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Optimizing Drought-Resistant Cowpea Cultivar Selection Mediated by Silicon Supplementation using TOPSIS tool

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Abstract

Cowpea (*Vigna unguiculata* (L.) Walp.) is an essential food in many arid regions of developing countries. However, its cultivation is threatened by climate change. Silicon (Si) fertilization has been used to reduce environmental stress impact. However, it is necessary to investigate how various plant cultivars treated with Si perform under drought stress conditions. Here, we develop and evaluate a computational model for selecting cowpea cultivars that are more tolerant to water deficit across different Si concentrations. This computational model integrates two mathematical methodologies: the Manhattan distance and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to analyze cowpea cultivar performance across various conditions, aiding in identifying the best-suited cultivars for different climates. Data from a factorial experiment (3×3×4) were evaluated, covering three cowpea cultivars (BRS Novaera, BRS Tumucumaque, and BRS Xiquexique), three water regimes (well-irrigated control at 75% of field capacity (FC), moderate drought at 60% FC, and severe drought at 45% FC), and four Si concentrations (0.0, 1.0, 2.0, and 4.0 mM). Si application had beneficial effects across the cowpea cultivars, mitigating drought stress impact. The most successful cultivars at Si concentrations of 0.0, 2.0, and 4.0 mM were BRS Xiquexique, BRS Tumucumaque, and BRS Novaera, respectively. However, the combined model results revealed that BRS Novaera cultivar displayed better performance under water stress when treated with Si. Our findings also highlight the sensitivity of cultivar selection to Si application compared to water stress. This methodology can benefit farmers by enabling precise adjustments of applied Si level, selecting tolerant cultivars, and considering the climatic conditions of the growing region.

Keywords *Vigna unguiculata* · Decision-making · Manhattan distance

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Introduction

The relentless pursuit of more resilient, productive, and adaptable cultivars crucial for ensuring global food security amidst the challenges posed by climate change and population growth (Cooper and Messina 2023; Shafi et al. 2023). Research has focused on identifying specific crops, such as cowpea (*Vigna unguiculata* (L.) Walp.), which play a socially relevant role due to their significant economic and nutritional importance in arid and semiarid regions (Rodrigues Maia 2023). Considering the anticipated negative impacts of climate change on the cultivation environments of essential agricultural species for human consumption, stress-tolerant cultivars may constitute an urgent strategy for implementing effective solutions (Kumari et al. 2022).

Cowpea is a relatively drought-tolerant crop, but it faces significant challenges due to global climate change, which increases climatic unpredictability and makes decisions in the field more complicated (Jayawardhane et al. 2022). Environmental stressors such as water deficit usually impair several metabolic pathways in plants, impacting essential physiological processes such as respiration, photosynthesis, and transpiration (Gupta et al. 2020; Leite et al. 2023). Later, drought-induced damage poses a considerable threat to both vegetative and reproductive stages, ranging from morphological to molecular changes, and results in severe growth decreases and reduced productivity (Luiz Piati et al. 2023).

Recent studies have focused on identifying mechanisms to enhance crop resilience in the face of water deficit, highlighting the urgency of addressing the challenges posed by stressful environments, such as increasing water scarcity (Mostofa et al. 2021; Khan et al. 2023; Leite et al. 2023). Mineral elements are considered an effective strategy for mitigating the impacts of abiotic stress on plants because they are capable of activating crucial responses to maintain growth and survival under unfavorable environmental conditions (Mir et al. 2022). In the last few years, silicon (Si) nutrition has become a promising tool in the pursuit of sustainable solutions (Irfan et al. 2023; Leite et al. 2024; Rea et al. 2022).

Silicon has been shown to be an effective alternative for enhancing plant resistance to abiotic stresses, displaying multifaceted role in the plant defense like increased cuticle thickness on leaves to provide a stronger physical barrier that reduces water loss through transpiration (Costa et al. 2024; Wang et al. 2021). Various studies demonstrate that silicon improves the antioxidant defense system of plants, contributing to the mitigation of oxidative damage caused by drought stress (Bhardwaj et al. 2022; El-Beltagi et al. 2024; Mushtaq et al. 2024; Saja-Garbarz et al. 2024; Teixeira et al. 2022). It is also capable of regulating the absorption and translocation of water and stomatal opening to control the transpiration rate, thus optimizing the efficient use and water status in plants (Cooke and Carey 2023; Saja-Garbarz et al. 2024). However, although Si nutrition has been proven to be effective in plant defense, investigative methods often encounter challenges related to the large volume of data produced by studies around the world. This big data requires careful interpretation to discern treatments capable of improving the yield of different cultivars under drought stress across diverse growing environments (Rea et al. 2022; Irfan et al. 2023; Rodrigues Maia 2023).

Computational mathematical methodologies, such as the Manhattan distance and the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), have already been successfully applied to select soybean and forage grass genotypes under water stress (Oliveira et al. 2022, 2024). These tools provide a rapid solution and facilitate the evaluation of different cultivars for the studied treatments, demonstrating robustness for evaluating a large number of variables. Together, these techniques offer a more efficient and detailed analysis, adequately comparing the cultivars and identifying those with greater productive potential and adaptability (Christian et al. 2022; Silva et al. 2022). This study aimed to apply an innovative methodology to enhance the selection of tolerant cowpea cultivars exposed to moderate and severe drought conditions, in conjunction with Si fertilization, to mitigate the effects of drought on the BRS Novaera, BRS Tumucumaque, and BRS Xiquexique cultivars. Furthermore, it offering practical insights that can inform decision-making processes for farmers and stakeholders involved in agricultural production in arid regions.

