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Selenium treatment enhances the germination and growth of corn seedlings

El tratamiento con selenio mejora la germinación y el crecimiento de las plántulas de maíz

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ABSTRACT

The germination process and early seedling development are crucial phases in the plant life cycle, and optimal germination can contribute significantly to crop yields. Selenium (Se) is an essential micronutrient for many organisms and performs a critical role in improving seed germination and early seedling growth. Seed priming is a promising alternative to other forms of seed treatment, with the potential to improve seed germination and seedling quality. This study investigated the effects of seed priming on the germination and seedling development of two native corn varieties in Mexico using different Se treatments. Five Se concentrations (0, 25, 50, 75, and 100 µM L^{-1}) were tested. The results showed that the Se concentrations of 50 and 75 µM L^{-1} had a notably positive effect on several germination and morphological variables, including germination percentage, germination rate, germination potential, and the germination velocity coefficient. However, the Se concentration of 100 µM L^{-1} consistently produced lower germination rates, indicating an adverse effect on the germination process and initial seedling development.

KEY WORDS: Germination, creole corn, small-scale farmers, selenium treatment, morphological variables.

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RESUMEN

El proceso de germinación y el desarrollo temprano de las plántulas son fases cruciales en el ciclo vital de las plantas, y una germinación óptima puede contribuir significativamente al rendimiento de los cultivos. El selenio (Se) es un micronutriente esencial para muchos organismos y desempeña un papel fundamental en la mejora de la germinación de las semillas y el crecimiento temprano de las plántulas. La imprimación de semillas es una alternativa prometedora a otras formas de tratamiento de semillas, con el potencial de mejorar la germinación de las semillas y la calidad de las plántulas. Este estudio investigó los efectos de la imprimación de semillas en la germinación y el desarrollo de plántulas de dos variedades de maíz nativo de México utilizando diferentes tratamientos con Se. Se probaron cinco concentraciones de Se (0, 25, 50, 75 y 100 µM L^{-1}). Los resultados mostraron que las concentraciones de Se de 50 y 75 µM L^{-1} tuvieron un efecto notablemente positivo sobre varias variables de germinación y morfológicas, incluyendo el porcentaje de germinación, la tasa de germinación, el potencial de germinación y el coeficiente de velocidad de germinación. Sin embargo, la concentración de Se de 100 µM L^{-1} produjo sistemáticamente tasas de germinación más bajas, lo que indica un efecto adverso sobre el proceso de germinación y el desarrollo inicial de las plántulas.

PALABRAS CLAVE: Germinación, maíz criollo, pequeños agricultores, tratamiento con selenio, variables morfológicas.

Introduction

Corn (*Zea mays*) has been Mexico's most important staple food for thousands of years and is deeply rooted in the country's culture and traditions (Eagles & Lothrop, 1994; Pierre *et al*., 2021). Corn is grown on millions of hectares of land throughout the country as a grain crop, forage corn, and popcorn, making it a critical source of income, particularly for small-scale farmers (Nawaz *et al.,* 2021). Creole corn is appreciated for its unique flavor, texture, and aromas, which differentiate it from other types of corn, and for the nutritional quality it provides (Domínguez-Hernández *et al*., 2022; Gaxiola-Cuevas *et al.,* 2017). Furthermore, landrace varieties tend to be more resistant to pests and diseases than commercial varieties.

In Mexico, 76.5 % of farmers use landrace seeds for cultivation (Diédhiou *et al*., 2021) and there are more than 61 endemic breeds (Arias *et al*., 2007). Native corn has significant productive potential due to its capacity for environmental adaptation. However, one disadvantage of native corn is a loss of seed viability due to inadequate post-harvest handling during seed storage, when seeds can be exposed to a range of environmental conditions (Odjo *et al*., 2022). Germination

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and seedling development are critical stages in the life cycle of a plant. Therefore, it is crucial to ensure germination and the development of good-quality seedlings as this promotes better crop performance (Nciizah *et al*., 2020).

Selenium (Se) is a micronutrient that is essential for many organisms. Although Se is not an essential element for plants, it is considered beneficial in trace amounts (Bano *et al*., 2021). Selenium has a significant impact on germination and seedling development in the early stages of ontogenesis and can stimulate plant growth (Adhikary *et al.,* 2022). Furthermore, Se is involved in several physiological and biochemical processes, such as antioxidant defense, photosynthesis, and osmotic regulation. While Se is beneficial in small amounts, it can be toxic to plants in excess (Gupta & Gupta, 2016).

Recent studies have demonstrated an increasing interest in understanding the impact of Se on seedling growth across various crops. León-Morales *et al.* (2019) investigated different Se concentrations (1.25, 2.5, and 5.0 µM) on serrano pepper (*Capsicum annuum*) and radish (*Raphanus sativus*) seedlings and showed that the Se treatments improved serrano pepper germination compared to the control. Similarly, Hu *et al.* (2022) investigated the effects of sodium selenite concentrations (0, 30, and 60 µmol L^{-1}) on rice seedling growth over 10 and 18 days. While increasing the Se concentration produced positive effects on the shoot and root lengths and dry biomass of the seedlings initially, by day 18, a concentration of 60 µmol L^{-1} resulted in reduced seedling dry biomass. In another study, Nawaz *et al*. (2021) immersed hybrid corn seeds in 0.075 mM Se for 12 h and 24 h to evaluate the effects on seedling germination and chlorophyll content. The results showed a significant increase in germination percentage (38 %) and emergence speed (42 %) in seeds treated with Se for 24 h compared to those treated with distilled water for the same period. However, no significant differences in the chlorophyll content of the corn seedlings were observed between the different Se treatments.

