50 YEARS
eISSN 1981-1829

Ciência e Agrotecnologia
Science and Agrotechnology

Agronomic performance and seed quality of canola cultivars grown at high altitudes in the Brazilian Cerrado

Desempenho agronômico e qualidade de sementes de canola em altas altitudes no Cerrado

Soryana Gonçalves Ferreira de Melo[1], Ítallo Jesus Silva[1], Rogério Alves Santana[2], José Cola Zanúncio[3], Marcelo de Almeida Guimarães[4], Bruno Galvêas Laviola[5], Anderson Barbosa Evaristo[6], Marcela Carlota Nery[1*]

ABSTRACT

Canola (*Brassica napus* L. var. oleifera) is a major oilseed crop for human consumption and biodiesel production, yet its agronomic performance and seed quality under high-altitude tropical conditions are not well documented. This study evaluated four canola cultivars (Alth B4, Diamond, Hyola 575 CL®, and Nuola 300) grown at an altitude of 1,387 m above sea level in the Brazilian Cerrado, a savanna area in Diamantina, Minas Gerais, Brazil. The experiment followed a completely randomized design with four replications, assessing plant growth, productivity, seed physiological quality, and oil content. The phenological cycle of the cultivars ranged from 140 to 146 days. Productivity was highest for Nuola 300 and Alth B4 (~2,034 kg ha^{-1}), exceeding the national average, while Diamond and Alth B4 exhibited superior seed vigor and germination performance. Oil content varied from 42.57% to 46.36%, with Alth B4 and Diamond showing the highest values. Principal component analysis highlighted strong associations between agronomic performance and seed quality, distinguishing Diamond, Nuola 300, and Alth B4 as the most adaptable to high-altitude savanna conditions, while Hyola 575 showed lower overall performance. These findings demonstrate that canola can achieve high productivity and seed quality in high-altitude Cerrado regions, identifying cultivars with strong potential for commercial cultivation in these conditions.

Index terms: Canola; high-altitude cultivation; seed quality; oil content; germination.

RESUMO

A canola, utilizada para consumo humano e produção de biodiesel, apresenta potencial de expansão no Cerrado brasileiro, especialmente em áreas de altitude. Este trabalho teve como objetivo avaliar o desempenho agronômico, a qualidade fisiológica e o teor de óleo de sementes de cultivares de canola cultivadas em área de cerrado em altitudes elevadas (>1.300 m). Os experimentos foram conduzidos em delineamento inteiramente casualizado no município de Diamantina, Minas Gerais, Brasil. Foram avaliados o desempenho agronômico (população inicial, altura da planta, inserção da primeira síliqua, número de síliquas por planta, sementes por síliqua e produtividade), a qualidade fisiológica (teor de água, peso de mil sementes, primeira contagem de germinação, germinação, índice de velocidade de germinação, emergência, estande inicial, índice de velocidade de emergência, teste de frio) e o teor de óleo das cultivares Alth B4, Diamond, Hyola 575 CL® e Nuola 300. O desempenho agronômico de todas as cultivares foi satisfatório, com produtividade e teor de óleo semelhantes à média nacional. As variáveis da qualidade fisiológica foram maiores para as cultivares Nuola 300, Alth B4 e Diamond. Esses resultados reforçam a viabilidade e a vantagem das cultivares para o cultivo em regiões de Cerrado de altitude. A qualidade fisiológica superior das sementes das cultivares Nuola 300, Alth B4 e Diamond, em comparação à Hyola 575, consolida sua escolha como promissora para o cultivo nessas condições.

Termos para indexação: *Brassica napus* L. var. oleífera; teor de óleo; germinação; emergência.

Agricultural Sciences

Ciênc. Agrotec., 50:e018725, 2026
http://dx.doi.org/10.1590/1413-7054202650018725

Editor: Renato Paiva

[1]Universidade Federal dos Vales do Jequitinhonha e Mucuri/UFVJM, Departamento de Agronomia, Diamantina, MG, Brasil
[2]Universidade Federal dos Vales do Jequitinhonha e Mucuri/UFVJM, Faculdade de Ciências Sociais Aplicadas e Exatas, Teófilo Otoni, MG, Brasil
[3]Universidade Federal de Viçosa/UFV, Departamento de Entomologia/BIOAGRO, Viçosa, MG, Brasil
[4]Universidade Federal do Ceará/UFC, Departamento de Fitotecnia, Fortaleza, CE, Brasil
[5]Embrapa Agroenergia, Brasília, DF, Brasil
[6]Universidade Federal dos Vales do Jequitinhonha e Mucuri/UFVJM, Instituto de Ciências Agrárias, Unaí, MG, Brasil

*Corresponding author: nery.marcela@ufvjm.edu.br

Received in September 22, 2025 and approved in March 16, 2026

Introduction

Canola (*Brassica napus* L. var. *oleifera*) accounts for approximately 32% of the edible vegetable oils and 11% of global biodiesel production, ranking as the third most produced oilseed worldwide (Hussain et al., 2019; Zeferino et al., 2023). Canola seeds contain approximately 40-47% oil and 25-35% protein, making them highly suitable for human consumption and biofuel production. The bran is widely utilized in animal feed (Raboanatahiry et al., 2021; Guimarães et al., 2022).

