ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.29, n.11, e292539, 2025
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v29n11e292539
Original Article

Kaolin waste as a water stress attenuator in cowpea cultivation[1]

Rejeito de caulim como atenuador do estresse hídrico no cultivo de feijão-caupi

Anna R. S. Nóbrega[2], José Dantas Neto[2], Maria S. de F. Araújo[2], André A. R. da Silva[3*], Mayra G. M. Lima[2], Luciano M. F. Saboya[2], Viviane F. Silva[4] & Pedro I. S. da Nóbrega[5]

[1] Research developed at Universidade Federal de Campina Grande, Campina Grande, PB, Brazil
[2] Universidade Federal de Campina Grande/Unidade Acadêmica de Engenharia Agrícola, Campina Grande, PB, Brazil
[3] Universidade Federal do Oeste do Pará/Unidade Acadêmica de Agronomia, Juruti, PA, Brazil
[4] Universidade Federal de Campina Grande/Unidade Acadêmica de Engenharia Florestal, Patos, PB, Brazil
[5] Universidade Federal do Rio Grande do Sul/Escola de Administração, Porto Alegre, RS, Brazil

HIGHLIGHTS:

The beneficial effects of kaolin depend on the dose applied.
Foliar application of kaolin waste attenuates the adverse effects of water deficit on photosynthetic pigments.
Kaolin waste reduces electrolyte leakage in cowpea plants under water deficit.

ABSTRACT: Water scarcity in semi-arid regions stands out as the main environmental factor limiting cowpea (*Vigna unguiculata* (L.) Walp) yield. Therefore, foliar application of kaolin waste emerges as a strategy to mitigate water stress, ensuring the growth and production of agricultural crops. Therefore, this study aims to evaluate the effect of kaolin waste applied via foliar application as a water stress attenuator on the cowpea cultivar 'BRS Tapaihum'. The experiment was conducted in a greenhouse at the Federal University of Campina Grande (UFCG). Treatments consisted of four irrigation depths (50, 75, 100, and 125% of real evapotranspiration - ETr), without and with kaolin waste (50 g L^{-1}), applied via foliar application, distributed in a completely randomized design, in a 4 × 2 factorial arrangement, with eight repetitions. Foliar spraying of kaolin waste associated with a level of 75% ETr promoted the highest value of plant height and, when associated with a level of 50% ETr, promoted the highest values of chlorophyll contents (a, b and total) and relative water content. Kaolin waste, when associated with the irrigation depth required by the crop (100% ETr), despite promoting the highest values of pod length and number of grains per pod, did not result in the highest total production per plant, obtained in the treatment with 100% ETr depth without foliar application of kaolin waste.

Key words: *Vigna unguiculata* (L.) Walp, vegetative development, water deficit, irrigation management, mineral waste

RESUMO: A escassez de água em regiões semiáridas se destaca como o principal fator ambiental limitante da produtividade do feijão-caupi (*Vigna unguiculata* (L.) Walp). Diante disso, a aplicação foliar de rejeito de caulim surge como estratégia mitigadora do estresse hídrico, garantindo o crescimento e a produção de culturas agrícolas. Sendo assim, essa pesquisa tem como objetivo avaliar o efeito do resíduo de caulim aplicado via foliar como atenuador do estresse hídrico da cultivar de feijão-caupi BRS Tapaihum. O experimento foi conduzido em casa de vegetação na Universidade Federal de Campina Grande (UFCG). Os tratamentos consistiram de quatro lâminas de irrigação (50, 75, 100 e 125% da evapotranspiração real - ETr) sem e com rejeito de caulim (50 g L^{-1}), aplicado via foliar, distribuídos em delineamento inteiramente casualizado, em arranjo fatorial 4 × 2, com oito repetições. A pulverização foliar de rejeito de caulim associado a lâmina de 75% da ETr, proporcionou o maior valor na altura das plantas de feijão-caupi e, quando associado à lâmina de 50% da ETr, promoveu os maiores valores dos teores de clorofila (a, b e total) e o teor relativo de água. O rejeito de caulim, quando associado à lâmina de irrigação requerida pela cultura (100% da ETr), apesar de proporcionar os maiores valores nas variáveis de comprimento de vagem e número de grãos por vagem, não resultou na maior produção total por planta, obtida no tratamento com a lâmina de 100% da ETr sem a aplicação foliar de rejeito de caulim.

Palavras-chave: *Vigna unguiculata* (L.) Walp, desenvolvimento vegetativo, déficit hídrico, manejo de irrigação, resíduo mineral

• Ref. 292539 – Received 08 Oct, 2024
* Corresponding author - E-mail: andrealisson_cgpb@hotmail.com
• Accepted 04 Jun, 2025 • Published 16 Jun, 2025
Editors: Antônio Gustavo de Luna Souto & Hans Raj Gheyi

Introduction

Cowpea (*Vigna unguiculata* (L.) Walp), also known as black-eyed pea or southern pea, among other popular names, is a legume of African origin, characterized by the high nutritional value of its grains, and is commonly produced by family farming (Ferreira et al., 2021; Soares et al., 2021). Brazil is among the main producers of this type of bean, with a production of 705.1 thousand tons and yield of 554 kg ha^{-1}. The Northeast is the largest producing region, reaching a total 496.9 thousand tons in the 2023/24 harvest, while the state of Paraíba has the seventh largest production of cowpea in the national scenario (Nascimento et al., 2022; CONAB, 2024; Souza et al., 2024).

In the Northeast, cowpea is a protein source of great social and economic importance, mainly because of its good adaptation to the climatic conditions of the semiarid region and with grain production in rainfed and irrigated crops, allowing agricultural production throughout the year (Ribeiro et al., 2022). However, intense water limitation is characterized as one of the main limiting factors for cowpea production, since water deficit causes significant reductions in the physiology, growth, and production of cowpea (Soares et al., 2021; Souza et al., 2024).

Thus, the study of the sensitivity of plants to different water conditions and the search for alternatives that minimize the effects of water stress are fundamental for the rational and effective use of water resources (Barbosa et al., 2020; Barros et al., 2021). In this context, foliar application of kaolin waste emerges as a promising strategy to mitigate the negative effects of water stress and promote the growth and development of agricultural crops (Roda et al., 2023).

Kaolin waste is the residue generated in kaolin extraction and processing, which is usually released indiscriminately into the environment, triggering negative environmental impacts on the soil, air, water resources, flora, and fauna (Melo et al., 2020; Alves et al., 2021). Thus, the use of this waste in other areas, such as agricultural production, contributes to better waste management within mining companies, providing an adequate destination for this waste and avoiding the generation of environmental impacts, complying with the Sustainable Development Goals (Almeida et al., 2023; ONU, 2024).

In the agricultural context, kaolin waste has been shown to be effective in controlling agricultural pests (Herrera-Feijoo & Vélez, 2023), in addition to being used as a constituent of substrates in the production of seedlings of plant species, promoting improvements in the growth and quality of seedlings (Oliveira et al., 2014; Melo et al., 2020; Alves et al., 2021). In addition, this waste has been studied as an anti-transpiration agent capable of increasing water use efficiency, showing that foliar application of kaolin waste can mitigate the negative effects of water stress in the cultivation of potatoes (*Solanum tuberosum* L.) (Mahmoud et al., 2020), olive (*Olea europaea* L.) (Brito et al., 2021), Persian walnuts (*Juglans regia* L.) (Mahmoudian et al., 2021), almonds (*Prunus dulcis*) (Gharaghani et al., 2023), and grapes (*Vitis vinifera* L.) (Cao et al., 2023).

However, to the best of our knowledge, there is still no research that addresses the use of this residue as a water stress attenuator in cowpea crop. Therefore, the objective of this study was to evaluate the effect of kaolin waste applied via foliar application as a water stress attenuator on the growth, physiology, and production traits of the cowpea cultivar 'BRS Tapaihum'.

Material and Methods

The experiment was carried out from October 2023 to January 2024, in a protected environment (greenhouse), belonging to the Academic Unit of Agricultural Engineering (UAEA) of the Federal University of Campina Grande (UFCG), Campus I, located in the municipality of Campina Grande, Paraíba, Brazil. The municipality is located at 07° 15' 18" South latitude, 35° 52' 28" West longitude and average altitude of 550 m above sea level, with a predominance of the mesothermal, semi-humid climate, classified according to Köppen as CSa type, characterized by hot and semi-arid conditions with rainy (February to July) and dry (August to January) seasons (Coelho & Soncin, 1982).