Materials and Methods

To implement a new selection methodology using a computational model, we utilized data from a previously validated experiment (Leite et al. 2023) that incorporates physical, morphological, and biochemical parameters to evaluate the response of cowpea cultivars to Si nutrition under different water regimes. In this study, we expanded the original database to include a new cowpea cultivar and an additional drought treatment.

Plant Materials and Silicon Treatments

The experiment was conducted in a greenhouse located at the Federal University of Piaui (UFPI), *Campus* Professora Cinobelina Elvas—CPCE (9°04′45.6″ S, 44°19′37.9″ W, and 277 m) from February to April 2021 (Leite et al. 2023). The trials employed a randomized block experimental design with four replications in a 3 × 3 × 4 factorial scheme. The factorial scheme consisted of three cowpea cultivars (BRS Novaera, BRS Tumucumaque, and BRS Xiquexique), three water regimes (control well irrigated at 75% field capacity [FC], moderate drought at 60% FC, and severe drought at 45% FC), and four Si concentrations, i.e., 0.0, 1.0, 2.0, and 4.0 mM. The temperature and relative humidity were monitored daily using a digital thermohydrometer throughout the experiment.

The plants were grown in 11 dm^{-3} plastic pots filled with high-fertility sandy loam soil. During the sowing phase, five viable seeds were planted at a depth of 3.0 cm. After 5 days of emergence, the plants were thinned, and only one plant per pot was retained. Each experimental plot consisted of a single pot containing one plant.

The soil presented a basal Si content of 5.3 mg dm^{-3}, determined through calcium chloride extraction at a concentration of 0.01 mol L^{-1}, following the methodology outlined by Korndörfer et al. (2004). Fertilization was adhered to recommended practices for cowpea cultivation (Melo et al. 2005), including the addition of 200 mg dm^{-3} phosphorus and 150 mg dm^{-3} nitrogen and potassium in the form of triple superphosphate, urea, and potassium chloride, respectively. Triple superphosphate was applied as a single dose and incorporated into the soil. Concurrently, nitrogen (N) and potassium (K) were applied via fertigation at three doses of 50 mg dm^{-3} starting 5 days after emergence. Zinc as $ZnCl_2$ (3 mg dm^{-3}), manganese as manganese chloride (1 mg dm^{-3}), and boron as boric acid (0.5 mg dm^{-3}) were also applied via fertigation, coinciding with the initial application of N and K.

To ensure effective irrigation management, the pots were daily weighed to determine the average volume of water lost by evapotranspiration. Then, water was added to maintain the soil humidity at 75% FC until the drought stress regimes were implemented. Additionally, during daily irrigation, the Si treatments were applied daily by adding potassium silicate (Si: 12%, K_2O: 15%) to the water (fertirrigation), according to the Si treatments. This approach enables plants to absorb this element even under normal developmental conditions. The drought treatments were started 21 days after sowing, and the soil humidity was reduced to 60% FC (moderate drought) and 45% FC (severe drought). The stress treatments were imposed for 28 days, when the plant material was harvested.

Growth Analysis, Water Status and Leaf Temperature

During harvest, the plants were separated into leaves, stems and roots. Then, the plant height, stem diameter, number of trefoils, leaf area, shoot fresh mass and root fresh mass were determined. The plant material was dried in an oven with forced air circulation at 65 °C and used to estimate the shoot dry mass, root dry mass and plant dry mass. Relative stress tolerance was determined by the ratio between the shoot dry mass of plants in a drought regime (moderate or severe) and the shoot dry mass of well-irrigated plants (Miranda et al. 2021).

The relative water content (RWC) was measured using 1.0 cm diameter leaf discs to determine the fresh mass, turgidity mass and dry mass after drying the plant material at 65 °C for 72 h. The RWC was estimated as described by Catsky (1960). Leaf succulence (LS) was determined considering the values of fresh leaf mass, dry leaf mass and leaf area, as adapted from (Mantovani 1999). The leaf osmotic potential (Ψs, in MPa) was determined after extracting the cell sap by pressing the leaf tissues of the first fully expanded leaves. The osmolarity of the cell sap was measured using a vapor pressure micro-osmometer (model 5600, Vapro®). The Ψs was estimated according to Van't Hoff's equation, as described by Bao et al. (2014).

Leaf temperature was recorded on the third fully expanded leaf from the apex of the plants using a portable infrared thermal camera (FLIRT6-267).

Gas Exchanges and Photosynthetic Pigments

The gas exchange parameters were estimated for fully expanded leaves (third leaf counted from the apex). The parameters net photosynthesis, A (μmol CO_2 m^{-2} s^{-1}), transpiration rate, E (mmol H_2O m^{-2} s^{-1}), stomatal conductance, gs (mol H_2O m^{-2} s^{-1}), and internal CO_2 concentration (Ci) were measured 21 days after drought imposition, from 8:00 to 11:30 h on full sun days, using an infrared gas analyzer (IRGA, Walz—GFS3000). Subsequently, the instantaneous carboxylation efficiency (A/Ci, μmol CO_2 m^{-2} s^{-1} ppm), instantaneous water uses efficiency (A/E, μmol CO_2 mmol H_2O^{-1}) and intrinsic water use efficiency (A/gs, μmol CO_2 mol H_2O^{-1}) were measured.

Photosynthetic pigments were extracted from leaf discs using a solution of dimethyl sulfoxide (DMSO) saturated with $CaCO_3$ in the dark. The extracts were subjected to absorbance readings at 480, 649 and 665 nm, and the concentrations of chlorophyll a (Chl a), chlorophyll b (Chl b) and carotenoids were estimated using equations based on the methodology described by Wellburn (1994).