It is important to highlight that the effects of Se on the germination, growth, and development of plants are influenced by Se concentration and exposure time and that these effects can vary significantly between different plant species. Therefore, further research must be undertaken to determine the optimal dose of Se for native corn varieties and to fully understand the possible benefits of corn germination. Related to this, seed priming has emerged as an interesting alternative to other forms of seed treatment, with the potential to improve germination and seedling quality. Therefore, the objective of this study was to evaluate whether Se priming treatment had a positive effect on germination and seedling development in native corn.

Material and Methods

Study area

The experimental work was conducted at the research facilities of the Academic Division of Agricultural Sciences at the Juárez Autonomous University of Tabasco, Mexico. The study site was geolocated at 17° 47′ N, 92° 57′ W and was situated at an altitude of 29 m above sea level.

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Seed selection

Two corn landraces of the "Mejen" breed from the Mexican state of Tabasco were evaluated: one was a yellow variety, and the other was a white variety. The seeds were collected during the autumn–winter period in 2022 in the community of Tamulté de las Sabanas, Centro, Tabasco (located at 18° 09′ 30″ N, 92° 47′ 00″ W and situated at an altitude of 10 m above sea level). The seeds were stored in plastic bottles following the typical conservation practices of the local seed producers. Each batch of seeds used in the study was selected manually using the criteria adopted by the local producers, which favored seeds of greater size and uniformity and healthy seeds with no malformation and an absence of physical damage (Magdaleno-Hernández *et al*., 2016).

Seed treatments, germination, and growth conditions

The seeds were sown in bench-type germination trays containing 49 cavities and had dimensions of 37 x 37 cm and a cone height of 18 cm. Clay loam soil was used, with a water retention capacity of 300 mL kg^{-1} and a permanent wilting point of 18.60 mL kg^{-1}. The chemical characteristics of the soil were as follows: pH = 5.36, electrical conductivity (EC) = 181 μS/cm, and organic matter = 5.11 %.

The experimental design was completely randomized with three repetitions in a 2 x 5 factorial arrangement, comprising two varieties of corn (yellow and white) and five Se concentrations in the form of reactive grade sodium selenate (≥ 98.0 % Na_2SeO_4). The five Se concentrations were as follows: 0 μM L^{-1} (Se-0) (control group), 25 μM L^{-1} (Se-25), 50 μM L^{-1} (Se-50), 75 μM L^{-1} (Se-75), and 100 μM L^{-1} (Se-100) (Table 1). These doses were selected based on previous studies by Nawaz *et al*. (2013).

Seeds were disinfected with 5.0 % sodium hypochlorite for 10 min, rinsed with distilled water for five times, and then air-dried for 2 h before priming with selenium. 100 g of seeds were placed in 200 mL of each treatment and in distilled water for controls. Seeds were kept in imbibition for 12 h, subsequently immersed in distilled water for 20 min, and rinsed five times (Adhikary *et al*., 2022) then two seeds per cavity were sown.

Table 1. Description of the selenium-soaked seed treatments

Treatments	Varieties	Na_2SeO_4 (μM L^{-1})
T1	Yellow	0
T2	Yellow	25
T3	Yellow	50
T4	Yellow	75
T5	Yellow	100
T6	White	0
T7	White	25
T8	White	50
T9	White	75
T10	White	100

Measurement of the germination rates

Measurement of the germination rates was carried out using a daily count and ended seven days after sowing (DAS) when no germination was observed. The germination percentage (%G), germination rate (GR), mean emergence time (MET), velocity coefficient (VC), and mean daily germination (MDG) were evaluated according to Kader (2005). The germination potential (GP) (Sun *et al.,* 2021) and seedling vigor index (SVI) were determined according to Abdul-Baki & Anderson (1973), while the promptness index (PI) and germination stress index (GSI) were calculated using the formula reported by Abdi *et al.* (2016).

Equation 1. $\text{Germination percentage} = \frac{n}{N} * 100$

where *n* is the total number of germinated seeds and *N* is the total number of seeds in the sample.

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Equation 2. $\text{Germination rate} = \frac{\Sigma ti * ni}{\text{Days to final germination}}$

where *ni* is the number of recently germinated seeds and *ti* is the number of days since sowing.

Equation 3. $\text{Germination potential} = = \frac{a}{N} * 100$

where *a* is the number of seeds germinated after three days and *N* is the total number of seeds in the sample.

Equation 4.

$$\text{Mean emergence time} = \frac{\Sigma\ (\text{plants emerged in one day})*(\text{days after planting})}{\text{Total plants emerged}}$$

Equation 5. $\text{Velocity coefficient} = \frac{\Sigma ni}{\Sigma(ni * ti)}$

where *ni* is the number of seeds germinated per day and *ti* is the number of days elapsed since sowing.