The greenhouse used was arched, 30 m long and 21 m wide, with a ceiling height of 3.0 m, covered with a low-density polyethylene. Meteorological data regarding the maximum and minimum air temperature and average relative air humidity inside the greenhouse during the experimental period are presented in Figure 1.

Treatments consisted of four irrigation depths - D (50, 75, 100, and 125% of real evapotranspiration - ETr), with and without the application of kaolin waste - K (50 g L^{-1}), distributed in a completely randomized design, in a 4 × 2 factorial arrangement, with eight replicates and one plant per plot, making a total of 64 experimental units. The concentrations of kaolin waste were applied by foliar spraying.

The irrigation depths were adapted from the study conducted by Carvalho et al. (2023), who evaluated the production of cowpea under different levels of irrigation. The kaolin concentration (50 g L^{-1}) was adapted from the study carried out by Bestete et al. (2018).

The experiment was conducted using 20-L polyethylene pots adapted as drainage lysimeters, with a spacing of 1 m between rows and 0.6 m between plants. The base of the pot was filled with a 3-cm-thick layer of crushed stone (no. zero) and a geotextile to prevent the drainage system from being clogged by soil material. A drain was installed in each pot, which consisted of a transparent tube of 10 mm in diameter, attached to the base of the container in order to facilitate the drainage process. A 2-L plastic container was connected to the drain to collect drained water and estimate water consumption by the plant.

Each pot received 24 kg of soil material, appropriately pounded to break up clods. Soil has a sandy loam texture and was collected at 0-30 cm depth in the municipality of Lagoa Seca, Paraíba state. The soil was analyzed in the Irrigation and Salinity Laboratory (LIS) of the Federal University of Campina Grande (UFCG), at the Campus of Campina Grande, Paraíba

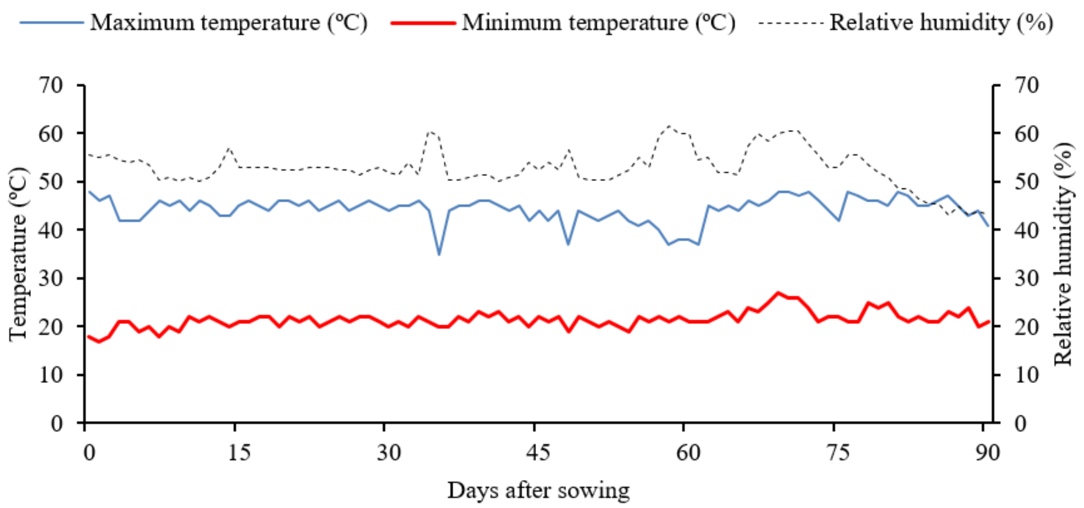


Figure 1. Maximum and minimum air temperature and mean relative air humidity observed inside the greenhouse during the experimental period (October 25, 2023 to January 23, 2024)

state, to determine the physical-hydraulic and chemical characteristics (Table 1), using the methodology proposed by Texeira et al. (2017). Based on the analysis, it can be seen that it was not necessary to carry out soil correction.

Cowpea seeds (*Vigna unguiculata* (L.) Walp) of the cultivar 'BRS Tapaihum', which has black and reniform grains, with an erect posture and semi-determinate growth habit, with a cycle of approximately 65 to 70 days, and is commonly cultivated in the Northeast region, were used in the study (Santos, 2011). The seeds used in the experiment were provided by Embrapa Meio Norte.

After raising soil moisture to the maximum retention level in the experimental units, sowing was carried out with five seeds per pot at 3 cm depth, distributed equidistantly. Five days after sowing (DAS), thinning was carried out, keeping only one plant per pot.

From 15 DAS, split fertilization with nitrogen, phosphorus and potassium (N-P-K) was carried through fertigation, according to the recommendation of Novais et al. (1991), adopting, respectively, the amounts of 100, 300, and 150 mg kg^{-1} of soil, in three fortnightly applications. Ammonium sulfate (21% N and 24% S), MAP (60% P_2O_5 and 12% N), and potassium chloride (60% K_2O) were used as sources of nitrogen, phosphorus, and potassium, respectively. To supply micronutrients, three applications were carried out, at fortnightly intervals of the compound Dripsol micro® (Mg^{2+} = 1.1%; B = 0.85%; Cu (Cu-EDTA) = 0.5%; Fe (Fe-EDTA) = 3.4%; Mn (Mn-EDTA) = 3.2%; Mo = 0.05%; Zn = 4.2%; 70% of EDTA chelating agent) at a concentration of 1 g L^{-1}, of foliar fertilization, sprayed on the adaxial and abaxial sides using a manual sprayer with capacity of 2 L.

Irrigations were carried out daily at 5 p.m., using water from the local urban supply (EC = 0.4 dS m^{-1}; pH: 7.3), manually with the aid of a watering can, applying the estimated volume of water according to the treatments to each pot. The volume applied in 100% ETr treatment in each irrigation event was estimated by means of water balance, according to Eq. 1.

$$\mathrm{WC} = \frac{(\mathrm{Vw} - \mathrm{Vd})}{(1 - \mathrm{LF})} \qquad (1)$$

where:

WC - water consumption (L);

Vw - volume of water applied to the plants on the previous day (L);

Vd - volume of water drained, quantified the next morning (L); and,

LF - leaching fraction of 10% applied every 15 days.

The volume of water applied in other management strategies was determined based on the consumption by plants under 100% ETr (real evapotranspiration), using the drainage lysimetry method (Bernardo et al., 2019). Therefore, for the irrigation of each treatment (50, 75, 100, and 125% ETr), the ETr value obtained was multiplied by the percentage of evapotranspiration of the treatment in question.

During the experiment, the volumes of water applied and drained were used to determine the water consumption of cowpea plants, as observed in Table 2.

Table 1. Physical-hydraulic and chemical characteristics of the soil used in the experiment

Physical-hydraulic characteristics							
Particle-size fraction (dag kg^{-1})			Textural class	Natural moisture (% dry soil basis)	Available water	Porosity (%)	Bulk density (kg dm^{-3})
Sand	Silt	Clay					
60.66	28.17	11.17	SL	0.61	9.78	56.60	1.15

Chemical characteristics											
pH_{se}	OM (%)	P (mg 100g^{-1})	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	SB	CEC	V%
			(cmol$_c$ kg^{-1})								
7.63	0.84	0.01	0.60	0.10	6.91	3.65	0.00	0.00	11.26	11.26	100

SL - Sandy loam; pH_{se} - pH of the saturation extract; OM - Organic matter; P - Assimilable phosphorus; K^+ - Potassium; Na^+ - Sodium; Ca^{2+} - Calcium; Mg^{2+} - Magnesium; Al^{3+} - Aluminum; H^+ - Hydrogen; SB - Sum of bases; CEC - Cation exchange capacity; V% - Percent base saturation

Table 2. Average water consumption of cowpea plants during the experiment for the different treatments of irrigation

Irrigation depth (% ETr)	Water consumption	
	L per plant	mm per plant*
D1 (50%)	19.30	272.97
D2 (75%)	28.94	409.46
D3 (100%)	38.59	545.94
D4 (125%)	48.24	682.43

*Depth calculated considering the area of the pot used in the experiment (0.0707 m^2)

The kaolin waste used in the experiment was obtained from a private mining company located in the municipality of Equador, RN, and sent for analysis by X-ray Fluorescence (XRF) Spectroscopy in the form of loose powder to the Reference Center in Mineral Technology of the Federal Institute of Rio Grande do Norte (IFRN), municipality of Currais Novos, Rio Grande do Norte state. It is a fine waste material resulting from the crushing operation of basaltic rocks. Table 3 shows the chemical composition of the kaolin waste used in the experiment.

