of K₂O. Topdressing nitrogen supply was carried out in two applications: the first one at four fully expanded true leaves, using urea (45% N) in the dose of 50 kg ha⁻¹ of N and the second one at six fully expanded true leaves, using ammonium sulfate (21% N and 24% S) in the dose of 20 kg of N ha⁻¹.

Sowing was carried out manually on May 10, 2017, after the necessary fertilization and under the straw no-tillage planting system, with soybean as the predecessor crop. The plant emergence of all cultivars occurred on the eighth day, and manual thinning was performed after the canopy establishment, adjusting the plant population to 40 plants m⁻². Cultural practices related to insect pests and weed control were carried out whenever necessary throughout the plant development cycle, following technical crop management recommendations.

PAR was measured in the canopy with the aid of bars containing five sensors consisting of amorphous silicon cells, connected in parallel and previously calibrated. Each bar was connected to an AM25T multiplexer channel, connected to a Campbell Scientific® CR 1000 datalogger. The transmitted PAR was measured at levels of 0.05 m from the soil surface (TPARs) and below the insertion of reproductive structures (TPARrs) by installing a longitudinally and transversely leveled bar in each plot perpendicularly to the central plant lines. The incident PAR (IPAR) was measured using two leveled bars installed above the plant canopy. The TPARs and TPARrs data were respectively measured in four and three blocks. Readings were collected every three seconds, and their means were stored every 15 seconds. PAR measurements were performed on days with no cloudiness between 11 and 15 hours local time (14 and 18 UTC) at 97, 98, and 105 days after seedling emergence, during the full bloom of the cultivars.

The measured variables were: interception efficiency of PAR by the canopy (IEC) calculated by $IEC = 100 \cdot (IPAR - TPARs) / IPAR$, interception efficiency of PAR by reproductive structures (IERS) calculated by $IERS = 100 \cdot (IPAR - TPARrs) / IPAR$, interception efficiency of PAR by vegetative structures (IEVS) calculated by $IEVS = 100 \cdot (TPARre - TPARs) / IPAR$, plant height in cm, measured from the base of the plant until the insertion of the last silique (PH), number of branches per plant (NB), lower branches area index (LBAI), upper branches area index (UBAI), total branch area index (TBAI), leaf area index (LAI), silique area index (SAI), flower area index (FAI), total plant area index (TAI), dry weight of lower branches (DWLB), dry weight of upper branches (DWUB), dry weight of total branches (DWTB), dry weight of leaves (DWL), dry weight of siliques (DWS), dry weight of flowers (DWF) and total dry weight (DWT). Each plant branch was divided into two parts and defined respectively by a lower (only with leaves) and an upper (only with flowers or siliques) part.

For the evaluation of morphological traits, nine plants were collected from the central rows of each plot when the plants were in bloom at 98 days after emergence. The sampled plants were cut at ground level, placed in brown paper packages, and taken to the laboratory. The plant height was measured, and then the branches, leaves, flowers,

and siliques were separated. Subsequently, a digital camera fixed at 0.4 m in height was used to photograph a random sample of one-fifth of each plant structure to calculate the area index of leaves, lower and upper branches, siliques, flowers and total canopy by proportionality ratio. The images were processed using the Quant.v.1.0.2 (Vale *et al.*, 2002) software. Then, the samples were placed in brown paper packages and dried in an oven with forced ventilation at 65 °C for 72 hours until reaching constant weight. The dry weight was measured by means of a precision scale.

Daily meteorological data (Figure 1) were collected from the automatic meteorological station of the National Institute of Meteorology, located 1,000 m away from the experimental area.