The cultivated area of canola in Brazil reached 211.6 thousand ha during the 2025 harvest, with an average yield of 1,534 kg ha^{-1} and total production of 324.5 thousand tons, concentrated primarily in the states of Rio Grande do Sul and Paraná (CONAB, 2026). The production potential of oilseed crops, such as canola in Brazil, is sufficient to meet domestic demand and contribute to the global market, reinforcing their importance in diversified production systems and crop rotation strategies (Strahl et al., 2021).

Canola was originally cultivated in regions between latitudes 35° and 55°, at altitudes below 600 m, under temperate climates with well-distributed rainfall throughout the growing season (Tomm et al., 2010). However, the process of tropicalization has expanded canola cultivation to several regions of Brazil (Araújo et al., 2021), prioritizing high-altitude areas (above 600 m), where milder temperatures compensate for lower latitudes (below 35°) (Tomm et al., 2010). This expansion enables the characterization of new cultivars and the identification of genotypes with genetic and productive potential adapted to diverse soil and climatic conditions (Araújo et al., 2021).

The cultivation of canola under mild temperatures and precipitation patterns typical of high-altitude regions (above 600 m), such as Diamantina (1,387 m), Minas Gerais, Brazil (Oliveira et al., 2017), may enhance crop productivity due to the species' adaptability to a wide range of soil and climatic conditions (Assis et al., 2023), despite potential variations in seed quality (Lamichaney & Maity, 2021).

Therefore, this study aimed to evaluate the agronomic performance, physiological quality, and oil content of seeds from canola cultivars grown in a high-altitude savanna environment (>1,300 m).

Material and Methods

Local characterization

The experiment was conducted in the Experimental Area and Seed Laboratory of the Department of Agronomy at the Federal University of the Vales do Jequitinhonha and Mucuri (UFVJM), Campus JK, Diamantina, Minas Gerais, Brazil (18º20”29.95” S, 43º57º289” W; altitude 1,387 m). The local climate is classified as Cwb according to the Köppen classification, characterized as a high-altitude subtropical climate with dry winters and mild, rainy summers, and an average annual temperature of 20 °C.

The soil is classified as a typical Ortic Quartzarene Neosol according to the Brazilian Soil Classification System (SiBCS). Soil chemical properties were determined by laboratory analysis prior to planting (Table 1).

Based on soil analysis, liming was carried out 30 days before sowing using calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). Basal fertilization consisted of the application of 60, 110, 55, and 20 kg ha^{1} of N, P_2O_5, K_2O, and S, respectively. Topdressing fertilization was performed 30 days after sowing with 30 kg ha^{-1} of N and 28 kg ha^{-1} of K_2O (Tomm et al., 2010).

Sowing was performed on April 27, 2021, and harvesting began on September 11, 2021, in accordance with the guidelines of the Agricultural Climate Risk Zoning (*Zoneamento Agrícola de Risco Climático* – ZARC) for canola cultivation (Brasil, 2021). Climatic data recorded during the growing season are presented in Figure 1.

Genotypes and experimental design

The experiment was conducted using a completely randomized design. The canola cultivars, Alth B4 (Argentina, 2020), Diamond (United States, 2018), and Hyola 575 CL® and Nuola 300 (United States, 2019) were sown manually in plots of 22 m². Each plot consisted of 28 rows spaced 0.35 m apart, with 0.055 m between plants and 0.50 m between plots. Irrigation was applied daily by sprinkler, according to crop requirements. Manual weeding was performed at 50 days after planting.

Agronomic performance

The initial population (IP) was determined 30 days after sowing by direct counting of the canola plants in the four central rows of each experimental plot, each row measuring 1.10 m in length. Plant height (PH), height of insertion of the first silique (HIS), number of siliques per plant (NSP), and number of seeds per silique (NSS) were determined in 10 plants randomly sampled from the useful area of each plot at harvest, and mean values per plot were used for analysis.

Table 1: Chemical properties of the soil (0–20 cm layer) from the experimental area prior to canola sowing in Diamantina, Minas Gerais, Brazil. pH measured in water (H_2O); available phosphorus (P) and zinc (Zn) extracted with Mehlich^{-1}; potassium (K); sulfur (S); boron (B); copper (Cu); iron (Fe); and manganese (Mn); exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}) extracted with 1 mol L^{-1} KCl; Potential acidity (H + Al) extracted with 0.5 mol L^{-1} calcium acetate (pH 7.0); cation exchange capacity (CTC); base saturation (V%); aluminum saturation (m%); and organic matter saturation (MO).

pH (H_2O)	P	K	S		B	Cu	Fe	Mg	Zn
6.72					mg dm^{-3}				
	6.71	115.74	5.06		2	0.24	141.57	12.00	2.48
Ca^{+2}	Mg^{2+}	Al^{3+}	H + Al	CTC		V	m		MO
		cmolc dm^{-3}				%			dag Kg^{-1}
3.93	0.41	<0.10	1.07	5.7		81	0		1.66

Replicate analyses were performed every 10-20 samples for each soil test.