The kaolin concentration (50 g L^{-1}) was obtained by the dissolution of the waste, weighed on an analytical scale of 0.0001 g, in 1 L of urban-supply water. A 2-L manual sprayer was used for applications on the adaxial and abaxial sides of the leaves (Figure 2). Foliar applications of kaolin doses were carried out at 15, 30, and 45 days after sowing, fortnightly throughout the crop cycle. During the experiment, three foliar applications of 50 g L^{-1} of kaolin waste were carried out.

Emergence of pests and diseases was monitored, and phytosanitary control measures recommended for the crop were adopted whenever necessary. The emergence of whitefly (*Bemisia tabaci*) and leafminer (*Liriomyza* sp.) was observed during the vegetative phase, and Actara (active ingredient: thiamethoxam) was used for chemical control. Regular

Table 3. Chemical composition of kaolin waste used in the experiment

Oxides	%	Elements	%
SiO_2	51.780	Si	24.210
Al_2O_3	40.950	Al	21.670
P_2O_5	3.150	P_x	1.380
K_2O	2.050	K	1.700
Fe_2O_3	1.260	Fe	0.880
CaO	0.168	Ca	0.120
Nb_2O_5	0.134	Nb	0.094
Cl	0.125	Cl	0.125
TiO_2	0.063	Ti	0.038
SO_3	0.057	S_x	0.023
Rb_2O	0.047	Rb	0.043
BaO	0.040	Ba	0.036
Bi_2O_3	0.033	Bi	0.030
MnO	0.027	Mn	0.021
Ta_2O_5	0.027	Ta	0.022
ZrO_2	0.025	Zr	0.019
SrO	0.016	Sr	0.014
ZnO	0.015	Zn	0.012
Co_3O_4	0.012	Co	0.009
PbO	0.009	Pb	0.008
Ga_2O_3	0.008	Ga	0.006

SiO_2 - Silicon dioxide; Al_2O_3 - Aluminum oxide; P_2O_5 - Diphosphorus pentoxide; K_2O - Potassium oxide; Fe_2O_3 - Iron III oxide; CaO - Calcium oxide; Nb_2O_5 - Niobium pentoxide; TiO_2 - Titanium dioxide; SO_3 - Sulfur trioxide; Rb_2O - Rubidium oxide); BaO - Barium oxide; Bi_2O_3 - Dibismuth trioxide; MnO - Manganese monoxide; Ta_2O_5 - Ditanthallium pentoxide; ZrO_2 - Zirconium dioxide; SrO - Strontium oxide; ZnO - Zinc oxide; Co_3O_4 - Cobalt III oxide; PbO - Lead monoxide; Ga_2O_3 - Digallium trioxide

A. B.

Figure 2. Appearance of primary leaves (A) and trifoliate leaves (B) with foliar application of kaolin waste

cultural practices, such as weekly manual weeding and surface scarification of the soil, in order to reduce competition between plants and promote crop development, were also carried out during the experimental period.

The effects caused by the different irrigation depths and by the foliar application of kaolin waste on irrigated cowpea crop were evaluated based on growth, physiological, and production variables.

Growth variables were evaluated at 45 DAS, considering plant height (PH), stem diameter (SD), number of leaves (NL), and leaf area (LA). Plant height was measured from the ground level to the apical bud of the main branch with a graduated ruler and was expressed in cm. Stem diameter was measured at 2 cm from the ground level, with readings taken in the plant collar region with a digital caliper (Matrix Tools for Existence®, resolution: 0.01 mm), being expressed in cm. Number of leaves was determined by manually counting the leaves longer than 3 cm. Leaf area was estimated by measuring the midrib length of each leaf, considering only the leaves with a minimum length of 3 cm, according to the methodology proposed by Grimes & Carter (1969), according to Eq. 2.

$$Y = \Sigma\left(0.4322X\right)^{2.3002} \quad (2)$$

where:

Y - leaf area per plant, cm^2; and,

X - leaf midrib length, cm.

At the end of the experiment (60 DAS), biomass production was evaluated in the different aerial parts of the plant (stem and leaves), which were separated and packed in properly identified paper bags, and dried in an air circulation oven maintained at 70 °C until reaching constant mass. Subsequently, the material was weighed on a precision semi-analytical scale to obtain leaf dry mass (LDM) and stem dry mass (STDM), whose sum resulted in shoot dry mass (SHDM).

At 45 DAS, the contents of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids were evaluated. These pigments were quantified according to the laboratory method developed by Arnon (1949), so that plant extracts were made from samples of leaf discs collected from the leaves of the middle third of the plant, from which the concentrations of chlorophyll and carotenoids were determined using a spectrophotometer at absorbance wavelengths (ABS) (470, 647, and 663 nm), using Eqs. 3, 4, 5 and 6:

$$\text{Chl a} = (12.25 \times \text{ABS663}) - (2.79 \times \text{ABS647}) \quad (3)$$

$$\text{Chl b} = (21.5 \times \text{ABS647}) - (5.10 \times \text{ABS647}) \quad (4)$$

$$\text{Chl t} = (7.15 \times \text{ABS663}) + (18.71 \times \text{ABS647}) \quad (5)$$

$$\text{Car} = \frac{(1000 \times \text{ABS470}) - (1.82 \times \text{Chl a}) - (85.02 \times \text{Chl b})}{198} \quad (6)$$

where:

Chl a - chlorophyll a content;
Chl b - chlorophyll b content;
Chl t - total chlorophyll content; and,
Car - carotenoid content.

The values obtained for chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents in the leaves were expressed in $\mu g \ mL^{-1}$.

At the same time (45 DAS), electrolyte leakage (% EL) and relative water content (RWC) were analyzed. Electrolyte leakage was determined using the methodology proposed by Scotti-Campos et al. (2013). Relative water content was determined by following the recommendations of Lima et al. (2015).

At the end of the crop cycle, harvesting began when the pods were dry, that is, when they showed cream color, typical for the harvest of dry grains. During this period, at 60 DAS, the following production variables were evaluated: number of pods per plant (NPP), obtained by counting the total number of pods per plant; mean pod length (MPL), determined by estimating the mean length, in cm, of five pods taken at random from each plot; mean number of grains per pod (NGP), obtained from the average count of the grains contained in the five pods taken at random for MPL measurement; total grain production (TP), determined based on the total grain production of each plant, expressed in g; and grain index (GI), determined from the relationship between pod dry mass and grain dry mass, with the sampling of five pods per plant (Oliveira et al., 2015; Souza et al., 2024).

The multivariate structure of the results was analyzed using principal component analysis (PCA), which synthesizes the amount of relevant information contained in the original dataset in a smaller number of dimensions, resulting from linear combinations of the original variables generated from eigenvalues (λ) greater than 1.0 in the correlation matrix, explaining more than 10% of the total variance, according to Govaerts et al. (2007).

From the reduction of the dimensions, the original data of the variables of each component were subjected to multivariate analysis of variance (MANOVA) by Hotelling's (1947) test at 0.05 probability level for the individual treatments (irrigation depths and foliar application of kaolin waste), as well as for the interaction between the factors. Only variables with a correlation coefficient greater than or equal to 0.65 (Hair et al., 2009) were maintained in each principal component (PC). These statistical analyses were performed using Statistica v.7.0 software (Statsoft, 2004).

The data relative to the variables leaf dry mass (LDM), carotenoid content (CAR), and grain index (GI) were removed from the multivariate analysis because they showed autocorrelation, not meeting the requirements for PCA. These data were subjected to the Shapiro-Wilk test and to the Bartlett test to check the normality of residuals and homogeneity of variances. Subsequently, analysis of variance (ANOVA) was performed at 0.05 probability level and, in case of significance, regression analysis was performed for the quantitative data and Tukey means comparison test ($p \leq 0.05$) was applied for qualitative data. In this case, statistical analysis was performed using R software (R Core Team, 2023) and the AgroR package (Shimizu et al., 2024).

