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Castor seed yield enhancement through seed invigoration with KNO_3 and salicylic acid through testa removal at caruncle, under early skipped irrigation regime

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Abstract

Drought is one of the most critical factors which badly affects crop productivity. A field experiment was conducted at Research Farm, MNS-University of Agriculture Multan which was laid down under RCBD factorial arrangements. Two genotypes, NIAB spineless castor and NIAB castor 2023 were evaluated under no drought and early water deficit condition by delaying the irrigation until symptoms of stress appears on castor plants. Moreover, the castor seeds were primed using, Testa removal at caruncle (TRC) + SA priming 40 mg/L, TRC + hydro priming, TRC+KNO_3 priming 1%, TRC + 1% KNO_3 + SA @ 40 mg/L. There were three replications for each treatment. The HSD Tuckey's test at 5% probability level was used for assessing the significance of the treatment means. When there is no water shortage, farmers can use either of the tested cultivar i.e. NIAB Castor-2023 for improved seed yield with maximum BCR through testa removal at caruncle followed by priming with 1% KNO_3 + SA @ 40 mg/L. While, under early water deficit situation farmers can still get better castor seed yield and BCR by testa removal at caruncle and priming seeds with 1% KNO_3 + SA @ 40 mg/L. For comparable yield, however farmers may use one of the tested cultivars even by removing testa at caruncle and priming seeds with 1% KNO_3 under early water deficit conditions.

Keywords: Castor seed, Drought, KNO_3, Seed priming, Salicylic acid, Testa removal at caruncle

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Introduction

A member of the euphorbiaceae family, the castor plant (*Ricinus communis* L.) naturally thrives in a wide variety of habitats. This plant's original homelands were in Africa and India. Size, shape, and composition of plant parts are influenced by environmental factors, agronomic practices, and the variety of the plant. Brazil and China produce as much as 90% of the world's castor oil (non-edible), even though 30 other nations also cultivate it. However, 85 percent of the world's castor oil comes from India, and the country has a stranglehold on international commerce (Ogunniyi, 2006). Because of its tolerance for dryness, the castor plant has been shown to be the perfect plant for semi-arid places worldwide (Abdelaziz et al., 2014). The oil that is extracted from seeds is usually 40-50% triglyceride oil, with ricinoleic acid constituting around 85% of this oil. Castor cultivars are used in over three hundred compounds because of their chemical composition, which includes 26-30% protein and 50-55% non-edible oil (Mirza, 2009).

With an estimated annual output of close to 1.5 million metric tons, the top four producers are Mozambique, India, China, and Brazil (Severino & Auld, 2014). To regulate their own development, plants produce salicylic acid (SA), a phenolic molecule consisting of seven carbon atoms (Batool et al., 2025). Priming of seeds was done using various hormones, chemical and inorganic substances, and plant extracts. Priming substances that are known to increase germination growth include potassium nitrate (KNO_3) and salicylic acid (SA). One desired trait that may be discovered is a genotype's responsiveness to a particular environment, as well as its consistent performance across contexts; the degree of this interaction depends on the genotype- environment interaction (Ahmad et al., 1996). Raza et al. (2023) found that SA increased water stress resistance in wheat seedlings. Potassium nitrate (KNO_3) and other components of the priming agent enhanced wheat's germination, development, robustness, and tolerance. Priming treatments with KNO_3 improve seedling growth, yield, and drought and salinity tolerance (Thongtip et al., 2022) demonstrated that seedling vigor, germination, growth, and drought tolerance may be improved by priming seeds with KNO_3 and SA. Priming castor bean seeds with KNO3 and SA may be an effective strategy for boosting emergence and early establishment, which is especially important during the early drought period, and, eventually, production.

Agronomic stability is defined as a genotype's capacity to produce well in relation to the potential of the test circumstances (Anastasi et al., 2015; Jisha et al., 2013). Four staple crops wheat, corn, rice, and cotton are hardy and bearable. Aptitude to endure hot, dry conditions and high levels of salt (Azeem, 2015) allow castor plant to grow and survive in harsh environmental conditions. Spraying canola leaves with salicylic acid increases their chlorophyll content (Baghai et al., 2002). According to Khan et al. (2003), foliar SA application decreased transpiration rates in maize and soybean leaves. Although there is evidence of SA and KNO_3 treatment during blooming, there is a lack of research on how to eliminate drought during the early stages of establishment in castor, especially when water is restricted. The removal of caruncles from castor seeds is also under-documented in the literature. Therefore, the study was undertaken to evaluate the performance of castor genotypes under early drought in response to removal of testa at caruncle and priming with potassium nitrate, salicylic acid.