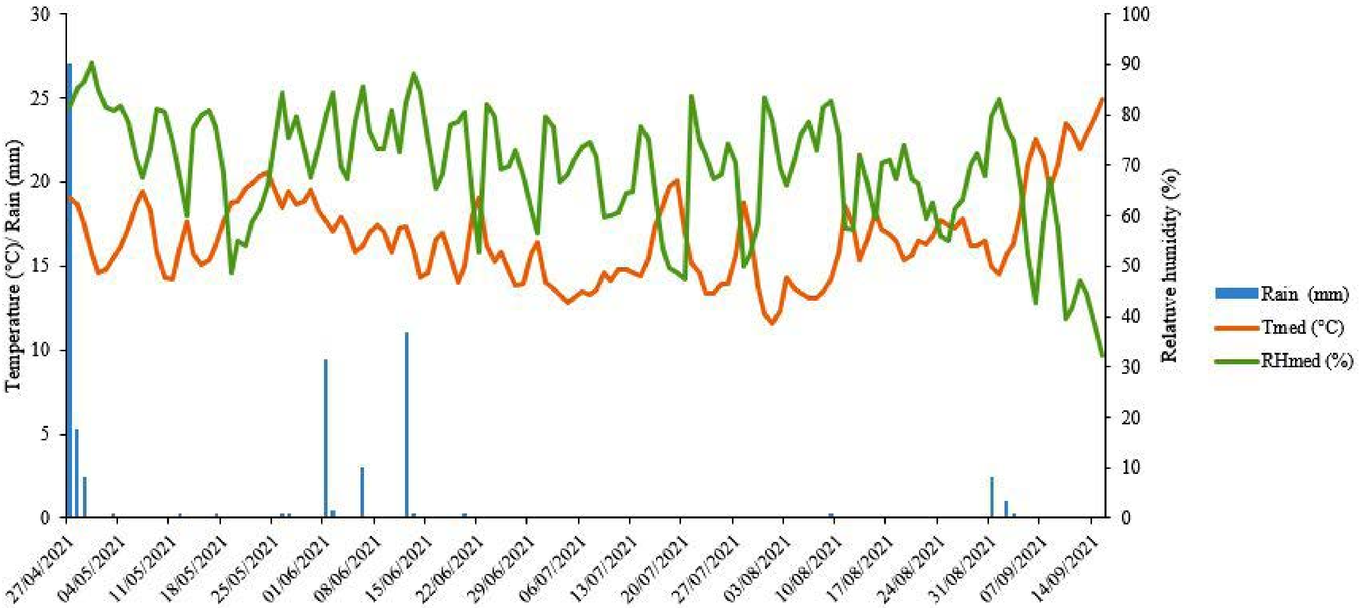

Figure 1: Monthly averages of mean temperature (Tmean, °C), relative humidity (RHmed, %), and rainfall (mm) from sowing to harvest of canola.

Plant height was measured as the distance (cm) from the soil surface to the apical bud using a graduated ruler. The height of the first silique insertion was similarly measured from the soil surface to the point of silique insertion on the stem. The number of siliques per plant and seeds per silique were determined by direct counting.

Grain yield or productivity (PROD) was obtained after harvesting and processing by weighing the seeds harvested from the usable area of each plot. Results were expressed in kg ha^{-1} and corrected for 10% seed moisture content.

Physiological quality and oil content of seeds

Seeds of all cultivars were harvested at the G5 phenological stage, when 60-80% of the siliques exhibited yellow and dry coloration, and the seeds were brown with an average water content of approximately 18% (Guimarães et al., 2022). After harvest, seeds were dried to a moisture content of 8-10% and processed. Due to differences in phenological cycle among cultivars, harvesting was performed individually when seed moisture reached 8-10%.

Seed water content was determined using the oven-drying method (Brasil, 2009). Newly harvested seeds were weighed, dried at 105 °C for 24 h, and then weighed again. The water content was calculated as the difference between the fresh and dry weights, divided by the fresh weight, and multiplied by 100.

The thousand-seed weight was determined using eight replications of 100 seeds per cultivar (Brasil, 2009), which were weighed on a semi-analytical electronic scale (Mars, model AD500). Results were expressed in grams, along with standard deviation and coefficient of variation (ISTA, 2019).

Germination tests were conducted according to the Rules for Seed Analysis (*Regras para Análise de Sementes* - RAS), using four replications of 50 seeds per cultivar. Seeds were placed on three sheets of Germitest paper, moistened with distilled water at 2.5 times the substrate's dry weight, and incubated in Gerbox-type plastic boxes in B.O.D. (Biochemical Oxygen Demand) germination chambers at 20 °C. Evaluations were performed on the 5th day (first germination count) and 7th day (final count) after sowing, recording the percentage of normal seedlings, defined as those possessing all essential structures necessary for plant development.

The germination speed index (GSI) was calculated based on daily counts until the seventh day, using the formula GSI = $\sum (ni/ti)$, where *ni* is the number of seeds germinated on day *i*, and *ti* is the number of days after sowing (Maguire, 1962).

The tetrazolium test was conducted on seeds remaining from the germination test that did not germinate but showed no signs of deterioration or flaccid tissues. The seeds were longitudinally sectioned, and one-half of each seed was immersed in a 0.5% 2,3,5-triphenyl tetrazolium chloride solution, kept in the dark at 30 °C for three hours in a B.O.D. chamber. Viability was determined based on the intensity and distribution of red staining, identifying viable dormant seeds (Brasil, 2009).

The emergence test was performed with four replications of 50 seeds per cultivar, sown in plastic boxes containing a soil:sand mixture (2:1), moistened with distilled water. Boxes were maintained in a growth room at 20 °C under a constant photoperiod. Initial stand (IS) was recorded on the fifth day after sowing, and the test was concluded when emergence stabilized for three consecutive days. The emergence speed index (ESI) was calculated using the same formula as the GSI, as described by Maguire (1962).