Statistical analysis

For the traits, IEC, IERS, IEVS, LBAI, UBAI, TBAI, LAI, SAI, FAI, TAI, PH, NB, DWLB, DWUB, DWTB, DWL, DWS, DWF, and DWT, analyzes of variance and F-tests were performed for block and cultivar effects, at 5% error probability. The estimates of the mean square of the cultivar (MSc), mean square error (MSe), and overall mean of the experiment (\bar{m}) were recorded, and the coefficient of variation (CV) was calculated next. The means were clustered using the Scott-Knott test, at a 5% significance level, when the cultivar effect was significant.

For the study of linear relationships, the phenotypic correlation (r_p) matrix was estimated between the traits IEC, IERS, IEVS, LBAI, UBAI, TBAI, LAI, SAI, FAI, TAI, PH, NB, DWLB, DWUB, DWTB, DWL, DWS, DWF, and DWT. Then, the significance of the r_p was verified using the Student's t-test ($p \leq 0.05$). Statistical analyzes were performed with Microsoft Office Excel® and the Genes software (Cruz, 2016).

Results and Discussion

The mean air temperature was respectively 15.8 and 16.3 °C in the vegetative subperiod and flowering. Two consecutive days had air temperatures of -0.6 and -1.7 °C respectively at 62 and 63 days after emergence (DAE) in the vegetative subperiod (Figure 1). However, those days with negative air temperatures did not cause crop damage as they occurred prior to flowering. According to Dalmago

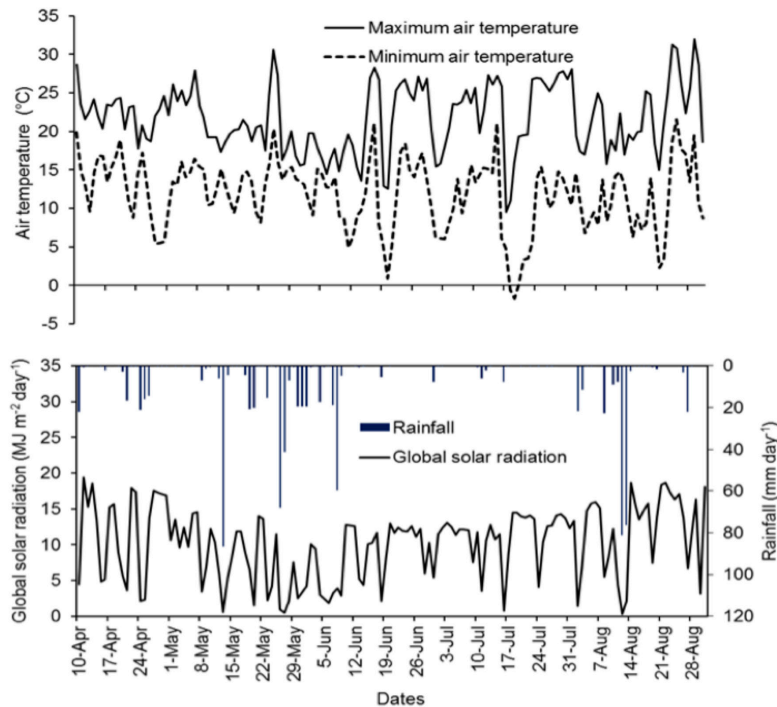


Figure 1. Maximum and minimum air temperature, global solar radiation and rainfall during the period of the experiment in Santa Maria - RS.

et al. (2010) and Kovaleski *et al.* (2019), negative temperatures can be harmful to canola if they occur shortly after emergence and during the flowering period. In addition, there was a gradual reduction in minimum air temperatures in the previous days, an important condition for possible plant acclimation to the cold condition (Dalmago *et al.*, 2010). Dry weight production by plants may not be affected by frost at a minimum air temperature of $-6\text{ }^{\circ}\text{C}$ occurred at the beginning of flowering in a growth chamber (Kovalesky *et al.*, 2019), suggesting little or no damage to the leaf area.