Membrane Damage

The membrane damage in leaves (MD_{leaf}) and roots (MD_{root}) was quantified through electrolyte leakage using a conductivity meter. The leaf discs were placed in closed flasks containing deionized water and incubated at room temperature on a rotary shaker for 12 h. Then, the electrolyte conductivity (EC) of the solution (S1) was determined. Subsequently, the homogenate was incubated at 100 °C for 15 min, and the conductivity of the solution was measured again (S2). Membrane damage (%) was calculated as S1/S2 × 100, as described in (Miranda et al. 2021).

Computational Proposed Method for Cultivar Selection

The proposed methodology for selecting cultivars subjected to various treatments utilizes the TOPSIS multicriteria decision-making method in conjunction with the Manhattan Distance metric. A detailed explanation of both concepts is provided in the following sections.

In a vector space, objects are considered more similar when the distance between them is smaller, in contrast to objects separated by greater distances (Huang 2008). Minkowski distances are a general class of distance metrics that measure the dissimilarity between two points in a vector space. It is defined as $d(x, y, p) = \left(\sum_{i=1}^{n} |x_i - y_i|^p\right)^{1/p}$, where p determines the specific distance metric. When $p = 1$, the result is the Manhattan distance. The selection of an appropriate distance metric depends on various factors, but (Aggarwal et al. 2001) found that the Manhattan distance is particularly well-suited for higher-dimensional vector spaces. Furthermore, previous studies have demonstrated the effectiveness of this metric (Oliveira et al. 2022, 2024). Therefore, in this research, which involves 15 variables, we employ the Manhattan distance within a 15-dimensional vector space.

After calculating the distances between the cultivars under the two water stress regimes and comparing them to the control regime, it was found that these distances could not be directly compared to assess the impact (Oliveira et al. 2022). Specifically, a cultivar might show a greater distance under the “Moderate” regime but a smaller distance under the “Severe” regime, making it difficult to determine which cultivar is less affected by water stress. This ambiguity highlighted the need for a decision-making methodology that could evaluate and select cultivars by considering their performance across both water stress regimes.

TOPSIS is a multicriteria decision-making method that ranks alternatives based on their performance relative to a set of evaluation criteria. The method operates through six steps: constructing and normalizing the decision matrix, calculating the weighted normalized decision matrix, determining the ideal and negative ideal solutions, calculating the separation measures, and computing the relative closeness to the ideal solution (Yadav et al. 2019). The fundamental principle is that the best alternative should be closest to the ideal solution and farthest from the negative ideal. In this study, TOPSIS was applied to rank three cultivars: Novaera, Tumucumaque, and Xiquexique, originally named BRS Novaera, BRS Tumucumaque, and BRS Xiquexique, respectively. The criteria used were the Manhattan distances between the control regime and two water stress conditions: Control/Moderate and Control/Severe. These distances measure the dissimilarity in each cultivar’s performance under different water stress levels, with the TOPSIS score indicating which cultivar is closest to the ideal solution. This systematic approach ensures a quantitative and well-founded selection of the most suitable cultivar.

To account for the different scales of the measured variables, a preprocessing step known as normalization was applied. This process involved dividing each variable’s value by the sum of all values for that variable, ensuring that the normalized values fell within the range [0, 1]. Consequently, the variables became dimensionless, allowing for meaningful comparisons across different criteria.

Based on the presented concepts, the proposed methodology was implemented as follows: (i) first, the average values were calculated for each block corresponding to the same cultivar and Si concentration; (ii) normalization was then applied to each variable; (iii) the Manhattan distances between the control and drought stress conditions (moderate and severe) were calculated for each cultivar and Si concentration; (iv) these distance measurements were input into the TOPSIS method, and the resulting scores were used to rank and select the cultivars; and (v) identical weights were initially applied in TOPSIS for both the Control/Moderate and Control/Severe comparisons, after which weight variations were tested to observe their impact on cultivar selection. The full implementation of this methodology, including the codes used in these steps, is available in the GitHub repository at the following link: https://github.com/brunobro/novel-approach-to-cowpea-cultivar-selection

Statistical Analysis

All statistical analyses were conducted using SISVAR for Windows version 5.6 (Ferreira 2019). A three-way analysis of variance (ANOVA) was employed to assess the effects of genotype, water condition, and silicon concentration, as well as their interactions, on the photosynthetic activity, antioxidant activity, and growth of cowpea plants. Significance levels of 99% and 95% were applied to determine the statistical relevance of the results. ANOVA was also used to identify variables with statistically significant differences in means, which were subsequently utilized in the calculation of Manhattan distances, as detailed in the previous section. Post hoc tests were not performed, as the selection of the best cultivars was carried out using the TOPSIS method, rendering post hoc comparisons unnecessary for the purposes of the proposed methodology.

Results

Effect of Si on Growth, Photosynthetic Parameters, Water Relations and Membrane Damage

Table 1 displays a summary of the analysis of variance (ANOVA), including the coefficient of variation. Analyses were carried out for the three sources of variation, namely water regime, cultivar and Si concentration. The results reveal that the water regime played a crucial role, exerting significant effects on nearly all measured variables. The cultivar also had a significant influence on several parameters but to a lesser extent on others, as will be explained below. Si concentration tends to have a more variable impact, and the interactions among the different sources of variation are also telling. The interaction between water regime and Si concentration significantly influenced plant height, leaf area, and shoot fresh mass, suggesting that the combination of these two factors can drive substantial changes. Similarly, the interaction between water regime and Si concentration had notable effects on variables such as leaf area and shoot fresh mass. While the interaction between cultivate and Si concentration displayed fewer significant effects. The three-way interaction among water regime, cultivate, and Si concentration was also significant for several parameters, such as leaf area and shoot fresh mass, indicating a complex interplay when all three factors are considered together.