Equation 6. $\text{Mean daily germination} = \frac{(\%\ \text{germination})}{(\text{Days to final germination})}$

Equation 7. $\text{Seedling vigor index} = \%\ \text{germination} * \text{seedling length (root + stem)}$

Equation 8. $\text{Promptness index} = \text{nd1}(1.0) + \text{nd2}(0.75) + \text{nd3}(0.5) + (\text{nd4}(0.25)$

where, *nd1*, *nd2*, *nd3*, and *nd4* are the number of seeds germinated on the fourth, fifth, sixth, and seventh days after sowing, respectively.

Equation 9. $\text{Germination stress index} = \frac{(\text{PI stressed seeds})}{(\text{PI control seeds})} * 100$

Morphological variables and SPAD units

Morphological variables were measured at 15 DAS. The number of visible primary and secondary roots was counted (RN), root length (RL) was measured from root collar to root tip, stem length (SL) was measured from root collar to the apex of the last leaf, and root fresh weight (RFW) and stem fresh weight (SFW) were measured in situ using a portable electric scale. The leaf greenness index (SPAD) was measured using a portable SPAD-502 chlorophyll meter (Konica Minolta Inc., Japan).

Data analysis

Duncan's multiple range test was used to analyze variance and compare the means of the variables at a probability level ≤ 0.05. In addition, possible correlations between germination and growth variables were evaluated. Pearson's correlation coefficients (r) were statistically evaluated using a t-test. These analyses were performed using Statgraphics Centurion XVI (StatPoint Technologies Inc., USA).

Results

Germination in the two corn varieties

Germination from seeds of two varieties of selenium-soaked corn was investigated. Germination began on the third day, with maximum germination obtained seven days after sowing the two landraces (Figure 1). For the white corn variety (Figure 1a), the largest %G (92.86 %) was obtained with Se treatments Se-25, Se-50, and Se-75, while for the yellow corn variety (Figure 1b), the largest %G (95.24 %) was produced with treatment Se-50, followed by treatment Se-25 (8.71 %).

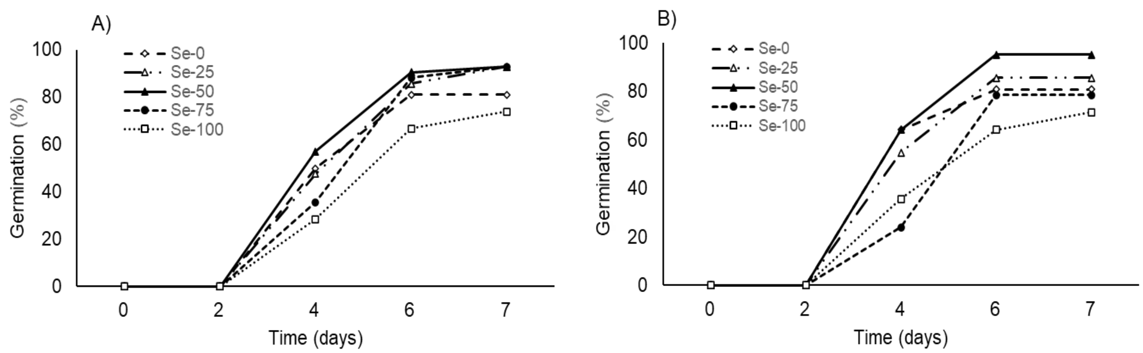

Figure 1. Seed germination percentage of two native corn varieties soaked with selenium. A). White corn, B). Yellow corn.

In relation to the %G by landrace, the white corn variety produced a marginally higher value (86.67 %) than the yellow corn variety (82.38 %); however, no significant differences were observed (Table 2). The yellow corn variety exhibited a substantially higher GP compared to the white corn variety, producing a germination rate of 35.80 %. This marked difference underlined the different germination capacities of the two corn varieties under experimental conditions.

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There were no significant statistical differences ($p \leq 0.05$) in %G, GR, VC, MDG, and PI between the two landraces (Table 2). However, the results showed a significant difference in MET ($p \leq 0.05$). Yellow corn emerged more quickly, averaging 3.97 days, while white corn took an average of 4.51 days to emerge. The GP of the yellow corn (23.81 %) was higher than that of the white corn (37.14 %). Applying Se to seeds can induce germination but can also cause stress due to exposure to a chemical element. The GSI for the white corn variety (81.27 %) surpassed that of the yellow corn variety by 36.8 %. This index demonstrated that the white corn seeds showed superior germination under stress conditions, indicating that they possessed greater resilience in challenging field environments. This indicator is crucial in the selection of high-quality seeds for agriculture as it helps identify varieties with greater potential for survival and growth in more adverse conditions.