Materials and Methods

Experimental details

The field experiment was initiated in the last week of July 2023 at farm area of MNS university of Agriculture Multan. The study was conducted using randomized complete block design in factorial arrangement with three replications. Early drought condition of few days was applied to three replications of each genotype at early growth stage, by skipping the irrigation until plants show morphological symptoms of reduced growth (40 DAS). Whereas normal irrigation (No early drought) was also included for comparison. Seeds were primed as per treatment for 36 hours under aerated conditions and redried under shade before sowing. Hydro priming treatment was performed using tap water.

Experimental material

The castor genotypes (NIAB castor-2023 and NIAB-spinless castor) were used in the study obtained from NIAB (Nuclear Institute for Agriculture and Biology), Faisalabad Pakistan. The fertilizer applied (DAP) was obtained from the Directorate of Farms, MNS-University of Agriculture, Multan. In the field, sowing was done through manual dibbling on both sides of bed (75 cm wide). Plant to plant and row-to-row distance were kept at 75 cm. The net plot size was 4.5m×3m. Before sowing the bed was prepared with bed maker on a well-prepared soil. The crop was irrigated as per climate, crop and soil needs, excluding drought imposing treatments. At early stage of crop life cycle (40 DAS) irrigation was skipped in the drought imposing treatment and castor plants were monitored and were irrigated upon early appearance of symptoms of stunted plant growth. Before the sowing of crop, soil samples were collected from the field by using the soil auger at the depth of 0-6 inches and 6-12 inches. The soil samples were air dried under the shade mixed thoroughly and passed out from 2 mm sieve for soil physico-chemical analysis. In field, castor seeds were sown @ 15 kg per hectare and DAP fertilizer 50 kg per hectare.

Experimental treatments

As the experiment consists of three factors, the following treatments were used:

Factor A (Early water deficit)

D1: Control (No Drought)
D2: Early water deficit (skip irrigation) (40 DAS)

Factor B (Cultivars)

C1: NIAB castor-2023
C2: NIAB spineless castor

Factor C (Seed priming)

P0: Untreated seed (testa intact and no priming)
P1: Testa removal at caruncle (TRC)
P2: TRC + salicylic acid (SA) @ 40 mg/L
P3: TRC + Hydro priming
P4: TRC + 1% KNO3
P5: TRC + 1% KNO3 + SA @ 40 mg/L

Data on emergence percentage, plant height (cm), stem diameter (cm), number of branches plant^{-1}, spikes per plant, numbers of capsules plant^{-1}, spike length (cm), 100 seed weight (g) and seed yield (kg ha^{-1}) were recorded following standard methodologies.

Statistical and economic analyses

The data obtained were analyzed, and the means of the treatments were compared by using HSD (Honest significant difference) Tukey's test at 5% probability level (Steel et al., 1997). The benefit cost ratio and net benefits were calculated as part of the economic analysis (CIMMYT, 1988).

Results

The soil physico-chemical properties of saturated soil based on its texture, pH level, electrical conductivity, organic matter content, phosphorus, potassium, and saturation percentage to assess the suitability for growth and subsequent soil management practices is presented in Table 1. The soil texture appeared to be loam in nature, characterized by a balanced mixture of sand, silt, and clay. Loam soil is highly regarded for its optimal physical properties, making it suitable for growing crops like castor. Loamy soil structure provides excellent aeration, drainage, and nutrient retention, promoting healthy plant growth (Usharani et al., 2019). The pH level affects nutrient availability and microbial activity. The tested soil had a pH of 8.4 at 0-6 inches which increased to 8.5 when soil depth was between 7-12 inches (Nathan et al., 2012). Vigorous root growth, rhizospheric acidification, ion homeostasis, osmotic adjustment, strong antioxidant defense and efficient nutrient acquisition results in castor plant tolerance to alkaline pH. For loam soil, an EC value of less than 2 dS/m is generally acceptable for most crops. For the tested soil at 0-6 inches depth, it was 1.13 dsm^{-1} increased to 1.35 dsm^{-1} as depth increased to 7-12 inches, making it fit for cultivated castor. Organic matter consists of decomposed plant and animal residues in the soil. The tested soil reflected lower o/m at 0.49% at 0-6 inches and 0.42% between 7-12 inches. It indicates relatively less water reaction microbial activity and nutrient supply. Tested soil had 10 ppm available P at 0-6 inches which reduced to 9.7 ppm at 0-12 inches. Improved phosphorus availability promotes vigorous root growth and enhances flowering and fruiting in crops. Improved potassium is essential for plant water regulation, enzyme activation, and disease resistance. The available potassium was 120 ppm at 0-6 inches and 118 ppm between 7-12 inches. Adequate potassium levels enhance drought tolerance, improve yield, quality and resistance to diseases (Havlin et al., 2016). Saturation percentage indicates the amount of water the soil that can retain when it is fully saturated. The treated soil showed 32% saturation at 0-6 inches and 31 % between 7-12 inches. Soil saturation ensures adequate water availability for plants while preventing waterlogging and root diseases (Marschner, 2011).