Regarding, the relative water content (RWC%) and osmotic potential (Ψs) factors, the water regime, cultivar, and water regime × cultivar interactions were significant, indicating their combined influence. Water regime, cultivar, water regime × cultivar, and water regime × Si concentration showed significant combined influence on Chl a, Chl b and carotenoids. Furthermore, net photosynthesis (A), transpiration rate (E), stomatal conductance (gs), internal CO_2 concentration (Ci), and related parameters (A/Ci, A/E, A/gs) have significant effects.

For the variables leaf and root Membrane Damage (MD_{leaf}, MD_{root}), both water regime and cultivar have a significant impact on MD under drought stress, indicating species cultivar-specific responses under drought stress.

TOPSIS Method for Cultivar Selection

The Manhattan distances for the control/severe drought and control/moderate drought comparisons, as well as the TOPSIS Score, (Fig. 1). The values are relative to each cultivar. Here, the proposed methodology was applied to each Si concentration, and the results are individually presented for each concentration (Fig. 1a–d).

The Manhattan distance values are displayed alongside the TOPSIS scores to highlight the variability found in each water stress treatment. However, merely investigating the distances is insufficient for selecting the best cultivar. Occasionally, a cultivar performs better in one treatment than in another. Therefore, the application of the TOPSIS multicriteria decision-making method is essential.

For all cases, the results are individually presented for each Si treatment. While it was feasible to include Si treatment as another criterion in the TOPSIS decision-making model, our objective was to ascertain which cultivar responded best to Si treatment within a specific water stress environment. Therefore, it was necessary to apply TOPSIS to the Manhattan distances for each treatment individually.

The above results were obtained by considering equal weights for comparing moderate and severe water stress criteria in TOPSIS. Thus, Table 2 results explain the changes in these weights. These findings allow understand how cultivar selection changes depending on the weight given to the comparison between control and drought treatments. The results are individually displayed for each Si concentration. In the weight's column, the weights set for the distances of each comparison between drought and control environment are displayed, with the sum of the weights being equal to 1. The Cultivar and TOPSIS Score columns show how the choice of cultivar and the score, respectively, vary depending on the weight chosen for the comparison distances.

In general, the results in Table 2 demonstrate the stability of the model, indicating that a ranking of cultivars should be re-evaluated when the weight of the water-stressed environment is modified. This dynamic is significant as it allows adjusting the model to the specific conditions of the cultivation area, assigning more importance (weight) to one type or another.

Discussion

The identification of cultivar-specific responses to Si treatment underscores the importance of precision agriculture in optimizing Si levels and cultivar selection for enhanced resilience to water deficit. In the current study, a new method was tested to select cowpea cultivars subjected to three water stress treatments and four Si levels. Previous reports suggested that the methodology used is robust to any number of variables (Oliveira et al. 2022, 2024), but it is computationally more efficient to select only variables with a statistically significant difference. Therefore, variables that do not present a significant mean difference are not able to contribute to the selection.

During the computational approach, we analyzed the ANOVA results in Table 1 for each of the variables. The stem diameter, plant height, leaf area, and shoot and root

Table 1 Analysis of variance of the studied variables included the following: stem diameter (SD), plant height (PH), number of trefoils (NT), leaf area (LA), shoot fresh mass (SFM), root fresh mass (RFM), shoot dry mass (SDM), root dry mass (RDM), plant dry mass (PDM), relative stress tolerance (RST), leaf succulence (LS), relative water content (RWC%), osmotic potential (Ψs), leaf membrane damage (MD_{leaf}), root membrane damage (MD_{root}), leaf temperature (LT), chlorophyll a (Chl a), chlorophyll b (Chl b), carotenoids (Car), net photosynthesis (A), transpiration rate (E), stomatal conductance (gs), internal concentration of CO_2 (Ci), instantaneous carboxylation efficiency (A/Ci), instantaneous water use efficiency (A/E) and intrinsic water use efficiency (A/gs)

	Probability > F												
Source of variation	SD	PH	NT	LA	SFM	RFM	SDM	RDM	PDM	RST	LS	RWC%	Ψs
Water regime (WR)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cultivar (C)	< 0.01	< 0.01	0.560	< 0.01	< 0.01	< 0.01	0.120	< 0.01	< 0.05	0.260	0.060	0.140	0.160
Silicon (Si) concentration (SC)	< 0.01	0.570	0.850	0.630	< 0.05	< 0.01	0.160	< 0.01	< 0.05	< 0.01	< 0.05	0.710	0.820
WR × C	< 0.05	< 0.01	0.060	< 0.01	< 0.01	< 0.01	0.300	< 0.01	< 0.05	0.820	0.250	0.280	0.140
WR × SC	0.480	0.880	0.220	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.360
C × SC	0.990	0.730	0.250	< 0.05	0.640	0.080	0.570	0.060	0.550	< 0.01	0.340	0.950	0.320
WR × C × SC	0.100	0.660	0.280	< 0.01	< 0.05	0.490	< 0.01	0.710	< 0.05	< 0.01	< 0.05	< 0.01	0.290
CV (%)	12.23	23.30	59.82	17.79	19.91	31.23	22.00	44.06	21.62	15.43	12.79	12.07	8.27
Std	1.95	16.97	4.78	532.03	30.18	6.25	4.05	0.74	4.61	30.67	0.42	15.45	0.16
Source of variation	LT	Chl *a*	Chl *b*	Car	*A*	*E*	*gs*	Ci	A/Ci	*A/E*	*A/gs*	MD_{leaf}	MD_{root}
Water regime (WR)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.230	< 0.01
Cultivar (C)	< 0.05	0.110	< 0.01	< 0.01	< 0.01	0.350	0.070	< 0.01	0.280	0.550	0.070	0.320	0.550
Silicon (Si) concentration (SC)	0.560	0.190	0.080	0.090	0.800	0.490	0.440	0.100	0.060	0.170	< 0.01	0.870	0.320
WR × C	0.370	< 0.01	< 0.01	< 0.05	< 0.01	< 0.01	< 0.01	< 0.05	< 0.01	0.130	0.090	0.490	< 0.05
WR × SC	< 0.05	0.090	< 0.01	0.220	< 0.01	< 0.05	< 0.01	0.890	< 0.01	< 0.01	< 0.01	0.940	0.130
C × SC	0.630	< 0.05	0.080	0.370	< 0.01	< 0.01	< 0.01	0.110	< 0.01	0.700	< 0.01	0.990	0.480
WR × C × SC	0.710	< 0.01	< 0.01	0.140	< 0.01	< 0.01	< 0.01	0.370	< 0.01	< 0.01	< 0.01	0.990	0.090
CV (%)	9.11	22.54	26.48	23.12	21.91	39.88	44.96	24.53	31.62	37.59	27.29	10.86	6.26
Std	9.41	0.74	4.53	1963.05	1729.26	713.50	6.06	1.14	0.04	111.40	0.043	9.41	0.74