Table 2. Germination rates in two varieties of corn soaked with selenium

Treatments	G (%)	GR	GP (%)	MET (days)	VC	MDG	PI	GSI (%)
Corn varieties								
White	86.67 a	8.97 a	23.81 b	4.51 a	0.58 a	14.34 a	6.42 a	81.27 a
Yellow	82.38 a	8.43 a	37.14 a	3.97 b	0.69 a	15.36 a	6.83 a	51.30 b
Selenium doses (μM L^{-1})								
0	80.95 c	8.88 ab	27.38 ab	3.98 b	0.75 a	15.99 a	9.25 a	73.26 ab
25	89.29 ab	9.28 ab	29.76 ab	4.32 ab	0.65 a	15.49 a	7.79 ab	84.30 a
50	94.05 a	9.80 a	35.71 a	4.18 ab	0.73 a	16.89 a	6.33 bc	67.81 ab
75	85.71 bc	8.44 b	38.10 a	4.09 ab	0.61 a	14.75 a	4.88 c	53.24 b
100	72.62 d	7.10 c	21.43 b	4.62 a	0.42 b	11.12b	4.88 c	52.82 b
Corn x selenium interaction								
White-0	80.95 bc	8.86 bcd	7.14 d	4.36 ab	0.61 abc	14.37 bc	8.92 a	-
White-25	92.86 a	10.08 ab	19.05 cd	4.65 a	0.65 ab	15.83 abc	7.67 ab	85.98 b
White-50	92.86 a	8.78 bcd	42.86 a	4.33 ab	0.57 bc	14.74 bc	4.42 c	49.53 de
White-75	92.86 a	9.41 abc	28.57 abc	4.59 a	0.57 bc	14.74 bc	6.08 bc	68.22 bcd
White-100	73.81 c	7.63 de	21.43 bcd	4.64 a	0.48 bc	12.04 cd	5.00 c	56.07 cde
Yellow-0	80.95 bc	8.90 bcd	47.62 a	3.61 b	0.89 a	17.62 ab	9.58 a	-
Yellow-25	85.71 ab	8.48 cd	40.48 ab	4.00 ab	0.64ab	15.16 bc	7.92 ab	82.61 bc
Yellow-50	95.24 a	10.73 a	28.57 abc	4.03 ab	0.89 a	19.05 a.	8.25 ab	86.09 b
Yellow-75	78.57 bc	7.47 de	47.62 a	3.60 b	0.66 ab	14.76 bc	3.67 c	38.26 e
Yellow-100	71.43 c	6.57 e	21.43 bcd	4.60 a	0.36 c	10.20 d	4.75 c	49.57 de

G= germination; GR= germination rate; GP= germination potential; MET= mean emergence time; VC= velocity coefficient; MDG= mean daily germination; PI= promptness index; GSI= germination stress index. Different letters within the same column indicate a significant difference between treatments at the $p < 0.05$ level with Duncan's test.

Effects of selenium levels on corn germination

Statistical differences ($p \leq 0.05$) were observed in all of the variables analyzed in response to the different Se concentrations. The Se treatment Se-50 produced the largest %G (94.05 %), followed by the Se-25 treatment (89.29 %). In contrast, a Se concentration of 100 µM L^{-1} (Se-100) inhibited germination and produced the lowest %G, which was lower than that of the control treatment (Se-0). Thus, it was shown that the lower Se concentrations benefitted germination and outperformed the control treatment (Table 2).

In relation to MET, the control group produced a quicker response than the Se treatments, with a germination time of 3.98 days. In particular, the Se treatment Se-100 yielded an emergence time of 4.62 days, indicating that the presence of Se prolonged the time needed for the seeds to germinate. In terms of the VC, the values ranged between 0.42 and 0.75. The Se doses Se-0 (control) and Se-50 produced the largest number of germinated seeds per day but did not show significant differences.

In terms of MDG, the Se treatment Se-100 produced the smallest number of germinated seeds per day, while the treatment Se-50 yielded the largest number of seeds germinated each day. The PI values ranged between 4.88 and 7.25, with the control treatment (Se-0) having the largest value, while Se doses Se-75 and Se-100 produced the smallest values. In relation to the GSI, Se treatments Se-0, Se-25, and Se-50 produced the largest percentages at 73.26 %, 84.30 %, and 67.87 %, respectively. The Se doses Se-75 and Se-100 produced the smallest stress values.

Interaction of selenium with the corn during germination

As described previously, the %G in the white corn and yellow corn varieties were 92.86 % (Se-25, Se-50, and Se-75) and 95.24 % (Se-50), respectively. However, when exposed to the maximum Se concentration (100 µM L^{-1}), the %G in both the white and yellow corn varieties reduced to 73.81 % and 71.43 %, respectively. This indicated that excessive concentrations of Se adversely affected germination regardless of the corn variety. Moreover, when assessing germination potential, the study found that the white corn Se-50 and yellow corn Se-0 and Se-75 treatments produced the most beneficial results, with germination rates of 42.86 %, 47.62 %, and 47.62 %, respectively (Table 2). These specific findings may improve the GP of corn, particularly in the yellow corn variety.

The white and yellow corn seeds responded differently to Se treatment with respect to several germination-related parameters. The MET for the yellow corn Se-0 and Se-75 treatments was 3.61 and 3.60 days, respectively, while the white corn Se-100 and Se-25 treatments produced the longest emergence times of 4.64 and 4.65 days, respectively.

In relation to the VC, the yellow corn Se-0 and Se-50 treatments produced the largest value (0.89), while the yellow corn Se-100 and white corn Se-100 treatments yielded the smallest

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values of 0.36 and 0.48, respectively. In terms of MDG, the white corn Se-25 and yellow corn Se-0 and Se-50 treatments produced the largest number of seeds germinated in a single day, with 15.83, 17.62, and 19.05 germinated seeds, respectively. In contrast, the yellow corn Se-100 and white corn Se-100 treatments produced the smallest number of germinated seeds in a day, at 10.20 and 12.04 seeds, respectively.