The cold test was conducted with four replications of 50 seeds per cultivar. Seeds were distributed evenly on Germitest paper, moistened with water equivalent to 2.5 times the substrate weight (Cicero & Vieira, 2020), rolled, placed in plastic bags, and incubated in a B.O.D chamber at 10 ºC for seven days. After this period, rolls were transferred to a germinator at 25 °C for five days, and the number of normal seedlings was recorded.

For oil content determination, seeds from each cultivar were crushed separately in a blender for two minutes and then dried in an oven at 100 °C for one hour. Samples were then transferred to 250 mL volumetric flasks, placed in a desiccator for 24 hours, weighed, and subjected to exhaustive extraction in a Soxhlet apparatus for eight hours using 200 mL of hexane as the solvent. The solvent was recovered using a rotary evaporator, and oil content was determined gravimetrically as the difference between flask weights before and after extraction (Zenebon et al., 2008).

All agronomic, physiological, and oil content evaluations are summarized in Figure 2.

Statistical analyses

Data normality was assessed using the Shapiro-Wilk test, homogeneity of variances by the Bartlett test, and independence of residuals using the Durbin-Watson test. Data were subjected to analysis of variance (ANOVA) using the F-test, and means compared using Fisher's LSD test with Bonferroni correction at a 5% probability level.

Agronomic performance, physiological quality, and oilseed content were further evaluated using principal component analysis (PCA), based on the eigenvectors and eigenvalues of the correlation matrix. All statistical analyses were performed using the "R" software version 4.4.2 (R Core Team, 2024), employing the functions aov(), anova(), shapiro.test(), bartlett.test(), durbinwatsonTest(), and LSD.test(). PCA was conducted using the prcomp() function, and a graphical representation was generated by fviz_pca_biplot().

Results e Discussion

Agronomic performance

The phenological cycles of the cultivars Alth B4, Diamond, Hyola 575, and Nuola 300 were 143, 140, 144, and 146 days, respectively. A phenological cycle ranging from 140 to 146 days provides an adaptive advantage, improving crop management efficiency and making canola a viable option in crop rotation or succession systems (Guimarães et al., 2020).

The initial population (IP) of the Diamond cultivar, which had the shortest phenological cycle, was significantly higher than that of Hyola 575, Alth B4, and Nuola 300 (Table 2). Differences in IP among cultivars may be influenced by genetic traits, environmental conditions, and interplant competition (Araújo et al., 2021).

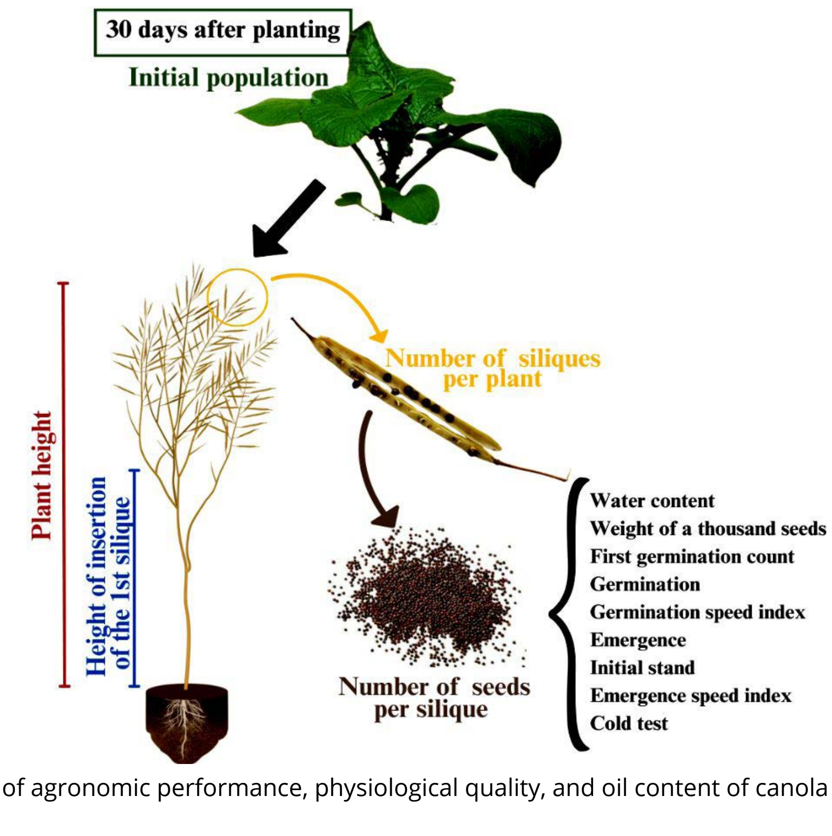

Figure 2: Assessments of agronomic performance, physiological quality, and oil content of canola cultivars.

Table 2: Initial population (IP; number of plants), plant height (PH; cm), height of insertion of the 1st silique (HIS; cm), number of siliques per plant (NSP), number of seeds per silique (NSS), and productivity (PROD; kg ha^{-1}) (means ± standard error) of four canola cultivars grown at high altitude with four replicates.