Results and Discussion

The multidimensional space of the original variables was reduced to two principal components (PC1 and PC2) with eigenvalues greater than $\lambda \geq 1.0$, according to Kaiser (1960). The eigenvalues and the percentage of variation explained by each component together represented 83.6% of the total variation, with PC1 explaining 63.3% of the total variance, containing most of the variables analyzed, and PC2 representing 20.3% of the remaining variance (Table 4). The interaction between the irrigation depths used and kaolin application (D × K) significantly influenced the two principal components (PC1 and PC2).

Variables that showed correlation coefficients greater than 0.65 ($r \geq 0.65$) were considered relevant. Thus, the variables that had the greatest discriminatory power in PC1 (Table 5) were: plant height, stem diameter, number of leaves, leaf area, chlorophyll b, percentage of electrolyte leakage, stem dry mass, shoot dry mass, number of pods per plant, total production, mean pod length and mean number of grains per pod. In PC2,

Table 4. Eigenvalues, percentage of total variance explained, and multivariate analysis of variance (MANOVA) between the original variables and principal components

	Principal components	
	PC1	PC2
Eigenvalues	9.50	3.05
Percentage of total variance	63.3	20.3
Hotelling test for irrigation depths (D)	0.01	0.02
Hotelling test for kaolin (K)	0.01	0.01
Hotelling test for the interaction (D × K)	0.01	0.01

PC1 - Principal Component 1; PC2 - Principal Component 2

Table 5. Correlation coefficients (r) between the original variables and the principal components (PC1 and PC2)

Variables	Correlation coefficients (r)	
	PC1	PC2
PH	-0.77*	-0.33
SD	-0.94*	0.30
NL	-0.93*	0.09
LA	-0.98*	0.13
Chl a	0.21	0.94*
Chl b	0.86*	0.44
Chl t	0.48	0.83*
% EL	0.67*	-0.53
RWC	0.19	0.81*
STDM	-0.95*	0.16
SHDM	-0.93*	-0.03
NPP	-0.92*	0.21
TP	-0.93*	0.22
MPL	-0.84*	0.03
NGP	-0.70*	-0.01

PC1 - Principal Component 1; PC2 - Principal Component 2; PH - Plant height; SD - Stem diameter; NL - Number of leaves; LA - Leaf area; Chl a - Chlorophyll a; Chl b - Chlorophyll b; Chl t - Total chlorophyll; % EL - Electrolyte leakage; RWC - Relative water content; STDM - Stem dry mass; SHDM - Shoot dry mass; NPP - Number of pods per plant; TP - Total production; MPL - Mean pod length; NGP - Mean number of grains per pod; * - Correlation coefficient greater than 0.65

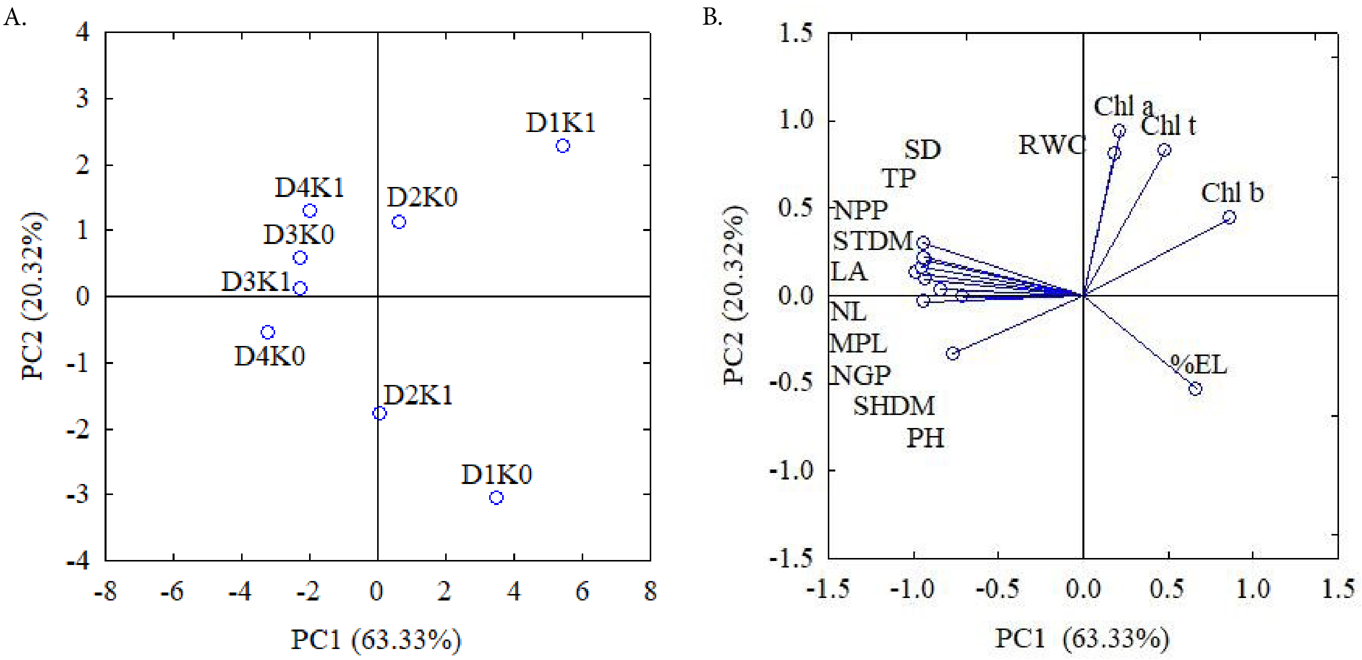
the variables chlorophyll a, total chlorophyll, and relative water content showed correlation coefficients higher than 0.65.

The two-dimensional projections of the effects of treatments and variables in the first and second principal components (PC1 and PC2) are presented in Figures 3A and B. A process possibly characterized by the effect of the interaction between the different irrigation depths and foliar application of kaolin waste is observed in PC1 and PC2.

The 125% ETr irrigation depth stood out in comparison to the others, leading to higher mean values for most variables (Table 6), both in plants under application of kaolin waste and in plants that did not receive foliar spraying of kaolin waste. This result reflects the fact that cowpea tends to have better development and, consequently, higher yields under greater water supply, despite being a legume crop considered tolerant to water deficit (Carvalho et al., 2023).

In principal component 1 (Table 6), it can be seen that plants irrigated with a 125% ETr depth and that did not receive foliar application of kaolin waste (D4K0) had the highest mean values of stem diameter (13.76 cm), number of leaves (60.38), leaf area (9863.03 cm²), shoot dry mass (41.73 g), and number of pods per plant (18.25). When comparing the results obtained in plants of the D4K0 treatment with those obtained in plants cultivated under the D4K1 treatment, increments of 2.53% (0.34 cm) in SD, 11.81% (6.38) in NL, 14.83% (1243.62 cm²) in LA, 13.21% (4.87 g) in SHDM, and 3.55% (0.63) in NPP were observed, showing that kaolin waste did not have a positive effect on these growth variables in cowpea plants when associated with high irrigation depths. On the other hand, the use of the irrigation depth of 125% ETr and foliar application of kaolin waste (D4K1) on cowpea plants promoted the highest mean value of stem dry mass (24.35 g).

In addition, in Table 6, it is observed that plants subjected to the treatment with water deficit (50% ETr) and with the application of kaolin waste (D1K1) had the lowest mean values of number of leaves (34.13), leaf area (4189.16 cm²), shoot dry mass (22.25 g), and number of pods per plant (10.50). In addition, the lowest mean value of stem diameter (10.52 mm) was observed in plants irrigated with a depth of 50% ETr and that did not receive foliar application of kaolin waste (D1K0). Also, in principal component 1, it is possible to observe (Table 6) that irrigation with a depth of 75% ETr and foliar application of kaolin waste (D2K1) resulted in the highest mean value of plant height (23.39 cm).