In the initial third of the vegetative subperiod (up to 23 DAE), several water surplus events were observed due to the high availability of rainfall. Consequently, they were associated with lower availability of solar radiation due to the significant cloudiness (Figure 1). This period coincided with the establishment and initial development of canola plants. The precipitation volumes decreased from the second half of June until the end of July, limiting water availability. Meanwhile, there was a higher density of solar radiation flow in the final third of the vegetative subperiod until the beginning of crop flowering.

After the beginning of flowering (75 DAE) for most cultivars, there was significant precipitation with four alternating days with water excess higher than 10 mm day^{-1} ensuring soil moisture at maximum storage capacity. The flux density of global solar radiation in the vegetative and flowering subperiods respectively averaged 12.2 and $15.2\text{ MJ m}^{-2}\text{ day}^{-1}$. The greater energy availability in the flowering subperiod favored energy storage in the canopy and, mainly, in the soil during the periods preceding low temperatures. This event can alter the radiation and energy balances in the plant-atmosphere soil system and reduces potential crop damage caused by possible frosts. In addition, solar radiation is a source of energy for the physical, chemical, and biological processes related to plant growth and development, which favored the development of the crop leaf area and the emission of reproductive structures.

The interception efficiency of PAR by the canopy (IEC) did not present a significant difference but ranged from 79.2 to 87.6% (Table 1). Typical values for leaf area index (LAI) are between 2.11 and 4.50 (Table 2) because the maximum interception by the crop canopy already occurs with LAI around 2.00 at

Table 1. Mean values of interception efficiencies of PAR by the canopy (IEC), reproductive (IERS) and vegetative structures (IEVS) in %, lower branches area index (LBAI), upper branches area index (UBAI), total branches area index (TBAI), leaf area index (LAI), silique area index (SAI), flower area index (FAI) and total plant area index (TAI).

Cultivar*	IEC	IERS**	IEVS**	LBAI	UBAI	TBAI	LAI	SAI	FAI	TAI
HYOLA 61	79.2	34.8 b	49.2 a	0.27 b	0.19 b	0.46 b	3.18 c	0.30 c	0.18	4.12 b
HYOLA 50	87.6	45.5 a	41.4 b	0.34 b	0.16 b	0.49 b	4.42 a	0.22 c	0.31	5.45 a
HYOLA 433	81.3	53.5 a	31.7 b	0.29 b	0.34 a	0.63 a	2.92 c	0.39 c	0.23	4.17 b
HYOLA 571	79.3	54.5 a	32.1 b	0.31 b	0.36 a	0.67 a	2.47 c	0.55 b	0.21	3.90 b
HYOLA 575	81.6	55.1 a	31.1 b	0.28 b	0.34 a	0.63 a	2.11 c	0.69 a	0.20	3.63 b
DIAMOND	84.3	48.0 a	39.0 b	0.32 b	0.41 a	0.73 a	2.52 c	0.81 a	0.29	4.34 b
ALHT B4	81.7	40.8 b	39.8 b	0.34 b	0.17 b	0.52 b	3.50 b	0.31 c	0.24	4.57 b
ALHT M6	87.1	29.0 b	59.0 a	0.49 a	0.08 c	0.56 b	4.50 a	0.04 d	0.17	5.26 a
Mean	82.8	45.2	40.4	0.33	0.26	0.59	3.20	0.41	0.23	4.43
C.V.	9.1	17.4	19.3	12.10	22.93	11.57	19.92	29.93	28.26	15.85

* Significant at 5 % error probability by the Scott-Knott test; ** Evaluated in three blocks.

Table 2. Mean values of plant height (PH), number of branches per plant (NB), dry weight of lower branches in grams per plant (DWLB), dry weight of upper branches in grams per plant (DWUB), total dry weight of branches in grams per plant (DWTB), dry weight of leaves in grams per plant (DWL), dry weight of siliques in grams per plant (DWS), dry weight of flowers in grams per plant (DWF) and total dry weight in grams per plant (DWT).