Cultivars	IP	PH	HIS	NSP	NSS	PROD
Nuola 300	242 ± 5.03d	149.50 ± 3.71ns	113.58 ± 2.27a	105 ± 11.91ns	15 ± 0.65 b	2.034 ± 5.72 a
Hyola 575	338 ± 4.68b	145.88 ± 4.04ns	87.50 ± 2.51b	88 ± 11.77ns	11 ± 0.77b	2.037 ± 3.27a
Alth B4	302 ± 3.11c	134.17 ± 6.66 ns	85.63 ± 3.11b	148 ± 13.54ns	22 ± 1.20a	1.277 ± 6.24c
Diamond	414 ± 2.65a	129.79 ± 9.76ns	75.73 ± 5.52b	118 ± 23.67ns	17 ± 2.44ab	1.467 ± 5.06b
F(p)	324.62(<1%)	2.06(>5%)	20.27(<1%)	2.52(p>5%)	9.72(<1%)	5656.24(<1%)
LSD	12.32	29.05	16.01	71.33	6.48	23.16
CV (%)	2.46	9.32	7.92	27.88	17.52	0.61

Means followed by the same letter in a column do not differ significantly according to the LSD-Fisher test with Bonferroni correction (df = 12, α = 0.05). Non-significant differences (ns) are reported at the 5% probability level based on the F test (α= 0.05). F(p) represents the F-statistic value (with p-value) for treatment and residual degrees of freedom (df = 3 and 12, respectively). LSD= least significant difference. CV (%) = coefficient of variation.

Plant height (PH) did not differ among cultivars, with an overall mean of 139.83 cm (Table 2), consistent with values reported by Nichelati et al. (2020). During harvest, noticeable defoliation was observed in the lower stem region of all cultivars. The absence of differences in PH among cultivars may be associated with this defoliation process in canola plants, which commonly occurs near physiological maturity and tends to affect cultivars in a similar manner (Santos et al., 2020).

The height of insertion of the first silique (HIS) was significantly greater in the Nuola 300 cultivar compared with the others (Table 2). The highest HIS observed in the Nuola 300 cultivar is agronomically desirable, as it facilitates mechanized harvesting and reduces losses caused by silique contact with the soil, thereby minimizing deterioration of the harvested product (Costa & Carlos, 2003).

The number of siliques per plant (NSP) did not differ significantly among cultivars (Table 2). Variations in NSP are primarily related to the survival of branches, shoots, flowers, and young siliques, which are influenced by environmental conditions during reproductive development (Diepenbrock, 2000). As canola is partially dependent on insect-mediated pollination, unfavorable climatic conditions or low pollinator activity may reduce silique formation and seed set (Durán et al., 2010).

The number of seeds per silique (NSS) was higher in the Alth B4 cultivar (Table 2). Variations in NSS among cultivars are influenced by the environment in which they are grown and the suitability of that environment for each cultivar, directly affecting yield (Escobar et al., 2011). Genes regulating silique development have previously been identified and are associated with intrinsic factors of the canola plant (Yang et al., 2023). The average NSS observed in this study is consistent with reported values ranging from 17 to 24 seeds per silique in different canola genotypes (Young et al., 2004; Durán et al., 2010).

Seed productivity (PROD) was highest for Nuola 300 (2,034 kg ha^{-1}) and Alth B4 (2,036 kg ha^{-1}) cultivars, followed by Diamond (1,467 kg ha^{-1}), with Hyola 575 presenting the lowest yield (1,277 kg ha^{-1}) (Table 2). The yields of Nuola 300 and Alth B4 cultivars exceeded the Brazilian national average of 1,534 kg ha^{-1} reported for 2023 (CONAB, 2025). Furthermore, the overall mean yield of the cultivars (1,703 kg ha^{-1}) was higher than that reported for canola grown at lower altitudes in southern Brazil (1,413 kg ha^{-1}) (Colet et al., 2020). Yield variability among cultivars is influenced by temperature, humidity, solar radiation, and nutrient availability (Mattioni et al., 2017).

These results highlight the genetic influence on agronomic traits and confirm the suitability of canola cultivation in high-altitude environments (>1,300 m), reinforcing its potential as an alternative oilseed crop in the savanna biome.

Physiological quality and oil content in seeds

The seed water content (WC) varied among canola cultivars, with the highest values observed in Diamond (11.00%) and Hyola 575 (10.64%) (Table 3). Despite the variation, WC remained within the acceptable tolerance range for standardization of physiological tests, which allows a maximum variation of 2% among samples (Marcos-Filho et al., 2015).

The thousand-seed weight (TSW) differed among cultivars, with a higher value (3.99 g) observed for Nuola 300 and Alth B4, and a lower value (3.81 g) for Hyola 575 and Diamond (Table 3). Based on TSW, all cultivars evaluated in this study can be classified as producing small seeds, as their TSW values are below the 200 g threshold (Brasil, 2009).

Germination percentages of Diamond, Nuola 300, and Alth B4 seeds met the minimum requirement of 80% for the production and commercialization of canola seeds established by MAPA Normative Instruction Nº 45 (Brasil, 2013). The first germination count (FC), germination speed index (GSI), and cold test (CT) were higher for Nuola 300, Alth B4, and Diamond than for Hyola 575 (Table 3). GSI values, in particular, were highest for Nuola 300 and Diamond, intermediate for Alth B4, and lowest for Hyola 575, indicating faster and more uniform seedling establishment for the former cultivars, a desirable trait for field performance (Singh et al., 2021). Similarly, final germination (G) was highest in the Diamond cultivar, followed by Nuola 300 and Alth B4, whereas Hyola 575 showed the lowest percentage (Table 3).