PC1 - Principal Component 1; PC2 - Principal Component 2; D1K0 - 50% ETr depth without kaolin application; D1K1 - 50% ETr depth with kaolin application; D2K0 - 75% ETr depth without kaolin application; D2K1 - 75% ETr depth with kaolin application; D3K0 - 100% ETr depth without kaolin application; D3K1 - 100% ETr depth with kaolin application; D4K0 - 125% ETr depth without kaolin application; D4K1 - 125% ETr depth with kaolin application; PH - Plant height; SD - Stem diameter; NL - Number of leaves; LA - Leaf area; Chl a - Chlorophyll a; Chl b - Chlorophyll b; Chl t - Total chlorophyll; % EL - Percentage of electrolyte leakage; RWC - Relative water content; STDM - Stem dry mass; SHDM - Shoot dry mass; NPP - Number of pods per plant; TP - Total production; MPL - Mean pod length; NGP - Mean number of grains per pod

Figure 3. Two-dimensional projection of the scores of the principal components for the factors irrigation depths and foliar application of kaolin waste (A) and of the analyzed variables (B) in the two principal components (PC1 and PC2)

Table 6. Mean values of the variables analyzed at 45 DAS according to the treatments applied

Variables	Mean values							
	D1K0	D1K1	D2K0	D2K1	D3K0	D3K1	D4K0	D4K1
PH	21.64 g	19.38 h	23.33 b	23.39 a	23.05 c	22.51 e	23.01 d	22.31 f
SD	10.52 h	11.14 g	12.66 e	12.47 f	13.35 c	13.11 d	13.76 a	13.42 b
NL	38.25 g	34.13 h	42.13 e	40.13 f	55.00 b	52.63 d	60.38 a	54.00 c
LA	4,586.6 g	4,189.2 h	6,839.1 e	6,505.7 f	8,707.9 b	8,419.6 d	9,863.0 a	8,619.4 c
Chl a	1,137.9 g	1,433.8 a	1,338.2 c	1,136.2 h	1,307.0 d	1,264.3 e	1,160.3 f	1,376.3 b
Chl b	579.81 c	675.87 a	584.85 b	512.89 g	548.16 d	515.64 f	465.68 h	546.60 e
Chl t	1,717.75 f	2,109.7 a	1,923.1 b	1,649.1 g	1,855.2 d	1,780.0 e	1,625.9 h	1,922.9 c
% EL	47.09 a	34.48 b	29.59 e	30.34 d	29.02 g	26.45 h	29.55 f	31.75 c
RWC	81.28 h	90.41 a	88.77 b	84.75 f	84.32 g	85.32 e	87.12 c	85.75 d
STDM	14.00 g	10.99 h	19.84 e	15.97 f	22.57 d	24.30 b	23.82 c	24.35 a
SHDM	29.73 f	22.25 h	32.64 e	28.54 g	39.42 b	38.28 c	41.73 a	36.86 d
NPP	11.13 f	10.50 g	14.25 d	12.88 e	17.63 b	15.00 c	18.25 a	17.63 b
TP	28.11 f	27.15 g	40.19 d	37.82 e	53.04 a	42.43 c	50.00 b	50.00 b
MPL	19.97 h	20.10 g	20.50 f	22.01 c	22.04 b	22.42 a	21.46 e	21.90 d
NGP	10.99 g	10.19 h	11.55 e	12.42 c	12.03 d	14.03 a	11.41 f	13.25 b

D1K0 - 50% ETr depth without kaolin application; D1K1 - 50% ETr depth with kaolin application; D2K0 - 75% ETr depth without kaolin application; D2K1 - 75% ETr depth with kaolin application; D3K0 - 100% ETr depth without kaolin application; D3K1 - 100% ETr depth with kaolin application; D4K0 - 125% ETr depth without kaolin application; D4K1 - 125% ETr depth with kaolin application; PH - Plant height; SD - Stem diameter; NL - Number of leaves; LA - Leaf area; Chl a - Chlorophyll a; Chl b - Chlorophyll b; Chl t - Total chlorophyll; % EL - Percentage of electrolyte leakage; RWC - Relative water content; STDM - Stem dry mass; SHDM - Shoot dry mass; NPP - Number of pods per plant; TP - Total production; MPL - Mean pod length; NGP - Mean number of grains per pod. Means followed by different letters in row indicate significant differences between treatments using Tukey test ($p \leq 0.05$)

These results show that severe water deficit negatively affects cowpea growth, evidencing that the greater availability of water for the crop allows for adequate growth (Carvalho et al., 2023). It is also observed that the reduction in water availability in the soil decreases turgor pressure, thus reducing the flow of sap through the conductive vessels, reducing cell elongation, plant growth, and yield (Souza et al., 2024). In addition, water restriction reduces stomatal opening and hinders carbon assimilation in photosynthetic metabolism, which impairs growth, dry matter production, and leaf area expansion (Melo et al., 2022).

In agreement with the results obtained, Mesquita et al. (2020) studied the effects of different irrigation depths on cowpea crop and observed that the irrigation depths caused a significant difference in stem diameter, plant height, and in the number of leaves, so these variables had the highest values under the largest irrigation depths. Mussato & Guimarães (2021) also highlighted that the increase in water availability directly resulted in increments in stem diameter and in number of leaves in cowpea plants.

Therefore, it can be observed in Table 6 that the lowest values of the growth variables in cowpea plants were found in the treatment with severe water deficit (50% of ETr). This can be explained by the fact that, under conditions of water deficit, plants may show physiological mechanisms that allow their development even under adverse conditions, and the main mechanisms of plant preservation are the decrease in leaf area and plant height, as well as the acceleration of senescence and leaf abscission under conditions of deficit (Silva et al., 2020).

It is also noteworthy that foliar application of kaolin did not mitigate the negative effects of water deficit on the growth of cowpea plants. On the other hand, some authors have highlighted the positive results of foliar application of kaolin on the growth of agricultural crops. Mohamad et al. (2021), when studying the effects of foliar application of kaolin on *Paulownia tomentosa*, known as princess tree, subjected to different levels of irrigation, observed that treatments with foliar application of 30 g L^{-1} of kaolin resulted in higher plant height, stem diameter, and plant dry mass, attributing these results to lower transpiration and greater water use efficiency.

The flowering and pod filling phases, in the reproductive stage of cowpea, are more vulnerable to water deficit in the soil, so any reduction in water supply will lead to a decrease in yield, causing not only embryo abortion, but also the loss of leaves and fruits (Soares et al., 2021). In agreement with the results of this study, Souza et al. (2024) found higher values of number of pods with the increase in irrigation depth, highlighting that, due to water restriction, it was possible to observe a significant reduction in this production variable in the different cowpea genotypes studied.

Table 6 also shows that irrigation with the 100% ETr depth promoted the highest mean value of total production (53.04 g) when kaolin was not applied (D3K0), and plants that received foliar application of kaolin waste, with the use of this same depth (D3K1), showed the highest mean values of pod length (22.42 cm) and number of grains per pod (14.03). When considering the MPL and NGP values for the treatment with the same irrigation depth, but without the application of kaolin (D3K0), increments of 1.72 and 16.62%, respectively, were obtained with the use of kaolin waste.

The lowest values of these production variables (TP, MPL, and NGP) were found in the treatments with the lowest irrigation depth applied (50% ETr), so compared to the treatments that resulted in the highest production values, there were increments of 95.35% in total production, 12.26% in pod length, and 37.71% in the number of grains per pod.

In Table 6, the 100% ETr depth promoted the highest mean values in the production variables TP, MPL and NGP, indicating the beneficial effect of this depth on cowpea crop production, adequately supplying its water needs. On the other hand, the depth corresponding to 50% ETr led to the lowest values of the production variables analyzed, which highlights that the increase in the production of cowpea plants accompanied the increase in water availability. The application of kaolin waste, in turn, despite favoring pod length and the number of grains per pod, did not promote the total production.

The results found can be discussed considering that, for most cowpea genotypes, the reduction in grain yield, after water deficit, decreases stomatal conductance and compromises photosynthetic processes and hence plant production (Melo et al., 2022).

Despite the lack of studies highlighting the effects of kaolin waste on cowpea cultivation, some authors have reported the benefits of this mineral in agricultural production, through its use as an anti-transpiration agent, contributing to the reduction of the negative effects of heat stress and increasing the efficient use of water. Cao et al. (2023), when analyzing the effect of foliar application of kaolin on grape plants, highlighted that kaolin particle film has the potential to be applied as an anti-transpiration agent to improve fruit quality in arid and semi-arid regions. Brito et al. (2021), when evaluating the effect of kaolin on olive (*Olea europaea* L.), indicated that foliar application of kaolin improved the performance of plants under sustained deficit, increasing crop yield, oil yield, and oxidative stability of olive oil.