The symbol "<" indicates statistical significance at the 0.01 or 0.05 level. *CV* coefficient of variation, *Std.* standard deviation

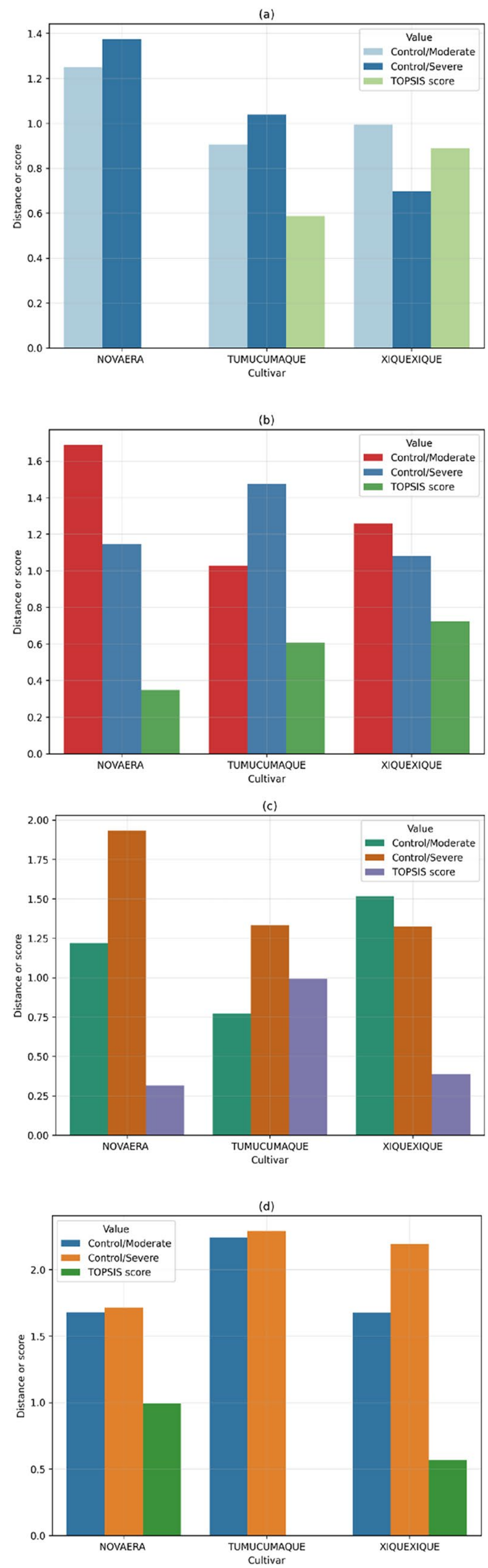

Fig. 1 Distances between the control environment and the stress environments and the TOPSIS score for each silicon (Si) concentration: **a** 0.0 mM, **b** 1.0 mM, **c** 2.0 mM, and **d** 4.0 mM

Table 2 TOPSIS scores for various choices of weights for comparisons between control and drought treatments (moderate and severe) within silicon (Si) levels

Weights		Cultivar	TOPSIS score
Control/ Moderate	Control/Severe		
0.0 mM Si			
0.1	0.9	Xiquexique	0.9853
		Tumucumaque	0.4978
		Novaera	0.0000
0.3	0.7	Xiquexique	0.9465
		Tumucumaque	0.5187
		Novaera	0.0000
0.7	0.3	Xiquexique	0.8111
		Tumucumaque	0.7200
		Novaera	0.0000
0.9	0.1	Xiquexique	0.9023
		Tumucumaque	0.7483
		Novaera	0.0000
1.0 mM Si			
0.1	0.9	Xiquexique	0.9431
		Novaera	0.7774
		Tumucumaque	0.1468
0.3	0.7	Xiquexique	0.8230
		Novaera	0.5495
		Tumucumaque	0.3989
0.7	0.3	Xiquexique	0.7832
		Novaera	0.6664
		Tumucumaque	0.1874
0.9	0.1	Xiquexique	0.9330
		Novaera	0.6488
		Tumucumaque	0.0564
2.0 mM Si			
0.1	0.9	Tumucumaque	0.9878
		Xiquexique	0.8508
		Novaera	0.0653
0.3	0.7	Tumucumaque	0.9897
		Xiquexique	0.5965
		Novaera	0.2007
0.7	0.3	Tumucumaque	0.9967
		Xiquexique	0.3784
		Novaera	0.2135
0.9	0.1	Tumucumaque	0.9991
		Xiquexique	0.3990
		Novaera	0.0657
4.0 mM Si			
0.1	0.9	Novaera	0.9989
		Xiquexique	0.1995
		Tumucumaque	0.0000
0.3	0.7	Novaera	0.9964
		Xiquexique	0.3731
		Tumucumaque	0.0000
0.7	0.3	Novaera	0.9921
		Xiquexique	0.7533
		Tumucumaque	0.0000
0.9	0.1	Novaera	0.9915
		Xiquexique	0.9216
		Tumucumaque	0.0000