Cultivar	PH	NB	DWLB	DWUB	DWTB	DWL	DWS	DWF	DWT
HYOLA 61	98.19 c	5.47 b	5.36 d	1.30 c	6.66 b	3.86 b	1.34 c	0.48 b	12.34
HYOLA 50	111.53 a	5.61 b	7.65 b	1.08 c	8.73 a	4.65 b	0.83 d	0.69 a	14.90
HYOLA 433	106.64 b	12.64 a	6.26 c	2.15 b	8.41 a	2.53 c	1.74 c	0.62 a	13.30
HYOLA 571	113.92 a	11.28 a	6.40 c	2.40 b	8.80 a	2.46 c	2.40 b	0.49 b	14.15
HYOLA 575	114.47 a	10.78 a	6.74 c	2.72 a	9.46 a	2.43 c	3.27 b	0.44 b	15.60
DIAMOND	106.44 b	11.89 a	6.74 c	2.87 a	9.61 a	2.38 c	4.15 a	0.54 b	16.68
ALHT B4	112.89 a	6.47 b	7.99 b	1.30 c	9.29 a	3.73 b	1.27 c	0.60 a	14.89
ALHT M6	108.39 b	4.83 b	9.51 a	0.39 d	9.91 a	5.99 a	0.07 d	0.48 b	16.45
Mean	109.06	8.62	7.08	1.78	8.86	3.50	1.88	0.54	14.79
C.V.	4.06	19.86	9.75	20.06	10.87	21.32	33.89	18.83	12.57

*Significant at 5% error probability and treatment means followed by different letters differ by the Scott-Knott's mean hierarchical clustering test.

the time of the year with a greater solar declination (Dalmago *et al.*, 2018; Nied *et al.*, 2014). Although the cultivars Hyola 50 and ALHT M6 exhibited higher IEC among the cultivars, there was no significant difference given the self-shading of all plant structures. Corroborates with findings from Dalmago *et al.* (2018) and Nied *et al.* (2014), this result reinforces the hypothesis of the importance of interception by the reproductive structures found by Fochesatto *et al.* (2016).

The stratification of the PAR interception efficiency measures by vegetative and reproductive structures enabled us to identify significant differences between cultivars, differently from what happened using the canopy information. According to Fochesatto *et al.* (2016) and Justes *et al.* (2000),

PAR is intercepted as the development of plant structures occurs. ALHT M6 and Hyola 61 obtained higher values of interception efficiency of vegetative structures (IEVS). Vegetative structures are efficient in intercepting PAR until the initial third of the flowering subperiod, near the maximum crop LAI, from which the stems, flowers, and siliques contribute significantly to the interception (Fochesatto *et al.*, 2016). Although the IEC is maximum throughout the reproductive period, the interception efficiency by vegetative structures is significantly reduced after the final third of flowering and after the maximum canola LAI (Nied *et al.*, 2014).

In contrast, the cultivars Hyola 575, Hyola 571, Hyola 433, Diamond, and Hyola 50 showed greater PAR interception efficiency by the reproductive

structures (IERS). The canola cultivars with the highest area index and dry weight showed dense reproductive structures, enabling greater efficiency and uniformity of PAR interception. After flowering, the reproductive structures of canola intercepted between 45 and 80% of the incident PAR (Fochesatto *et al.*, 2016).

The different results between cultivars regarding IERS and IEVS confirmed the need for stratification of the PAR transmitted by the canopy to better grasp the relationships with other plant traits, especially in the characterization of cultivars. Without this stratification, we could mistakenly conclude that the cultivars intercept the PAR in the same way. For this reason, Fochesatto *et al.* (2016) measured only the radiation transmitted by the reproductive structures to evaluate the effects of cultivar and nitrogen doses. Moreover, Justes *et al.* (2000) also evaluated the leaf area, silique, and flower indices with an approach associated with the fragmentation of PAR estimates transmitted by these extracts. They observed that differences in plant architecture or morphological growth traits, depending on the cultivar, are crucial for the adequate comprehension of these relationships.