Table 6 shows that the treatments with the highest water restriction (50% ETr) obtained the highest mean values of chlorophyll b content (675.87 μg mL^{-1}) when kaolin waste was applied (D1K1); when foliar application of kaolin was not performed (D1K0), the treatment resulted in the highest electrolyte leakage in the leaf blade (47.09%) of cowpea plants. The lowest mean value of chlorophyll b content was obtained with the highest irrigation depth (125% ETr) and without foliar application of kaolin waste (D4K0); for electrolyte leakage, irrigation with a depth of 100% ETr, associated with the application of kaolin waste (D3K1), led to the lowest mean value of this variable.

In principal component 2 (Table 6), the highest mean values of chlorophyll a (1433.84 μg mL^{-1}), total chlorophyll (2109.70 μg mL^{-1}) and relative water content (90.41%) were observed in the D1K1 treatment, i.e., with the use of the 50% ETr depth and foliar application of kaolin waste. Compared to the treatment that used the same depth, but without the application of kaolin (D1K0), there were increments of 26% in Chl a content, 22.82% in Chl t content and 11.24% in RWC, showing the positive effect of foliar application of kaolin waste on these physiological variables under water deficit.

The lowest mean values of chlorophyll a (1136.20 μg mL^{-1}), total chlorophyll (1625.98 μg mL^{-1}), and relative water content (81.28%) were obtained, respectively, with the irrigation depth of 75% ETr and foliar application of kaolin waste (D2K1), irrigation depth of 125% ETr and without foliar application of kaolin (D4K0), and with the irrigation depth of 50% ETr and without foliar application of kaolin waste (D1K0) in cowpea plants.

Plants subjected to water deficit exhibit physiological changes, since the decrease in water availability reduces the water content in their tissues, increasing crown temperature, with a reduction in chlorophyll content and, consequently, lower photosynthetic activity (Kumar et al., 2016; Barros et al., 2021). However, it was observed in the present study that the foliar application of kaolin waste at a dose of 50 g L^{-1} promoted increments in the relative water content and in the contents of photosynthetic pigments in cowpea plants. Kaolin is mainly composed of silicon, and it is noteworthy that this is a beneficial element that contributes to the improvement of the physiological attributes of plants (Dias et al., 2025), in addition to limiting water loss through transpiration and hindering fungal infection on the leaf surface, with positive results regarding the mitigation of the effects of abiotic stresses (Santos et al., 2024).

Mahmoudian et al. (2021) highlight that kaolin application significantly reduced the negative effects of water stress on leaf relative water content, indicating that foliar application of kaolin reduces transpiration rate and increases water content in plant tissues. The authors conclude that foliar application of kaolin under water deficit conditions improves chlorophyll content, relative water content and gas exchange and reduces leaf temperature. This occurs because foliar spraying of kaolin forms a protective film on the leaves, preventing excessive water loss through transpiration and increasing the efficient use of water in the plant.

Mahmoud et al. (2020), when studying the effects of foliar application of kaolin on potato (*Solanum tuberosum* L.) growth and production, reported that the highest values of chlorophyll a, chlorophyll b, and total chlorophyll were observed when potato plants were foliar sprayed with kaolin at a dose of 10 cm^3 L^{-1}. Gharaghani et al. (2023), when investigating the interaction between deficit irrigation and foliar spraying of kaolin on the growth, yield, physiology, and nut quality of 'Tardy nonpareil' almond, observed that kaolin spraying improved transpiration rate, photosynthesis rate, stomatal conductance, and total chlorophyll content compared to plants that were not subjected to kaolin application.

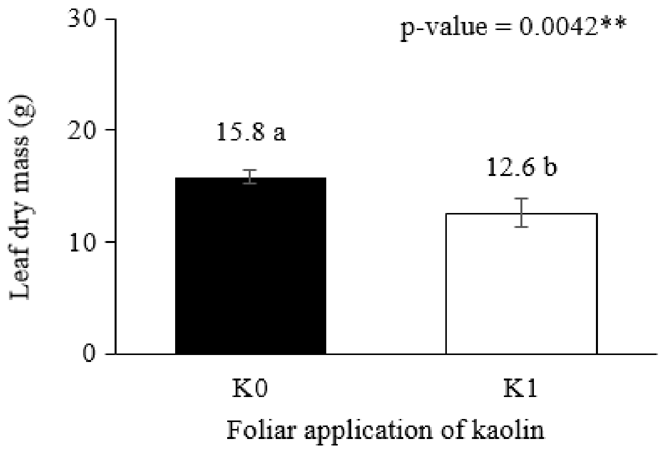
Carotenoid content (CAR), grain index (GI), and leaf dry mass variables, for being autocorrelated, as previously described, were presented with a univariate analysis. As observed in the analysis of variance (Table 7), irrigation depths and foliar application of kaolin waste did not significantly influence CAR and GI. In relation to leaf dry mass (LDM), foliar application of kaolin at a dose of 50 g L^{-1} significantly affected this variable.

It can be seen in Figure 4 that the highest mean value of leaf dry mass (LDM) was obtained in cowpea plants without foliar application of kaolin waste (K0), when compared to the LDM of plants subjected to foliar application of kaolin waste. Therefore, it is understood that the application of kaolin waste on the leaves of cowpea plants had no beneficial effects on leaf biomass under the conditions evaluated.

Table 7. Summary of the analysis of variance for the variables carotenoid content (CAR), grain index (GI) and leaf dry mass (LDM) of cowpea plants grown under different irrigation depths and foliar application of kaolin waste

SV	DF	Mean squares		
		CAR	GI	LDM
Depths	3	3381.08 ^{ns}	8.57 ^{ns}	28.14 ^{ns}
Kaolin	1	77.86 ^{ns}	34.93 ^{ns}	168.09**
Depths × Kaolin	3	7432.61 ^{ns}	27.85 ^{ns}	20.47 ^{ns}
Residual	56	4820.65	15.29	18.84
Total	63	-	-	-
Means	-	430.63	80.88	14.20
CV (%)	-	16.12	4.84	30.57

SV - Source of variation; DF - Degrees of freedom; CV - Coefficient of variation; ** - Significant at 0.05 probability level; ^{ns} - Not significant



Means followed by different letters indicate significant differences between treatments using Tukey test ($p \leq 0.05$); vertical error bars represent the standard error of the mean (n = 8)

Figure 4. Leaf dry mass at 45 days after sowing with (K1) and without (K0) foliar application of kaolin waste

Unlike these results, Mohamad et al. (2021) analyzed the effect of kaolin (30 g L^{-1}) on *Paulownia tomentosa* plants under water stress conditions and observed a significant increase in leaf dry mass compared to plants that did not receive foliar application of kaolin. Therefore, as cowpea is a demanding crop in terms of the agroclimatic characteristics of the cultivation site, such as temperature, photoperiod, wind, and solar radiation, in addition to water availability (Bastos et al., 2021), cowpea plants may have suffered other types of unanalyzed stresses that influenced this result, preventing the possible positive effect of kaolin waste on leaf biomass.

Climate change exposes cowpea plants to different levels of water availability, causing negative effects on their growth, physiological aspects and production, depending on the amount of water available. In this context, it is essential to search for measures to mitigate the negative effects caused by water stress, which includes more research that relates kaolin waste as a mitigator of water stress in cowpea cultivation. Therefore, studies on this topic indicate the need for adequate irrigation management practices during the cowpea development cycle, associated with the use of kaolin waste as a water stress-mitigating agent, in order to promote better physiological, growth, and production levels.

Conclusions

1. Foliar spraying of kaolin waste at the concentration of 50 g L^{-1} mitigated the deleterious effects of moderate water deficit on cowpea in terms of physiological parameters related to chlorophyll content (a, b and total) and relative water content. However, it did not generally benefit the growth and production of this legume under water stress conditions.

2. Foliar spraying of kaolin waste promoted the highest values of chlorophyll contents (a, b and total) and relative water content, with the depth of 50% ETr, the highest value of plant height for cowpea, with the depth of 75% ETr, the highest values of pod length and number of grains per pod, with the depth of 100% ETr, although it did not result in the highest total production per plant, obtained in the treatment with the 100% ETr depth without foliar application of kaolin waste (D3K0).