Seed emergence (E) and initial stand (IS) were highest for Alth B4 compared with the other cultivars (Table 3). The higher mean values of E and IS observed for Alth B4 may be associated with greater seed vigor, which promotes more uniform and robust seedling establishment (Nascimento et al., 2019).

The overall lower physiological performance observed in Hyola 575 may be associated with secondary dormancy, as detected by the tetrazolium test in viable but non-germinated seeds from the germination test, as previously reported in seeds of *Brassica napus*. Seed dormancy in *Brassica napus* is genetically regulated and influenced by environmental factors induced during seed maturation (Fei et al., 2007; Brown et al., 2022; 2024). This phenomenon is largely related to increased abscisic acid (ABA) accumulation and reduced gibberellin (GA) activity, which inhibits germination (Cotado, Garcia, & Munne-Bosch, 2020).

Oil content (OC) of the seeds ranged from 42.57% to 46.36%, with the highest values observed for the Alth B4 and Diamond cultivars, intermediate values for Nuola 300, and the lowest for Hyola 575 (Table 3). These values exceed those reported by Santiago et al. (2022) for canola cultivated in Lavras, Minas Gerais, Brazil (28.80%), and fall within the typical range of 40-47% reported for canola seeds (Raboanatahiry et al., 2021). Lower oil contents have been reported for cultivars grown in Chile under lower plant population densities (Vujaković et al., 2015).

Principal component analysis

The first two principal components (PC1 and PC2) explained 64.94% of the total variability in the dataset (Figure 3). The discriminatory power of each variable for the principal components was assessed based on its correlation with the respective component (Hongyu et al., 2016). Accordingly, the greater the distance of a variable vector from a given sample, the lower the performance of that sample with respect to the corresponding variable (Araújo et al., 2021).

In PC1, the vectors of physiological quality (GSI, CT, OC, G, FC, E, TSW, IS) and agronomic performance (NSP, NSS, PROD, HIS) formed angles in the two positive quadrants for Diamond, Nuola 300, and Alth B4, indicating strong relevance and correlation with these cultivars. In PC2, the loadings of the physiological quality (WC, ESI) and agronomic traits (PH, IP) were large in magnitude, although PC2 explained a lower proportion of the total variance (20.95%).

The PCA results demonstrate clear differentiation in agronomic performance and physiological quality among the four canola cultivars grown at high altitude. The Diamond hybrid was notably associated with high GSI (20.08) and other physical quality attributes. Alth B4 stood out for PROD (1.2776 kg/ha), TSW, and E (98%), while Nuola 300 was closely related to E (93%) and IS. In contrast, Hyola 575 exhibited a distinct profile compared to the other cultivars, particularly in terms of oil content and seed physiological performance.

Table 3: Water content (WC; %), thousand-seed weight (TSW; g), first germination count (FC; %), germination (G; %), germination speed index (GSI), emergence (E; %), initial stand (IS; %), emergence speed index (ESI), cold test (CT; %), and oil content (OC; %) (means ± standard error) of four canola cultivars grown at high altitude, with four replicates.

Variables	Cultivars						CV (%)
	Nuola 300	Hyola 575	Alth B4	Diamond	F(p)	LSD	
WC	$8.95^{0.60}$b	$10.64^{0.44}$a	$7.43^{0.39}$c	$11.00^{0.28}$a	13.89(<1%)	1.36	9.31
TSW	$3.99^{0.05}$a	$3.81^{0.04}$b	$3.99^{0.02}$a	$3.81^{0.02}$b	8.91(<1%)	0.16	1.80
FC	$82.00^{8.91}$a	$51.00^{8.66}$b	$87.00^{4.57}$a	$93.00^{2.63}$a	7.72(<1%)	30.08	17.33
G	$92.00^{4.08}$a	$65.00^{5.85}$b	$89.00^{3.11}$a	$98.00^{1.15}$a	13.80(<1%)	17.54	9.15
GSI	$18.14^{2.59}$a	$9.15^{1.16}$b	$15.30^{1.11}$a	$20.08^{0.90}$a	9.02(<1%)	7.08	20.26
E	$93.00^{3.11}$a	$79.00^{2.59}$b	$98.00^{1.89}$a	$91.00^{1.73}$a	11.19(<1%)	10.69	5.31
IS	$88.00^{1.83}$ab	$64.00^{2.50}$c	$94.00^{2.31}$a	$82.00^{2.63}$b	31.89(<1%)	10.42	5.72
ESI	$10.83^{0.25}$a	$9.29^{0.31}$b	$10.46^{0.28}$ab	$10.99^{0.40}$a	6.08(<1%)	1.39	6.01
CT	$100.00^{0.50}$a	$96.00^{0.82}$b	$97.00^{0.96}$ab	$99.00^{0.58}$ab	5.69(<5%)	3.28	1.51
OC	$44.16^{0.57}$bc	$42.57^{0.43}$c	$45.51^{0.52}$ab	$46.36^{0.16}$a	13.52(<1%)	2.01	2.02

Means followed by the same letter in a column do not differ significantly according to the LSD-Fisher test with Bonferroni correction (df = 12, α = 0.05). Non-significant differences (ns) are reported at the 5% probability level based on the F test (α= 0.05). F(p) represents the F-statistic value (with p-value) for treatment and residual degrees of freedom (df = 3 and 12, respectively). LSD = least significant difference. CV (%) = coefficient of variation.