mass (both fresh and dry) were differently altered based on the water regime, cultivar, Si concentrations, and their interactions. The data suggest that these factors, along with their combinations, significantly affect stem diameter. As for the variable Number of Trefoils, significant differences were observed for water regime and cultivar, whereas no significant difference was reported for Si concentration and its interactions. Our findings are in concordance previous studies from (Rizwan et al. 2015), who reported a mitigation of drought stress by Si supplementation.

In relation to the variables relative stress tolerance, leaf succulence, and relative water content (RWC%), all factors and most interactions were significant, suggesting that water regime, cultivar, and Si concentration influence these variables in treated cowpea cultivars. For the osmotic potential (Ψs), the water regime, cultivar, and water regime × cultivar interactions are significant, indicating their combined influence. Regarding, cowpea photosynthetic reactions, significant effects on most factors and interactions were observed, suggesting their combined influence on physiological processes related to photosynthesis and water use efficiency. In the line with our results, Si is known to regulate stomatal activity, photosynthesis, and water use efficiency, all of which contribute to improved vegetative growth (Souri et al. 2021). In this context, recent studies (Bhardwaj et al. 2022; El-Beltagi et al. 2024; Mushtaq et al. 2024) have demonstrated that silicon treatment under drought conditions not only enhances photosynthetic performance and membrane stability but also improves antioxidant capacity, thereby reducing oxidative damage. In addition, Si can facilitate nutrient uptake by plants, while reducing their absorption of harmful metals (Asgher et al. 2024; Puppe et al. 2023).

The results presented in this study indicate that water regime, cultivar, and Si concentration, along with their interactions, play crucial roles in determining various physiological and growth parameters of cowpea plants under water stress. A study investigated the foliar application of Si to various cowpea cultivars and revealed that Si promoted beneficial effects across plant cultivars. This benefit likely stems from Si's role in optimizing biochemical and physiological processes, ultimately leading to improved growth indicators (Silva et al. 2019; Teixeira et al. 2022). Likewise, other researchers have noted that cowpea cultivars display different degrees of tolerance to abiotic stress. This diversity arises from inherent disparities in the physiological, biochemical, and anatomical traits of each cultivar (Leite et al. 2023).

Based on the previous analyses, our data suggest that the cultivar selection methodology considered the use of variables that achieved statistical significance in the interactions between the three sources of variation, resulting in 15 selected variables. According to the graphical representation (Fig. 1a), in the Si absence, the cultivar Xiquexique exhibited the smallest distance in the comparison between the Control/Severe treatments. In contrast, in the analysis of the Control/Moderate comparison, the cultivar Tumucumaque showed the smallest distance. Notably, the cultivar Novaera demonstrated significantly greater distances in both comparative scenarios, indicating that it is the cultivar subject to the greatest variation in the measured variables when subjected to water stress.

Upon analyzing the TOPSIS score, the cultivar Xiquexique was the best choice despite having a greater distance in the Control/Moderate comparison. However, a more significant difference in distances between the Xiquexique and Tumucumaque cultivars was observed in the Control/Severe comparison. Thus, the Xiquexique cultivar seems to be much shorter than the Tumucumaque cultivar in this comparison. In the Control/Moderate comparison, the difference is much smaller. Therefore, TOPSIS was selected as the best cultivar for Xiquexique, which showed the least changes in relation to the control when Si was not applied.

The data revealed that the Novaera cultivar performed better under Si at 1.0 mM (Fig. 1b). In the control/severe comparison, this distance was smaller than that of the TUMUCUMAQUE cultivar and almost the same as that of the Xiquexique cultivar. However, in the control/moderate comparison, the distance from the Novaera cultivar was much greater. Despite this, TOPSIS still ranks 3rd. The Xiquexique cultivar is also the best for this Si application.

When 2.0 mM Si was applied, TOPSIS showed an inversion in the selection, with the Tumucumaque cultivar being selected in the 1st position (Fig. 1c). Novaera cultivar had a TOPSIS score very similar to that of the Xiquexique cultivar. In contrast to the results observed with 1.0 mM Si application, the Novaera cultivar showed a shorter distance in the Control/Moderate comparison. At 4.0 mM Si application, the Novaera cultivar was selected in the first position (Fig. 1d), once the distances in both comparisons were very close, with the Novaera and Xiquexique cultivars having practically the same distances in the Control/Moderate comparison, with values of 1.679774 and 1.674988, respectively.

A foundational study (Leite et al. 2023) revealed that Si supplementation increased Si accumulation in the tissues of both cowpea cultivars, Novaera and Xiquexique. This response was particularly pronounced in the well-watered Tumucumaque cultivar when treated with Si at 1.0 and 2.0 mM. These findings support the selection method proposed in this study and align with prior research that did not include the Xiquexique cultivar.

Certain cultivars had higher scores in the control/moderate drought comparison, while others had higher scores in the control/severe drought comparison (Fig. 1). Therefore, adjusting the weights of these criteria in TOPSIS will likely result in a different selection of cultivars. Si application, cultivar Xiquexique was selected for three different weight choices (Table 1), without. However, when the weight in the control/moderate criterion was 0.9, the Tumucumaque cultivar was selected in the first position. This result is expected, where the Tumucumaque cultivar had a shorter distance in the control/moderate drought comparison (Fig. 1a). The selection position of the Novaera cultivar remained unchanged, regardless of the assigned weights.