3. Foliar spraying of kaolin is recommended in cowpea cultivation, aiming at efficient use of water, due to its anti-transpiration function. In addition, further research is recommended to analyze kaolin as a heat stress attenuator and as a prevention of pest infestation.

Contribution of authors: Ana R. S. Nóbrega: Research design, data collection, analysis and interpretation and manuscript preparation. José D. Neto: Research design, analysis and interpretation and work supervision. Maria S. de F. Araújo: Research design, manuscript preparation and work supervision. André A. R. da Silva: Manuscript preparation. Mayra G. M. Lima: Data collection, analysis and interpretation. Luciano M. F. Saboya: Manuscript preparation. Viviane F. Silva: Manuscript preparation. Pedro I. S. Nóbrega: Research design and manuscript preparation. Ana R. S. Nóbrega: Research design and data collection.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflicts of interest.

Financing statement: The authors declare no conflicts of interest.

Acknowledgments: To the Graduate Program in Agricultural Engineering (PPGEA) of the Federal University of Campina Grande (UFCG), for the opportunity to take the Academic Master's Degree course and to the Coordination for the Improvement of Higher Education Personnel (CAPES) finance code 001, for granting a scholarship to the first author.

Literature Cited

Almeida, K. M. de; Vidal, F. W. H.; Castro, N. F. Melhoria do beneficiamento de caulim do seridó com uso do classificador hidrociclone. Observatório de la Economía Latinoamericana, v.21, p.23810-23825, 2023. https://doi.org/10.55905/oelv21n12-019

Alves, J. C.; Pôrto, M. L. A.; Arruda, J. A.; Silva, J. M. Produção de mudas de paineira em substratos com rejeito da indústria de caulim. Gaia Scientia, v.15, p.123-138, 2021. https://doi.org/10.22478/ufpb.1981-1268.2021v15n2.55146

Arnon, D. I. Copper enzymes in isolated chloroplasts. Polyphenoloxidases in *Beta vulgaris*. Plant Physiology, v.24, p.1-15, 1949. https://doi.org/10.1104/pp.24.1.1

Barbosa, J. R.; Pereira Filho, J. V.; Oliveira, V. M. de; Sousa, G. G. de.; Goes, G. F.; Leite, K. N. Produtividade da cultura da soja irrigada com déficit hídrico regulado no cerrado piauiense. Revista Brasileira de Agricultura Irrigada, v.14, p.4200-4210, 2020. https://doi.org/10.7127/rbai.v14n401196

Barros, J. R. A.; Guimarães, M. J. M.; Simões, W. L.; Melo, N. F.; Angelotti, F. Water restriction in different phenological stages and increased temperature affect cowpea production. Ciência e Agrotecnologia, v.45, p.1-12, 2021. https://doi.org/10.1590/1413-7054202145022120

Bastos, E. A. Clima - Feijão Caupi. Embrapa, 2021. Available at: <https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/feijao-caupi/pre-producao/caracteristicas-e-relacoes-com-o-ambiente/clima>.

Bernardo, S.; Mantovani, E. C.; Silva, D. D.; Soares, A. A. Manual de irrigação. 9.ed. Viçosa: UFV, 2019. 545p.

Bestete, L. R.; Torres, J. B.; Pereira, F. F. Harmonious interaction of kaolin and two insect predator species in plant protection. International Journal of Pest Management, v.64, p.166-172, 2018. https://doi.org/10.1080/09670874.2017.1350888

Brito, C.; Gonçalves, A.; Silva, E.; Martins, S.; Pinto, L.; Rocha, L.; Arrobas, M.; Rodrigues, M. A.; Moutinho-Pereira, J.; Correia, C. M. Kaolin foliar spray improves olive tree performance and yield under sustained deficit irrigation. Scientia Horticulturae, v.277, e109795, 2021. https://doi.org/10.1016/j.scienta.2020.109795

Cao, X.; Wang, Y.; Wang, Z. L.; Tian, X. L.; Han, X.; Wu, D.; Yao, F.; Hui, M.; Li, H.; Wang, H. Effects of kaolin particle film coatings on the water-saving efficiency and fruit quality of Cabernet Sauvignon (*Vitis vinifera* L.) grape plants in the Ningxia region of China. Horticulture, Environment, and Biotechnology, v.64, p.421-435, 2023. https://doi.org/10.1007/s13580-022-00498-4

Carvalho, E. D. O.; Costa, D. L.; Luz, D. B. D.; Rua, M. L.; Velame, M. D. L.; Monteiro, A. C.; Santos, M. A. Economic indicators for cowpea cultivation under different irrigation depths. Revista Brasileira de Engenharia Agrícola e Ambiental, v.27, p.618-624, 2023. https://doi.org/10.1590/1807-1929/agriambi.v27n8p618-624

Coelho, M. A.; Soncin, N. B. Geografia do Brasil. São Paulo: Ed. Moderna, 1982. 368p.

CONAB - Companhia Nacional de Abastecimento. Produção e balanço de oferta e demanda de grãos. CONAB, 2024. Available at: https://www.conab.gov.br/component/k2/item/download/53992_345d644b7b9a24036330a74b9a649fdf.

Dias, G. F.; Bonou, S. I.; Oliveira Viana, P. M. de; Alencar, R. S. de; Ribeiro, L. D.; Cavalcante, I. E.; Mikhaelly, Y.; Araújo, L. de; Lucena, R.A.M.; Gonçalves, T. W. da S.; Melo, A. S. de. Silício como agente mitigador da restrição hídrica em feijão-caupi: avaliação de parâmetros de crescimento. Journal of Education Science and Health, v.5, p.1-11, 2025. https://doi.org/10.52832/jesh.v5i1.486

Ferreira, D. P.; Sousa, D. P.; Nunes, H. G. G. C.; Pinto, J. V. N.; Farias, V. D. S.; Costa, D. L. P.; Moura, V. B.; Teixeira, E.; Sousa, A. M. L.; Pinheiro, H. A.; Souza, P. J. de O. P. Cowpea ecophysiological responses to accumulated water deficiency during the reproductive phase in Northeastern Pará, Brazil. Horticulturae, v.7, p.1-14, 2021. https://doi.org/10.3390/horticulturae7050116

Gharaghani, A.; Javarzari, A. M.; Rezaei, A.; Nejati, R. Kaolin spray improves growth, physiological functions, yield, and nut quality of ‘Tardy Nonpareil’ almond under deficit irrigation regimens. Erwerbs-Obstbau, v.65, p.989-1001, 2023. https://doi.org/10.1007/s10341-022-00732-4

Govaerts, B.; Sayre, K. D.; Lichter, K.; Dendooven, L.; Deckers, J. Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rainfed maize/wheat systems. Plant and Soil, v.291, p.39-54, 2007. https://doi.org/10.1007/s11104-006-9172-6

Grimes, D. W.; Carter, L. M. A. Linear rule for direct nondestructive leaf area measurements. Agronomy Journal, v.61, p.477-479, 1969. https://doi.org/10.2134/agronj1969.00021962006100030048x

Hair, F. J.; Black, W. C.; Babin, B. J.; Anderson, R. E.; Tatham, R. L. Análise multivariada de dados. 6.ed. Tradução Sant’Anna, A. S. Porto Alegre: Bookman, 2009. 688p.

Herrera-Feijoo, R. J.; Vélez, M. C. Caolín en el control de plagas agrícolas: Um estudio bibliométrico global de tendencias, colaboraciones y aplicaciones em la agricultura sostenible. Código Científico Revista de Investigación, v.4, p.88-114, 2023. https://doi.org/10.55813/gaea/ccri/v4/n2/233

Hotelling, H. Multivariate quality control illustrated by air testing of sample bombsights. In: Eisenhart, C.; Hastay, M. W.; Wallis, W. A. (eds.). Techniques of statistical analysis. New York: McGraw Hill, p.111-184, 1947.