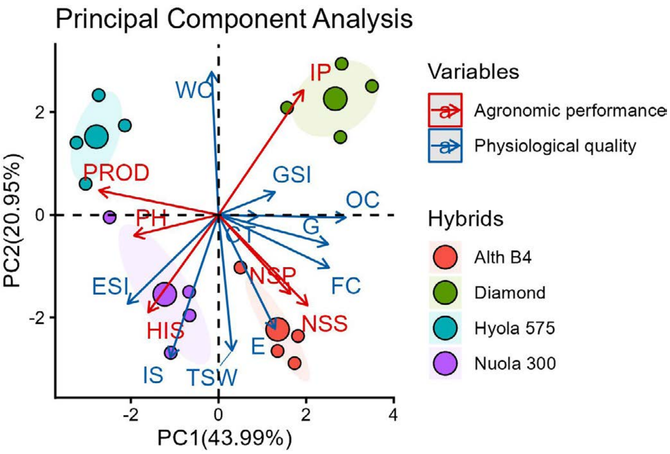

Figure 3: Principal component analysis (PCA) biplot illustrating agronomic performance and seed physiological quality variables of four canola cultivars grown at high altitude with four replications. Agronomic variables include initial population (IP), plant height (PH), height of insertion of the first silique (HIS), number of siliques per plant (NSP), number of seeds per silique (NSS), and productivity (PROD). Physiological and seed quality variables include water content (WC), thousand-seed weight (TSW), first germination count (FC), germination (G), germination speed index (GSI), emergence (E), initial stand (IS), emergence speed index (ESI), cold test (CT), and oil content (OC). The cultivars evaluated were Nuola 300, Hyola 575, Alth B4, and Diamond.

Conclusions

The canola cultivars Alth B4, Diamond, Hyola 575, and Nuola 300 demonstrated satisfactory agronomic performance under high-altitude savanna conditions (>1,300 m), with productivity and oil content comparable to or exceeding national averages. Among the cultivars, Nuola 300, Alth B4, and Diamond showed superior physiological seed quality and agronomic performance, indicating their suitability and potential for commercial cultivation in high-altitude environments. In contrast, Hyola 575 exhibited lower physiological quality, likely due to seed dormancy, which makes it less suitable under the conditions evaluated.

Author contributions

Conceptual idea: Melo, S. G. F.; Nery, M. C.; Methodology design: Melo, S. G. F.; Silva, I. J.; Barbosa, A. E.; Nery, M. C.; Laviola, B. G.; Data collection: Melo, S. G. F.; Silva, I. J. Data analysis and interpretation: Melo, S. G. F.; Santana, R. A; Guimarães, M. A.; Zanuncio, J. C.; Nery, M. C.; Writing: Melo, S. G. F.; Nery M. C.; Guimarães, M. A.; Zanuncio, J. C.

Acknowledgements

The authors thank the research funding agencies Coordenação de Aperfeiçoamento de Pessoal de Nível Superior— Brazil (CAPES) for funding the scholarship. The Fundação de Amparo à Pesquisa do Estado de Minas Gerais—FAPEMIG, the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the Postgraduate Program in Plant Production at UFVJM.

Data availability statement

Data available upon request to authors.

References

Araújo, L. N et al. (2021). Tropicalização da canola: Híbridos comerciais mostram potencial para cultivo no Cerrado brasileiro. *Revista da Faculdade de Ciências Agrárias*, *53*(2):20-26.

Assis, R. M. et al. (2020). Canola agronomic performance in three sowing dates in Jataí-GO. *Bioscience Journal*, *36*:e36105.

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. (2013). *Instrução Normativa nº 45, de 17 de setembro de 2013*. Brasília, DF: MAPA. https://wikisda.agricultura.gov.br/pt-r/Laboratórios/Metodologia/Sementes/RAS_2024

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. (2021). *Portaria SPA/MAPA Nº 490, de 9 de novembro de 2021*. Brasília, DF: MAPA.

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. (2009). *Regras para análise de sementes*. Departamento Nacional de Produção Vegetal: Brasília, DF, Brasil, 399p.

Brown, C. H. et al. (2022). A review of the genetic, physiological, and agronomic factors influencing secondary dormancy levels and seed vigour in *Brassica napus* L. *Canadian Journal of Plant Science*, *103*(2):149-160.

Brown, C. H. et al. (2024). The evaluation of secondary seed dormancy potentials of spring *Brassica napus* L. genotypes and the relationship with seed germination, vigor, and seed quality traits. *Crop Science*, *64*(3):1542-1558.

Cicero, S. M., & Vieira, R. D. (2020). Testes de frio. In F. C. Krzyzanowski et al. (Eds.). *Vigor de sementes: Conceitos e testes*. Londrina: Abrates. (pp.277-307).

Colet, F. et al. (2020). Agronomic performance of canola hybrids cultivated in a low altitude region in Southern Brazil. *Scientia Agraria Paranaensis*, *19*(2):117-123.

Companhia Nacional de Abastecimento - CONAB. (2025). *Acompanhamento da safra brasileira, 2025/2026, 3º levantamento*. Available in: https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/safra-de-graos/boletim-da-safra-de-graos/3o-levantamento-safra-2025-26/3o-levantamento-safra-2025-26

Costa, J. G. C. D., & Rava, C. A. (2003). Linhagens de feijoeiro comum com fenótipos agronômicos favoráveis e resistência ao crestamento bacteriano comum e antracnose. *Ciência e Agrotecnologia*, *27*(5):1176-1182.