At 1.0 mM Si application, the Novaera cultivar moved up one position for two weight choices when the Control/Severe criterion was given greater weight. Conversely, when the control/moderate drought criterion is given greater weight, the Tumucumaque cultivar takes first position, while Novaera falls to last. This result is consistent with previous observations. Novaera cultivar had a greater distance in the Control/Moderate comparison than in the Tumucumaque cultivar, while in the Control/Severe comparison, the opposite was observed. At 2.0 mM Si application, the Tumucumaque cultivar ranked 1st for all weight choices, while the other cultivars varied in their positions. Novaera cultivar ranked last for higher weights in the Control/Severe criterion. Conversely, at 4.0 mM Si application, the Novaera cultivar performed significantly better than the other cultivars, regardless of the weight criterion. Tumucumaque cultivar consistently remained in the last position.

Conclusion

In summary, our findings indicate that the selection of cultivars is more influenced by Si levels than by drought treatments. The most successful cultivars at Si concentrations of 0.0, 2.0, and 4.0 mM were Xiquexique, Tumucumaque, and Novaera, respectively. It is worth emphasizing that these results are subject to changes if the weight of the control/severe attribute is significantly greater at a Si concentration of 0.0 mM. Cowpea plants supplied with Si at 1.0 mM exhibits varied positions assigned by TOPSIS, except for Novaera, which consistently ranked 2nd or 3rd. The lack of consistency in these selections is expected, as cultivars respond differently to various concentrations of Si. Thus, the methodology presented here proved to be essential for reliable analysis, assigning greater importance (weight) to a specific type of water stress environment, depending on the climatic conditions and soil of the cultivation. Consequently, our new methodology emerges as a significant tool for a more sustainable agriculture by enabling the selection of cultivars optimized for specific cultivation conditions. Thus, the insights gained from this research offer practical guidance for farmers and stakeholders engaged in agricultural activities in arid regions.

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Data availability statement The data and computational scripts used are available at https://github.com/brunobro/novel-approach-to-cowpea-cultivar-selection

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

References

Aggarwal CC, Hinneburg A, Keim DA (2001) On the surprising behavior of distance metrics in high dimensional space. LNCS, pp 420–34.
Asgher M, Rehaman A, Nazar ul Islam S, Khan NA (2024) Multifaceted roles of silicon nano particles in heavy metals-stressed plants. Environ Pollut 341:122886.
Bao A-K, Wang Y-W, Xi J-J, Liu C, Zhang J-L, Wang S-M (2014) Co-expression of xerophyte *Zygophyllum xanthoxylum* ZxNHX and ZxVP1-1 enhances salt and drought tolerance in transgenic Lotus corniculatus by increasing cations accumulation. Funct Plant Biol 41(2):203
Bhardwaj S, Sharma D, Singh S, Ramamurthy PC, Verma T, Pujari M et al (2022) Physiological and molecular insights into the role of silicon in improving plant performance under abiotic stresses. Plant Soil 486(1):25–43. https://doi.org/10.1007/s11104-022-05395-4
Catsky J (1960) Determination of water deficit in discus cut out from leaf blades. Biol Plant 2(1):76–78
Christian MM, Shimelis H, Laing MD, Tsilo TJ, Mathew I (2022) Breeding for silicon-use efficiency, protein content and drought tolerance in bread wheat (*Triticum aestivum* L.): a review. Acta Agric Scand B Soil Plant Sci 72(1):17–29.
Cooke J, Carey JC (2023) Stress alters the role of silicon in controlling plant water movement. Funct Ecol 37(12):2985–2999
Cooper M, Messina CD (2023) Breeding crops for drought-affected environments and improved climate resilience. Plant Cell 35(1):162–186
Costa MG, de Mello PR, Palaretti LF, de Souza Júnior JP (2024) The effect of abiotic stresses on plant C:N:P homeostasis and their mitigation by silicon. Crop J 12(2):340–353
de Leite WS, de Miranda RS, de Rocha MM, Dutra AF, Santos AS, da Silva AC et al (2023) Silicon alleviates drought damage by