PAR interception efficiency measures (ϵ PAR), either by a canopy or stratified in vegetative and reproductive structures, are important to estimate the accumulated PAR interception (Σ iPAR) in failure situations or the absence of data collection. Σ iPAR is required to measure the PAR use efficiency (RUE) for canola and other crops. Therefore, RUE depends on ϵ PAR. Canola hybrids with thicker and larger leaves present higher RUE and seed yield in favorable environments (Zhang and Flottmann, 2016).

The LAI was respectively higher for ALHT M6 and Hyola 50 with values of 4.50 and 4.42. The PAR interpretation efficiency by the canola canopy is maximum with LAI around 2.00, which is equivalent to about half of the maximum canola LAI (Dalmago *et al.*, 2018; Nied *et al.*, 2014). The cultivars Hyola 575, Hyola 571, Hyola 433, Diamond, and Hyola 61 showed a lower LAI. However, most of the PAR interception occurred by the plant reproductive structures in these cultivars. Canola LAI reaches its maximum at full bloom, and then stems, flowers, and siliques intercept most of the PAR (Dalmago *et al.*, 2018; Fochesatto *et al.*, 2016). Therefore, as the assessment was performed during the flowering subperiod, the LAI reduces

its participation, and reproductive structures have greater importance in PAR interception.

The LBAI was higher for ALHT M6, with a lower UBAI. The highest UBAI was observed in Diamond, Hyola 571, Hyola 433, and Hyola 575. Some factors may have affected UBAI, as the instability of this variable is attributed to the plant population density, the indeterminate growth habit, and high morphological plasticity of canola plants, which allows a great capacity to adjust to variations in canopy density (Krüger *et al.*, 2011).

The SAI was higher in the cultivars Diamond and Hyola 575. This result is associated with the high UBAI and IEVS. Siliques are located in the middle layer of the plant inflorescence, and longer siliques are formed in the middle part of the main stem and lateral branches. The consequences in yield are greater seed weight and seed number in the siliques of this layer (Oleksy *et al.*, 2018).

Although there was no significant difference between cultivars for FAI, there was a significant difference for the DWF. The number of flowers in canola is directly linked to the crop's productive potential. Flower abortion between cultivars varies from 10.53 to 45.96%. In addition, cultivars with longer thermal times between the period of maximum flower emission and the end of flowering present higher percentages of flower abortion (Battisti *et al.*, 2013).

Considering the vegetative and reproductive structures of the crop, the cultivars Hyola 50 and ALHT M6 showed the highest TAI. This trait can be related to the LAI for both cultivars and the high LBAI of ALHT M6. Increased LAI of vegetative and reproductive structures provides higher PAR interception and energy for plant growth and development. Thus, we can infer that a rapid leaf area development is necessary to increase the production and accumulation of reserves (photoassimilates) for use during the reproductive period.

Results obtained for the canola morphological traits are shown in Table 2. The cultivars presented PH equal or greater than 98.19 cm, differing from each other. The cultivars Hyola 575, Hyola 571, ALHT B4, and Hyola 50 showed a higher PH. For NB, the cultivars Hyola 433, Diamond, Hyola 571, and Hyola 575 presented larger values. Comparing PH and NB, we observed that the cultivars Hyola 571 and Hyola 575 were associated with plant size and branching potential

superior to other cultivars. Meantime, ALHT B4 and Hyola 50 presented adequate height but low branching potential.

ALHT M6 presented higher DWLB even though it had the lower NB among the cultivars. The cultivars Diamond and Hyola 575 had the highest DWUB, probably due to their high branching potential associated with precocity. We observed that cultivars containing more branches increased the dry weight production in top branches. Compared to cultivars with low branching potential, they tend to have higher dry weight production in lower plant branches.