The GSI was largest in the yellow corn Se-25, white corn Se-25, and yellow corn Se-50 treatments, with values of 82.61 %, 85.98 %, and 86.09 %, respectively, which indicated a higher level of Se tolerance. In contrast, yellow corn treatments Se-75 and Se-100 and white corn treatment Se-50 yielded the smallest response to Se. With respect to the yellow corn Se-100 treatment, the study showed that when this corn variety was exposed to a high concentration of Se, germination was inhibited and prolonged, which was indicative of the stressful effect of Se on the germination process.

Corn seedling development variables and units SPAD

Main effects on the two corn varieties

Morphological variations in seedlings are important indicators for evaluating crop development and performance, diagnosing developmental problems, supporting appropriate management decision-making, and selecting the most promising varieties. Thus, the effects of soaking corn seeds in Se treatments on root and seedling growth variables were determined (Table 3).

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Table 3. Morphological variables of seedlings of two native varieties of corn

Treatments	RN	RL (cm)	RFW (mg)	SL (cm)	SFW (mg)	SVI	SPAD
Corn varieties							
White	9.13b	23.99 a	1490.23 a	8.64 b	969.61 a	2820.33 a	37.29 a
Yellow	9.93 a	24.42 a	1293.25 a	9.91 a	983.52 a	2825.14 a	32.63 b
Selenium dose (µM L^{-1})							
0	8.00b	20.90 d	1499.78 ab	7.18c	831.43 b	2273.45 d	28.83d
25	9.67 a	25.52 b	1639.08 a	9.42 b	1186.77 a	3110.71 ab	36.58 b
50	10.17 a	23.85 c	1298.28 ab	9.48 b	1146.67 a	3136.90 a	39.05 a
75	10.33 a	23.33c	1393.08 ab	10.20 a	914.30 b	2865.24 bc	36.13 b
100	9.50 a	27.43 a	1128.45 b	10.10 ab	803.67 b	2727.38 c	34.20 c
Corn x selenium interactions							
White-0	6.33 b	19.17 g	1068.30 b	7.17 d	863.07 b	2131.67 e	29.83 f
White-25	9.33 a	24.67 cd	2052.37 a	8.40 c	1110.90 a	3067.14 ab	36.90 c
White-50	11.00 a	23.87 de	1581.87 ab	8.93 c	1142.20 a	3045.71 ab	39.30 b
White-75	10.00 a	23.03 ef	1522.87 ab	9.37 bc	893.10 b	3008.57 ab	45.53 a
White-100	9.00 a	29.23 a	1225.73 b	9.33 bc	838.80 b	2848.57 abc	34.90 de
Yellow-0	9.67 a	22.63 f	1931.27 a	7.20 d	799.80 b	2415.24 de	27.83 g
Yellow-25	10.00 a	26.37 b	1225.73 b	10.43 a	1262.63 a	3154.29 a	36.27 cd
Yellow-50	9.33 a	23.83 de	1014.70 b	10.03 ab	1151.13 a	3228.10 a	38.80 b
Yellow-75	10.67 a	23.63 def	1263.30 b	11.03 a	935.50 b	2721.90 bcd	26.76 g
Yellow-100	10.00 a	25.63 bc	1031.17 b	10.87 a	768.53 b	2606.19 cd	33.50 e

RN= root number; RL=root length; RFW= root fresh weight; SL= stem length; SFW= stem fresh weight; SVI= seedling vigor index. Different letters within the same column indicate a significant difference between treatments at the $p < 0.05$ level with Duncan's test.

In relation to the RN in the two corn varieties, it was observed that the yellow corn variety had a significantly larger number of roots than the white corn variety—averaging 9.3 roots per plant—although the roots were statistically similar in size. In addition, the yellow corn seedlings had a longer SL 15 DAS, reaching an average of 9.91 cm, while the white corn variety recorded an average SL of 8.64 cm. For the other variables measured, which included RFW, SFW, and SVI, no significant statistical differences were found.

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Effect of selenium on the growth of corn seedlings

In relation to the effects of Se on the RN, variations between 8.0 and 10.33 were observed, with the control group (Se-0) producing the fewest number of roots, while the Se dose Se-75 produced the largest number of roots. With regard to RL, the control group produced the shortest root length (20.90 CM), while the Se treatment Se-100 yielded the longest length (27.43 cm). However, in terms of RFW, the Se-100 treatment produced roots with the smallest fresh weight (1128.45 mg). In terms of SL, a trend of increasing growth was observed as the Se dose increased, with the treatments Se-75 and Se-100 producing the largest growth, with stem lengths of 10.20 cm recorded, while the control group (Se-0) produced the smallest plants (7.18 cm). This pattern was also observed in the SFW, where the control group and the Se-100 treatment produced the smallest fresh weights (Table 3).

In relation to the SVI, the treatments Se-25 and Se-50 produced greater vigor in the seedlings, with values of 3110.71 and 3136.90 recorded, respectively. Therefore, although Se improved root and stem growth in the seedlings, it also reduced root and stem weight. In terms of SPAD units, the Se-50 treatment produced the greenest plants, while the control group (Se-0) yielded plants with lower greenness intensity. Therefore, these results are directly related to the photosynthesis of the plant.