increasing antioxidant and photosynthetic performance in cowpea. J Agron Crop Sci 209(6):772–787.
de Miranda RS, de Souza FIL, Alves AF, de Souza RR, Mesquita RO, Ribeiro MID et al (2021) Salt-acclimation physiological mechanisms at the vegetative stage of cowpea genotypes in soils from a semiarid region. J Soil Sci Plant Nutr 21(4):3530–3543.
de Oliveira BR, Duarte MAQ, Zuffo AM, Steiner F, Aguilera JG, Dutra AF et al (2024) Selection of forage grasses for cultivation under water-limited conditions using Manhattan distance and TOPSIS. PLoS ONE 19(1):e0292076
Silva DC da, Melo AS de, Melo YL, Andrade WL de, Lima LM de, Santos AR (2019) Silicon foliar application attenuates the effects of water suppression on cowpea cultivars. Ciência e Agrotecnol, 43.
Silva WJ dos, Alcântara Neto F de, Al-Qahtani WH, Okla MK, Al-Hashimi A, Vieira PF de et al (2022) Yield of soybean genotypes identified through GGE biplot and path analysis. PLoS One 17(10):e0274726.
El-Beltagi HS, Alwutayd KM, Rasheed U, Sattar A, Ali Q, Alharbi BM et al (2024) Sole and combined foliar application of silicon and putrescine alleviates the negative effects of drought stress in maize by modulating the morpho-physiological and antioxidant defence mechanisms. Plant Soil Environ 70(1):26–39. https://doi.org/10.17221/423/2023-PSE.html
Ferreira DF (2019) Sisvar: a computer analysis system to fixed effects split plot type designs. Rev Bras Biom 37(4):529–535
Gupta A, Rico-Medina A, Caño-Delgado AI (2020) The physiology of plant responses to drought. Science (1979) 368(6488):266–269.
Huang A (2008) Similarity measures for text document clustering. NZCSRSC 2008:49–56
Irfan M, Maqsood MA, Rehman H ur, Mahboob W, Sarwar N, Hafeez OBA et al (2023) Silicon nutrition in plants under water-deficit conditions: overview and prospects. Water (Basel) 15(4):739.
Jayawardhane J, Goyali JC, Zafari S, Igamberdiev AU (2022) The response of cowpea (*Vigna unguiculata*) plants to three abiotic stresses applied with increasing intensity: hypoxia, salinity, and water deficit. Metabolites 12(1):38
Khan MIR, Khan NA, Sofo A, Siddique KHM (2023) Beneficial elements in plants: developing resilience under stressful environments. Plant Soil 486(1–2):1–5
Korndörfer GH, Pereira HS, Nolla A (2004) Análise de silício no solo, planta e fertilizantes. Uberlândia: UFU.
Kumari A, Lakshmi GA, Krishna GK, Patni B, Prakash S, Bhattacharyya M et al (2022) Climate change and its impact on crops: a comprehensive investigation for sustainable agriculture. Agronomy 12(12):3008
Leite MRL, Alcântara Neto F de, Dutra AF, Mendes LW, Miranda RS de, Melo VMM et al (2024) Distinct sources of silicon shape differently the rhizospheric microbial community in sugarcane. Appl Soil Ecol 193:105131.
Luiz Piati G, Ferreira Lima S de, Lustosa Sobrinho R, Santos OF dos, Vendruscolo EP, Oliveira JJ de et al (2023) Biostimulants in corn cultivation as a means to alleviate the impacts of irregular water regimes induced by climate change. Plants 12(13):2569.
Mantovani A (1999) A method to improve leaf succulence quantification. Braz Arch Biol Technol 42(1):9–14
Melo FB, Cardoso MJ, Salviano AAC (2005) Soil fertility and fertilization. In: Freire-Filho FR, Lima JAA, Ribeiro VQ (eds) Cowpea: technological advances, 1st edn. Embrapa Meio-Norte, Brasília-DF, pp 229–242
Mir RA, Bhat BA, Yousuf H, Islam ST, Raza A, Rizvi MA et al (2022) Multidimensional role of silicon to activate resilient plant growth and to mitigate abiotic stress. Front Plant Sci, p 13.
Mostofa MG, Rahman MdM, Ansary MdMU, Keya SS, Abdelrahman M, Miah MdG et al (2021) Silicon in mitigation of abiotic stress-induced oxidative damage in plants. Crit Rev Biotechnol 41(6):918–934.
Mushtaq N, Altaf MA, Ning J, Shu H, Fu H, Lu X et al (2024) Silicon improves the drought tolerance in pepper plants through the induction of secondary metabolites, GA biosynthesis pathway, and suppression of chlorophyll degradation. Plant Physiol Biochem 214:108919
Oliveira de BR, Zuffo AM, Aguilera JG, Steiner F, Ancca SM, Flores LAP et al (2022) Selection of soybean genotypes under drought and saline stress conditions using manhattan distance and TOPSIS. Plants 11(21):2827. Available from: https://www.mdpi.com/2223-7747/11/21/2827/htm
Puppe D, Kaczorek D, Stein M, Schaller J (2023) Silicon in plants: alleviation of metal(loid) toxicity and consequential perspectives for phytoremediation. Plants 12(13):2407. Available from: https://www.mdpi.com/2223-7747/12/13/2407/htm
Rea RS, Islam MR, Rahman MM, Nath B, Mix K (2022) Growth, nutrient accumulation, and drought tolerance in crop plants with silicon application: a review. Sustainability 14(8):4525.
Rizwan M, Ali S, Ibrahim M, Farid M, Adrees M, Bharwana SA et al (2015) Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: a review. Environ Sci Pollut Res 22(20):15416–15431
Rodrigues Maia F (2023) Cowpe bean production—(*Vigna unguiculata* (l.) walp). A drought-resistant plant is very common in regions of the Brazilian semi-arid. J Interdisciplinary Debates 4(04):242–263.
Saja-Garbarz D, Libik-Konieczny M, Janowiak F (2024) Silicon improves root functioning and water management as well as alleviates oxidative stress in oilseed rape under drought conditions. Front Plant Sci 15:1359747.
Shafi S, Shafi I, Zaffar A, Zargar SM, Shikari AB, Ranjan A et al (2023) The resilience of rice under water stress will be driven by better roots: evidence from root phenotyping, physiological, and yield experiments. Plant Stress 10:100211
Souri Z, Khanna K, Karimi N, Ahmad P (2021) Silicon and plants: current knowledge and future prospects. J Plant Growth Regul 40(3):906–925
Teixeira GCM, de Prado RM, Rocha AMS, de Oliveira Filho ASB, da Sousa Junior GS, Gratão PL (2022) Action of silicon on the activity of antioxidant enzymes and on physiological mechanisms mitigates water deficit in sugarcane and energy cane plants. Sci Rep 12(1):17487
Wang M, Wang R, Mur LAJ, Ruan J, Shen Q, Guo S (2021) Functions of silicon in plant drought stress responses. Hortic Res 8(1):254
Wellburn AR (1994) The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. J Plant Physiol 144(3):307–313
Yadav V, Karmakar S, Kalbar PP, Dikshit AK (2019) PyTOPS: a python based tool for TOPSIS. SoftwareX 9:217–222