ALHT M6 showed greater magnitude for DWT, being attributed to its branching potential of lower branches. The NB per plant varies with plant population and spacing (Krüger *et al.*, 2011). Another important aspect related to dry weight production is the branch position in the plant. Likewise, the lower branches receive more photoassimilates and produce a higher amount of dry weight when compared to the upper branches.

ALHT M6 had a higher DWL, differing significantly from the others, which might be related to the high LAI of the cultivar. The LAI evolution in environments without limitations of PAR, water, and nutritional resources depends on the cultivar and thermal accumulation expressed in degree-days. Temperature causes the most significant changes in the accumulation and temporal dynamics of the morphological traits related to LAI and shoot dry weight (Pinto *et al.*, 2017). The DWS of Diamond was the largest, indicating a greater productive potential of this cultivar. The fresh weight of siliques varies over the cycle influenced by environmental conditions, regardless of the position in the canola inflorescence.

The variability of the crop biophysical indicators obtained by the cultivars' diversity allowed Pearson's correlation analyses (Figure 2) and to establish important relationships for the crop. The interception efficiency of PAR by the canopy showed a positive correlation only with the interception efficiency of PAR by vegetative structures and to DWF, to a smaller extent. With the stratification of transmitted PAR measurements by the canopy in vegetative and reproductive structures, there were higher correlation coefficients and significant correlations with a higher number of traits. While IEC correlations were significant for only two traits, IEVS and IERS were significant

with nine traits. This finding reiterates the need for stratification of canopy transmitted PAR measures in canola plants.

The IEVS showed a positive and negative association respectively with the lower and upper branches area index, and the inverse situation was found in the association of IERS with the same traits. This finding also evidenced the need to stratify the morphological measures, as done for the PAR measurements. We observed that IEVS presented a negative correlation with the IERS and a positive correlation with LAI. Measures of area indexes of branches, siliques, and flowers presented higher correlation coefficients with the IERS and IEVS than only dry weight measures. These results corroborate what was verified by Fochesatto *et al.* (2002) and Justes *et al.* (2000).

Although the cultivars differed in terms of PH, this trait was not correlated with PAR interception, as canola has high phenotypic plasticity and the ability to emit branches. On the other hand, there was a positive correlation between the NB and UBAI. As a result, plants with a greater NB tend to have a larger number of upper branches and greater IERS (Fochesatto *et al.*, 2016).

The NB showed a positive correlation with TBAI, UBAI, and SAI and a negative correlation with LAI. LBAI correlated negatively with UBAI and SAI. Therefore, plants with higher branching potential have better UBAI, which was highly correlated with TBAI and SAI and with the dry weights DWUB and DWS. This correlation indicates that the NB and UBAI or DWUB measurements are important to characterize cultivars, as they are highly correlated with silique yield indicators, SAI and DWS.

LAI was strongly and positively correlated with TAI as it is the component with the highest participation and negatively correlated with SAI, DWS, UBAI, and DWUB due to likely phenological differences between the cultivars. However, LAI is a significant indicator of plant growth, and the limitation in leaf number, thickness, and size is a morphological characteristic that can reduce canola seed productivity (Zhang and Flottmann, 2016). On the other hand, large LAI can intensify competition for solar radiation and interfere negatively with the energy balance of the source/drain ratio. Moreover, the PAR that reaches the lower third of the plant is reduced (Chavarría *et al.*, 2011), damaging photoassimilates' source/drain ratio, especially in