Interaction of selenium with the corn varieties on seedling growth

Selenium is a nutrient that can aid plant development, and how it interacts with different corn varieties can have a significant influence on growth. The results indicated that a lack of Se (Se-0) negatively impacted white corn seedling development, with smaller roots and lower fresh weight produced compared to other treatments. In contrast, the Se-100 treatment produced longer roots in the white corn seedlings, reaching 29.23 cm. In addition, the yellow corn variety treated with 50 µM L^{-1} doses (Se-50) produced the largest number of roots (11.0), indicating a positive response to the presence of Se. Furthermore, in terms of fresh weight, Se-25 yielded the largest root weight (2052.37 mg) in the white corn variety (Table 3). These variations in response between the two corn varieties may be due to their capacity to utilize Se based on the concentration levels present.

There were significant differences ($p \leq 0.05$) in all of the seedling growth variables, with SL varying between 7.17 cm and 11.03 cm. The Se-0 treatment for the white corn variety produced the shortest SL, while the Se-75 treatment for the yellow corn variety yielded the longest SL. In relation to the SFW, the yellow corn Se-100 treatment produced the smallest weight, while the yellow corn Se-25 treatment recorded the largest stem weight. When evaluating the SVI, it was observed that the yellow corn Se-25 and Se-50 treatments produced the largest growth rates, while the white corn Se-0 treatment produced the smallest value, indicating an unfavorable effect on seedling vitality under these conditions. In terms of SPAD units, the white corn Se-75 treatment stood out, producing the largest leaf greenness value of 45.53 units, indicating a higher

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chlorophyll concentration. Conversely, the control treatments (Se-0) in both the yellow and white corn varieties produced the lowest leaf greenness values at 27.83 and 29.83 units, respectively.

Correlation analysis

Pearson correlations between germination and seedling growth variables are presented in Figure 2. Significant ($p \leq 0.05$) and highly positive correlations were observed between %G and the variables VC, GR, MDG, GSI, SFW, SVI, and SPAD. In addition, significant differences and correlations were found between VC and GR, and between VC with MDG and PI. Furthermore, GR showed a positive correlation with MDG, PI, SFW, SVI, and SPAD, while MDG had a positive correlation with PI. The variable GSI was correlated with the variables RL, SFW, SVI, and SPAD. However, SFW and SVI were only positively correlated with SPAD.

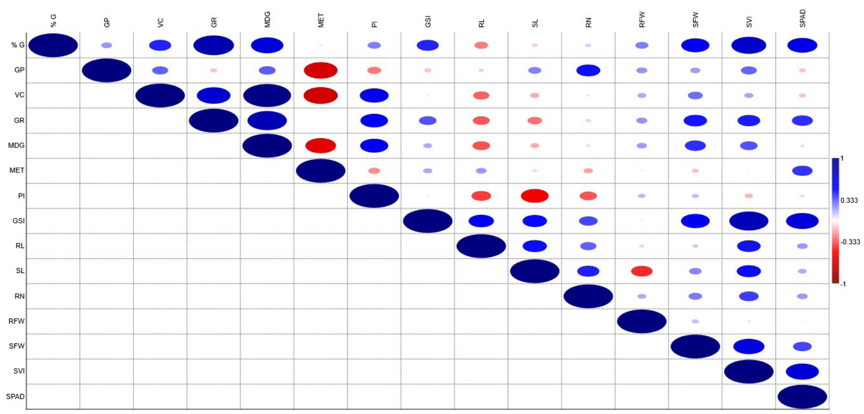

Figure 2. Pearson's correlation.

The larger size and blue color of the circle indicates a positive correlation, while red circles indicate negative correlations between variables.

G= germination; GP= germination potential; VC= velocity coefficient; GR= germination rate; MDG= mean daily germination; MET= mean emergence time; PI= promptness index; GSI= germination stress index, RL=root length; SL= stem length; RN= root number; RFW= root fresh weight; SFW= stem fresh weight; SVI= seedling vigor index, SPAD, related to two varieties of corn (white and yellow) soaked in selenium.

In contrast, significant ($p \leq 0.05$) negative correlations were found between variables, including between GP and VC with MET. In addition, MDG was negatively correlated with MET and RL, while PI showed negative correlations with RL, SL, and RN. Finally, GSI and SL were correlated with SFW.

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Discussion

Effects of the corn varieties on germination

Ensuring optimal germination is essential in agriculture, performing a crucial role in achieving crop uniformity and maximizing crop yields. As stated by Omar *et al*. (2022), when seeds germinate at different rates or exhibit different degrees of vigor, disparities in plant size and maturity can occur, thus complicating harvesting and reducing yield.

According to Aristizábal & Álvarez (2006), seeds with a GR greater than 80 % can be considered high germination, while seeds with a rate between 60 % and 80 % are medium germination and seeds with a rate below 60 % are low germination. In this context, both corn varieties investigated in this study were in the high germination category. Having access to high-quality seeds, in terms of high germination rates, is essential to crop performance and agricultural sustainability (Elias *et al.,* 2012). This highlights the importance of high-quality seeds to food security and sustainable development.