Cotado, A., Garcia, M. B., & Munne-Bosch, S. (2020). Physiological seed dormancy increases at high altitude in Pyrenean saxifrage (*Saxifraga longifolia Lapeyr*.). *Environmental and Experimental Botany*, *171*:103929.

Diepenbrock, W. (2000). Yield analysis of winter oilseed rape (*Brassica napus* L.): A review. *Field Crops Research*, *67*(1):35-49.

Durán, A. X. et al. (2010). Evaluation of yield component traits of honeybee-pollinated (Apis mellifera L.) rapeseed canola (*Brassica napus* L.). *Chilean Journal of Agricultural Research*, *70*(2):309-314.

Escobar, M. et al. (2011). Genotype × environment interaction in canola (*Brassica napus* L.) seed yield in Chile. *Chilean Journal of Agricultural Research*, *71*(2):175-186.

Fei, H. et al. (2007). Expressão gênica durante a maturação de sementes em Brassica napus em relação à indução de dormência secundária. *Genomics*, *89*(3):419-428.

Guimarães, C. G. et al. (2022). *Canola: Panorama atual e tecnologias de produção no Brasil*. (Documentos 40), Brasília, DF: Embrapa Agroenergia, 69p.

Hongyu, K., Sandanielo, V. L. M., & Oliveira Junior, G. J. (2016). Análise de componentes principais: Resumo teórico, aplicação e interpretação. *E&S - Engineering and Science*, *5*(1):83-90.

Hussain, Z. et al. (2019). Electrospun microbial-encapsulated composite-based plasticized seed coat for rhizosphere stabilization and sustainable production of canola (*Brassica napus* L.). *Journal of Agricultural and Food Chemistry*, *67*(18):5085-5095.

International Rules for Seed Testing - ISTA. (2019). *International rules for seed testing*. Available in: <https://www.seedtest.org/en/publications/international-rules-seed-testing.html>.

Lamichaney, A., & Maity, A. (2021). Implications of rising atmospheric carbon dioxide concentration on seed quality. *International Journal of Biometeorology*, *65*(6):805-812.

Marcos-Filho, J. et al. (2015). *Fisiologia de sementes de plantas cultivadas*. Londrina: Abrates, 660p.

Mattioni, T. C. et al. (2017). Root growth and productivity of conventional and herbicide-tolerant canola in contrasting environments. *Australian Journal of Crop Science*, *11*(11):1462-1468.

Maguire, J. D. (1962). Speed of germination-Aid in selection and evaluation for seedling emergence and vigor. *Crop Science*, *2*(2):176-177.

Nascimento, M. D. G. R. et al. (2019). Vigor tests in seeds creole of *Phaseolus lunatus* L. *Bioscience Journal*, *35*(5):1463-1469.

Nichelati, F. D. et al. (2020). Interferência de plantas daninhas na cultura da canola (*Brassica napus* L.). *Revista Ciência Agrícola*, *18*(1):39-47.

Oliveira, J. D. et al. (2017). Productive performance of blackberry cultivars in altitude region. *Ciência Rural*, *47*(12):e20170021.

R Core Team. (2024). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. Available in: <https://www.r-project.org/>.

Raboanatahir, N. et al. (2021). Colza (Brassica napus): Processamento, utilização e melhoramento genético. *Agronomy*, *11*(9):1776.

Santiago, A. C. et al. (2022). Path analysis and near-infrared spectroscopy in canola crop. *Ciência Rural*, *53*(6):e20220071.

Santos, C. J. O. G. et al. (2020). Efeito da desfolha na altura de plantas e produtividade de grãos de canola (*Brassica napus* L.). *Ciência Agrícola*, *18*(1):11-19.

Singh, J. et al. (2021). Germination and early growth response of guar cultivars to low temperatures. *Industrial Crops and Products*, *159*:113082.

Strahl, M. A. et al. (2021). Qualidade fisiológica de sementes de canola (*Brassica napus* L.) submetidas a microbiolização com *Trichoderma* spp. *Científica*, *49*(2):75-79.

Tomm, G. O. et al. (2010). *Panorama atual e indicações para aumento de eficiência da produção de canola no Brasil*. Passo Fundo: Embrapa, 82p (Documento, 95).

Vujaković, M. et al. (2015). Dependence of rapeseed quality and yield on density, variety and year of production. *Ratarstvo i povrtarstvo/ Field and Vegetable Crops Research*, *52*(2):61-66.

Zeferino, M. et al. (2023). Mercado mundial de óleos vegetais: Panorama e perspectivas. *Análises e Indicadores do Agronegócio*, *18*(9):51-58.

Zenebon, O. et al. (2008). Procedimentos e determinações gerais. In Instituto Adolfo Lutz. *Métodos físico-químicos para análise de alimentos*. São Paulo: Instituto Adolfo Lutz, (pp.114-115).

Yang, M. et al. (2023). Fine mapping of a pleiotropic locus (*BnUD1*) responsible for the up-curling leaves and downward-pointing siliques in *Brassica napus*. *International Journal of Molecular Sciences*, *24*(4):3069.

Young, L. W. et al. (2004). High temperature stress of *Brassica napus* during flowering reduces micro- and megagametophyte fertility, induces fruit abortion, and disrupts seed production. *Journal of Experimental Botany*, *55*(396):485-495.