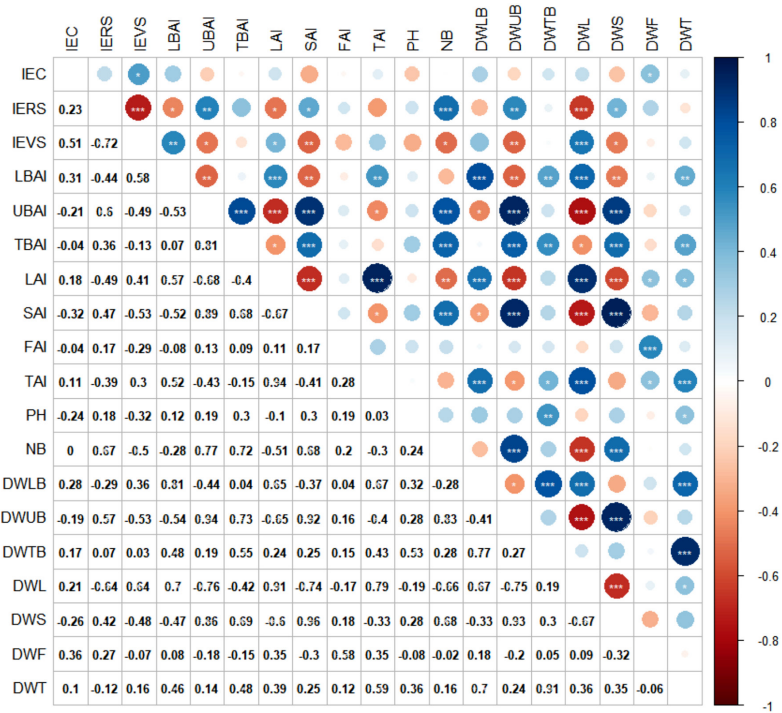


Figure 2. Estimates of Pearson's correlations between interception efficiencies of PAR by the canopy (IEC), vegetative (IEVS) and reproductive (IERS) structures in %, plant height (PH), number of branches per plant (NB), lower branches area index (LBAI), upper branches area index (UBAI), total branch area index (TBAI), leaf area index (LAI), silique area index (SAI), flower area index (FAI) and total plant area index (TAI), dry weight of lower branches in grams per plant (DWLB), dry weight of upper branches in grams per plant (DWUB), total dry weight of branches in grams per plant (DWTB), dry weight of leaves in grams per plant (DWL), dry weight of siliques in grams per plant (DWS), dry weight of flowers in grams per plant (DWF) and total dry weight in grams per plant (DWT) * Significant at 5% error probability by the Student's t-test.

periods with low PAR availability during the winter period in southern Brazil.

The SAI was positively correlated to UBAI, i.e., the presence of branches at the top of the plant favors the silique area index. From the period of flowering until maturity, the silique area index can be compensated by the promotion of floral branching in a low plant density condition. The dynamics of floral branches are strongly affected by different cultivars (Rondanini *et al.*, 2017). The cultivars with the highest number of siliques in the main stem have longer siliques and a positive correlation between siliques and the main branch. Thus, cultivars with the highest number of siliques in the main stem should be selected to maximize seed yield (Krüger *et al.*, 2011).

The PH was correlated with TDW, mainly due to the plant branching potential by lower branches.

Increased PH reduces canola branching. Another correlation analysis study showed a high and positive correlation between the number of branches per plant, the number of siliques in the main stem, and plant height in canola (Basalma, 2008).

The NB per plant showed a correlation with DWUB and DWS. The DWS presented a significant difference in the intermediate third between the main stem and the primary branch and between the intermediate third and the upper third of the main stem.

Canola dry weight measurements are easier to determine than area index measurements. However, the biophysical relationships of the PAR interception with area indices traits in canola present a more solid scientific basis for the interpretation of the cause-effect relationships of the processes involved. Meanwhile, dry weight measurements can be determined to ease the measurement of area indices for different plant

structures. The findings from the correlation analysis reinforce and confirm these inferences.

Conclusions

The characterization of canola cultivars is performed in more detail with measures of interception efficiency of photosynthetically active radiation in a stratified way by vegetative and reproductive structures than only with the plant canopy.

The morphological traits are related to the interception efficiency of photosynthetically active radiation by vegetative and reproductive structures.

Canola plants with a larger number of branches have more siliques and greater interception efficiency of photosynthetically active radiation by reproductive structures.

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