In relation to VC, the results reported in this study are similar to those reported by Escobar-Álvarez *et al.* (2021), who reported VC values ranging from 0.35 to 0.71 in four varieties of Creole corn from Guerrero, Mexico. With respect to MET, the results from this study align with those reported by Mejía-Ramírez *et al.* (2019), who recorded the emergence of four varieties of corn within a range of 4 to 5 DAS. Laynez-Garsaball *et al.* (2007) reported METs of 3.9 and 4.2 days for two improved varieties of corn. Mean emergence time is a crucial measure in agriculture as varieties with a higher emergence percentage in a shorter timeframe are more favorable (Imran *et al.,* 2013). Prompt emergence of seedlings promotes better aerial and root development, promoting crop establishment. In addition, this provides valuable information on the vigor and uniformity of seed germination, which can significantly influence crop establishment and yield.

The GSI is a crucial factor in selecting high-quality seeds. It allows for the identification of varieties with greater potential for survival and growth in adverse environments, such as those with greater resistance to salinity, drought, or edaphoclimatic conditions (Hernández-Avera *et al*., 2015). In this study, the germination capacities of two native corn varieties were evaluated, and a favorable response was observed. Espinosa-Paz *et al.* (2017) conducted a study on drought-stressed areas in Mexico and found that landrace corn varieties, including Olotillo, Azul, Amarillo, Tuxpeño, Jarocho, and Rocamex, exhibited greater tolerance to stress during germination. These varieties are important due to their ability to survive and produce in soils with limited organic matter, nitrogen, and other nutrients. The cultivation of stress-tolerant landraces can significantly contribute to food security in regions prone to adverse climatic conditions. In addition, these local varieties can play a key role in genetic improvement programs aimed at developing crops that are more resistant to drought and other types of environmental stress.

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Effects of selenium dose on corn germination

The improvement in seed germination observed in this study could be attributed to the ability of Se to increase water absorption and enhance the activity of enzymes involved in the germination process. Several authors (Al-Omairi & Al-Hilfy, 2021) have obtained similar results. While they showed that two Se doses applied to two corn varieties produced comparable germination percentages, the largest Se dose (5 mg L^{-1}) resulted in slightly lower germination percentages in both corn varieties (although it was larger than that in the control group). In the current study, the high Se concentrations (100 µM L^{-1}) limited germination in the two corn varieties, which was possibly related to a decrease in the enzymatic activity responsible for the hydrolysis of metabolites essential for embryonic development (Khaliq *et al*., 2015). Furthermore, León-Morales *et al.* (2019) conducted a study on the germination of chili (*Capsicum annuum* L.) using selenite and sodium selenate. They found that concentrations of 1.25, 2.5, and 5 µM L^{-1} of both Se compounds promoted higher germination rates than in the control group. In contrast, Ahmed (2010) found that the germination of lettuce, tomato, and radish seeds decreased as the Se concentration increased (0 to 200 ppm Na_2SeO_4). These results are consistent with the current study, where it was observed that Se concentrations of 100 µM L^{-1} inhibited germination in the two corn varieties.

The MET obtained in this study was similar to that reported by Hu *et al.* (2022), who demonstrated accelerated seed germination and increased emergence rates in rice seeds by priming with Se doses of 0, 30, and 60 µM L^{-1}. Similarly, Khaliq *et al.* (2015) reported a decrease in MET in two rice cultivars when exposed to concentrations of 45 µM L^{-1} and 60 µM L^{-1} of sodium selenite.

Regarding the RI and GSI, research has shown that pretreatment with Se modulates physiological indices and the antioxidant machinery, improving tolerance to drought stress in corn (Nawaz *et al.,* 2021). In addition, the efficacy of seed priming with Se during germination in rice under arsenic stress has been demonstrated, with the addition of Se significantly reducing grain arsenic content (Moulick *et al.*, 2016). Therefore, the basic mechanisms behind the beneficial effects of Se in plants are associated with the ability of this element to modulate the antioxidant machinery, consequently increasing plant tolerance to stress induced by abiotic factors (Hawrylak-Nowak *et al.,* 2018).

Morphological variables of the seedlings of the two corn varieties

Variables relating to root and seedling development provide important information on the growth and health of corn seedlings, which is crucial for evaluating their adaptability and performance in different conditions. Studies have shown that the fresh weight of the stem and radicle, as well as the ratio of seedling height to root length, are important indicators of corn seedling development (Laynez-Garsaball *et al.,* 2007).

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The current study showed slightly higher SL values than those reported by Bolívar *et al.* (2007), who reported an average SL of 10.41 cm eight days after sowing in open fields for nine varieties of corn in Venezuela. Similarly, Pérez-Mendoza *et al.* (2020) obtained similar SLs for two hybrid corn varieties, H-80E (9.35 cm) and HV-65 (9.05 cm), which were superior to the hybrid H-159E (6.23 cm). Regarding RL, the results of the current study were slightly larger (24.20 cm) than those reported by Pérez-Mendoza *et al.* (2020), who obtained an average of 20.28 cm. These differences in seedling development can be attributed to the biochemical processes and enzymatic reactions that take place during the germination process, which is reflected in the growth and uniformity of the seedlings (Ruiz-Torres *et al.,* 2012).