Kaiser, H. F. The application of electronic computers to factor analysis. Educational and Psychological Measurement, v.20, p.141-151, 1960. https://doi.org/10.1177/001316446002000116

Kumar, M. Impact of climate change on crop yield and role of model for achieving food security. Environmental Monitoring and Assessment, v.188, p.1-14, 2016. https://doi.org/10.1007/s10661-016-5472-3

Lima, G. S. de.; Gheyi, H. R.; Nobre, R. G.; Soares, L. A. dos A.; Xavier, D. A.; Santos Júnior, J. A. dos. Water relations and gas exchange in castor bean irrigated with saline water of distinct cationic nature. African Journal of Agricultural Research, v.10, p.1581-1594, 2015. https://doi.org/10.5897/AJAR2015.9606

Mahmoud, S. H.; El-Tanahy, A. M. M.; El-Sawy, S. M. Amelioration productivity of potato crop grown under high temperature condition spraying with kaolin and α-tocopherol. Plant Archives, v.20, p.3568-3575, 2020.

Mahmoudian, M.; Rahemi, M.; Karimi, S.; Yazdani, N.; Tajdini, Z.; Sarikhani, S.; Vahdati, K. Role of kaolin on drought tolerance and nut quality of Persian walnut. Journal of the Saudi Society of Agricultural Sciences, v.20, p.409-416, 2021. https://doi.org/10.1016/j.jssas.2021.05.002

Melo, A. S. de.; Melo, Y. L.; Lacerda, C. F. de; Viégas, P. R. A.; Ferraz, R. L. de S.; Gheyi, H. R. Water restriction in cowpea plants [*Vigna unguiculata* (L.) Walp.]: Metabolic changes and tolerance induction. Revista Brasileira de Engenharia Agrícola e Ambiental, v.26, p.190-197, 2022. https://doi.org/10.1590/1807-1929/agriambi.v26n3p190-197

Melo, F. J. S.; Alves, J. M.; Severo, P. J. S.; Santos, L. C.; Mesquita, E. F.; Marcelino, R. M. O. S.; Santos, E. N.; Rocha, J. L. A. Uso de resíduos de mineração como substrato na formação de mudas de (*Carica papaya* L.). Brazilian Journal of Development, v.6, p.45579-45596, 2020. https://doi.org/10.34117/bjdv6n7-255

Mesquita, A. C.; Gomes, L. F.; Santos Junior, J. B. M. dos; Souza, I. J. da S.; Nogueira, W. R. da S.; Felix, A. T. R. Bactérias diazotropicas no crescimento inicial e alterações bioquímicas de *Vigna unguiculata* sob deficit hídrico. Research, Society and Development, v.9, e484985641, 2020. https://doi.org/10.33448/rsd-v9i8.5641

Mohamad, M. E.; Awad, A. A.; Gendy, A. S. Influence of calcium carbonate and kaolin on growth, drought resistance index and physiological traits of Paulownia (*Paulownia tomentosa*, Thunb.) seedlings under drought stress conditions. Plant Archives, v.21, e09725210, 2021.

Mussato, M. L.; Guimarães, S. L. Inoculação com estipes de rizóbio e seus efeitos sobre parâmetros fitométricos da leguminosa *Dolichos lablab* L. Rongai (1962) submetido à disponibilidade hídrica. Ensaios e Ciência, v.25, p.437-443, 2021. https://doi.org/10.17921/1415-6938.2021v25n4p437-443

Nascimento, E.; Souza, A. R. de; Nascimento, R. do; Silva, A. A. R. da; Bezerra, C. V. de C.; Lima, R. F. de; Guimarães, R. F.; Batista, M. C. Co-inoculation with *Bradyrhizobium* spp. and *Azospirillum brasilense* in cowpea under salt stress. Revista Brasileira de Engenharia Agrícola e Ambiental, v.27, p.3-8, 2022. https://doi.org/10.1590/1807-1929/agriambi.v27n1p3-8

Novais, R. F.; Neves, J. C. L.; Barros, N. F. Ensaio em ambiente controlado. In: Oliveira, A. J.; Garrido, W. E.; Araújo, J. D.; Lourenço, S. (eds.). Métodos de pesquisa em fertilidade do solo. Brasília: EMBRAPA-SEA, p.189-254, 1991.

Oliveira, F. de A.; Medeiros, J. F de; Alves, R. de C.; Lima, L. A.; Santos, S. T. dos; Régis, L. R. de L. Produção de feijão caupi em função da salinidade e regulador de crescimento. Revista Brasileira de Engenharia Agrícola e Ambiental, v.19, p.1049-1056, 2015. https://doi.org/10.1590/1807-1929/agriambi.v19n11p1049-1056

Oliveira, L. S. B.; Andrade, L. A. de; Alves, A. de S.; Gonçalves, G. S. Substrato e volume de recipiente na produção de mudas de jatobá (*Hymenaea courbaril* L.). Nativa, v.2, p.103-107, 2014. https://doi.org/10.31413/nativa.v2i2.1303

ONU - Organização das Nações Unidas. sobre o nosso trabalho para alcançar os objetivos de desenvolvimento sustentável no Brasil. ONU, 2024. Available at: < https://brasil.un.org/pt-br/sdgs>.

R CORE TEAM. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, https://www.R-project.org/. 2023.

Ribeiro, R. M. R.; Sousa, G. G. de; Barbosa, A. S.; Lacerda, C. F. de; Freire, M. H. D. C.; Moraes, J. G. L. Irrigation strategies with saline water and phosphate fertilization in cowpea culture. Brazilian Journal of Agricultural Sciences, v.17, e.2572, 2022. https://doi.org/10.5039/agraria.v17i3a2572-Protocol2572.

Roda, N. M.; Pontin, J. C.; Branchi, B. A.; Longo, R. M. Uso de caulim processado como técnica sustentável de mitigação dos efeitos das mudanças climáticas na produção agrícola. Revista de Administração, Ciências Contábeis e Sustentabilidade, v.13, p.171-183, 2023. https://doi.org/10.18696/reunir.v13i1.1241

Santos, C. A. F. BRS Tapaihum, BRS Carijó e BRS Acauã: novas cultivares de feijão caupi para o vale do São Francisco. In: Congresso brasileiro de olericultura, 51. Viçosa: ABH. 2011. p.3086-3094.

Santos, G. P. dos.; Avelino, G. G.; de Oliveira Silva, F.; de Sousa Leite, W. Desempenho de cultivares de feijão-caupi sob aplicação foliar de silício no cerrado piauiense. International Journal of Agrarian Sciences, v.3, p.32-48, 2024. https://doi.org/10.31692/2595-2498.v3i1.95

Scotti-Campos P.; Pham-Thi, A. T.; Semedo, J. N.; Pais, I. P.; Ramalho, J. C.; Matos, M. do C. Physiological responses and membrane integrity in three Vigna genotypes with contrasting drought tolerance. Emirates Journal of Food and Agriculture, v.25, p.1002-1013, 2013. https://doi.org/10.9755/ejfa.v25i12.16733

Shimizu, G.; Marubayashi R.; Goncalves, L. AgroR: Experimental statistics and graphics for agricultural sciences_. R package version 1.3.6, <https://CRAN.R-project.org/package=AgroR>. 2024.

Silva, A. L.; Batista, P. S. C.; Oliveira, K. J. O.; Cruz, C. A.; Cangussu, L. V. S.; Santiago, W. E. Agronomic performance of cowpea cultivars in different populations. Revista Brasileira de Agropecuária Sustentável, v.10, p.193-198, 2020.

Soares, L. A. dos A.; Medeiros, T. L. F.; Colman, V. C. G.; Palmeira, I. V. de S.; Silva, I. J. da; Moreira, R. C. L. Estratégias de irrigação com déficit hídrico nos estádios fenológicos do feijão-caupi sob adubação potássica. Irriga, v.26, p.111-122, 2021. https://doi.org/10.15809/irriga.2021v26n1p111-122

Souza, T. M. A. de; Souto, L. S.; Dutra Filho, J. de A.; Santos, C. S. de A; Silva, L. de A.; Peixoto, T. D. C.; Sá, F. V. da S. Cowpea growth and production under water stress and soil mulching. Revista Brasileira de Engenharia Agrícola e Ambiental, v.28, e271643, 2024. https://doi.org/10.1590/1807-1929/agriambi.v28n3e271643

STATSOFT, Inc. Statistica (data analysis software system), version 7.0. Tulsa, OK: StatSoft, Inc. 2004.

Teixeira, P. C.; Donagemma, G. K.; Fontana, A.; Teixeira, W. G. Manual de métodos de análise de solo. 3 ed. Brasília: Embrapa Solos. 2017, 573p.