The SVI of the two corn varieties investigated in this study was 2,820.33 and 2,825.00 for the white corn and yellow corn, respectively. This was higher than the indices reported by Pérez-Mendoza *et al.* (2020), which ranged from 1,342.2 to 2,265.1. The SVI is an important parameter for estimating seed quality, which is then reflected in the quality of the seedlings (Rodríguez-Guilón *et al.,* 2008).

The SPAD units provide values that indicate the intensity of the green color in a leaf and correspond to its chlorophyll concentrations (Brewer *et al.,* 2022). A comparison of the SPAD units showed that the white corn variety had a greater green color intensity than the yellow corn variety. This finding indicated that the white corn variety had a higher chlorophyll content or better photosynthetic efficiency (Martínez & Guiamet, 2004). However, it is important to consider the potential influence of environmental factors on SPAD readings when interpreting these results.

Effect of selenium dose on the growth of the corn seedlings

In terms of the effect of Se dose on the growth of corn seedlings, the findings of the current study are consistent with those of several previous studies. For example, Lin-Xuan *et al*. (2023) observed an increase in RN and RL at medium Se doses (15 and 30 mg L^{-1}) in *Sophora tonkinensis* plants. Similarly, León-Morales *et al*. (2019) noted a significant increase in chili root length in Se treatments, recording almost double the amount of growth compared with the control plants. Furthermore, the results of Hu *et al.* (2022) support this pattern, reporting an increase in the length and dry weight of shoots and roots of rice treated with different Se doses. Other studies have indicated that the stimulation of root growth could be associated with the activation of cellular respiration and nutrient cycling during the initial seed treatment (Vázquez-Ramos & de la Paz-Sánchez, 2003), which confirms the crucial role of Se in root production and growth. The interaction between Se concentrations and different corn varieties can have a significant impact on the number of plant roots. However, understanding the factors that regulate the accumulation and distribution of Se in crop plants is crucial for improving plant growth and development (Pinzon-Nuñez *et al.*, 2023). The findings of the current study on stem growth were consistent with those of Nawaz *et al.* (2013). At higher Se concentrations (100 µM L^{-1}), no impact on seedling growth was observed; as such, Se improved plant-water relations by reducing the osmotic potential of seedlings growing under stress.

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Although Se improved seedling root and stem growth, a reduction in root and stem weight was also observed. This concurs with the notion presented by Nishiuchi *et al.* (2012), who proposed that shoot elongation could consume more nutrients from the endosperm, thus reducing seedling weight. In addition, it is known that improvements in the growth and development of seedlings treated with micronutrients allows greater accessibility to these minerals in the seeds. These minerals are essential for the synthesis of proteins and enzymes that are responsible for the efficient utilization of other soil nutrients in seedlings, which consequently improves seed germination and seedling establishment (Nciizah *et al*., 2020).

Thus, it can be inferred that soaking corn seeds in Se can have a selective impact on certain morphological aspects of the seedlings, highlighting the importance of considering not only intraspecific variations but also specific management conditions and genetic interactions. Previous studies have shown that the addition of Se (in the form of sodium selenite) to serrano pepper and radish seeds increased the height, number, and length of the roots and the dry weight of the seedlings (León-Morales *et al.,* 2019). This may be due, in part, to the role of Se in enhancing photosynthesis, nutrient absorption, and antioxidant defense.

Finally, in terms of SPAD units, the 50 µM L^{-1} dose of Se produced the greenest plants, while the control group (0 µM L^{-1}) produced plants with the lowest greenness intensity. As such, these results are directly related to plant photosynthesis and may be due to Se helping to improve cellular functions, and therefore, the growth and development of the plants (Hasanuzzaman *et al*., 2021). Adhikary *et al.* (2022) used Se and zinc (Zn) nanoparticle treatments of rice seeds and demonstrated that Se treatments can help improve chlorophyll content in rice seedlings.

Conclusions

This study demonstrated that corn seeds treated with Se had higher germination and seedling growth rates compared with untreated (control) seeds. The effects of Se on the corn seeds were primarily observed using Se concentrations of 50 µM L^{-1} and 75 µM L^{-1} and included positive effects on several variables including %G, GR, GP, and the VC. Conversely, the Se concentration of 100 µM L^{-1} showed consistently lower results for most of the variables, indicating an adverse effect. Overall, these results indicate that Se can have a beneficial effect on seed germination and other physiological indices in corn seedlings. However, the optimum concentration of Se for corn growth and development may depend on a range of factors, including plant variety, soil type, and other environmental conditions.

Authors' contributions

Conceptualization of the work: author 1, author 6; methodology development: author 1, author 6; software management, author 1, author 2; experimental validation: author 1, author 2; analysis of results, author 1, author 2, author 3; data management, author 1, author 6; manuscript writing and preparation, author 1, author 3, author 6; drafting, revising and editing: author 1, author

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4, author 5; project manager: author 2, author 6; fund acquisition: author 6.

All authors of this manuscript have read and accepted the published version of this manuscript: LYMH, CMQ, NCAS, CJAL, ECL, and AEMM.

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Conflict of interest

The authors declare no conflict of interes.

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