The climatic data variables presented in Fig. 1 reveals that the maximum temperature resulted in heat stress, causing wilting, reduced photosynthesis and in severe cases, cell damage while reduced temperature slows the metabolic activities, potentially causing dormancy or even frost damage (Hatfield et al., 2011). Temperature remained within the range for castor growth having considerable variation in maximum and minimum temperature. Fig. 1 depicts the rainfall which shows hardly any significant rain during the growing season of castor 2023. While Fig. 1 shows humidity during the castor growing season. Humidity was not exceptionally high, which is understandable due to limited rains received. Humidity also provides favorable conditions for the growth and spread of fungal and bacterial diseases. In addition, the high humidity can cause stomata to remain open longer, increasing the risk of pathogen entry (Panchal et al., 2016). Data regarding the effect of different seed priming treatments on emergence percentage (EP) on different cultivars under different water regimes is presented in Table 2. EP was significantly affected by different seed priming treatments under different water regimes. Maximum seed emergence percentage was recorded under the treatment levels of TRC + 1% KNO3 + SA @ 40 mg/L (99.94 %) in NIAB spineless under control condition.

Table 1 Physico-chemical analysis of the soil for a field experiment

Soil characteristics	Soil depth	
	0-6 inches	7-12 inches
Soil texture	Loam	
pH	8.4	8.5
EC (dsm^{-1})	1.13	1.35
Organic matter (%)	0.49	0.42
Available phosphorus (ppm)	10.0	9.7
Available potassium (ppm)	120	118
Saturation (%)	32	31

While minimum emergence percentage was observed (45%) under untreated seeds in NIAB Castor 2023 under early water deficit conditions. Significant differences were observed between different irrigation regimes on different cultivars regarding EP. Plots where castor seeds whose testa were removed at caruncle and treated with 1% solution of KNO3 and 40 mg per liter of SA were applied to NIAB spineless castor under early water deficit revealed maximum emergence (91.00%) which was similar statistically to the same cultivar under water deficit where testa was removed at caruncle and primed with 1% KNO3 (Table 2).

Interactive effect of seed priming and early water deficit on plant height in castor cultivars

Under early water stress, the plant height under treatment levels of TRC+ salicylic acid SA @ 40 mg/L was (179.33 cm), under treatment of TRC+1% KNO_3 was (175.02 cm), and treatment TRC+1% KNO_3+SA @ 40 mg/L gave (176.06 cm) which also expressed the same lettering in NIAB spineless showed statistically similar heights of the castor plants. NIAB castor 2023 sown in plots where seeds were treated with TRC+ hydro priming (194.38), TRC+1% KNO_3 (191.16), TRC+1% KNO_3+SA @ 40 mg/L showed (185.19 cm). The castor plants could not vary for plant height significantly in plots with testa removed at caruncle and 1% KNO3 for priming seeds was used under normal irrigation across cultivars. However, opposite was the case under early drought-imposed plots (Table 3). Whereas shortest plants in early water deficit were observed in case of NIAB Castor 2023 (108.58 cm) under untreated situation. In NIAB castor 2023 under the controlled condition, untreated seed (165.20 cm) having the same letters in the same treatment as in NIAB spineless castor (167.52 cm) and could not differ significantly from each other. In NIAB castor 2023 under the control condition, testa removal at caruncle TRC (173.26 cm) having the same letters in the same treatment as in NIAB spineless castor (174.33 cm) and could not vary from one another.

Interactive effect of seed priming and early water deficit on stem diameter in castor cultivars

NIAB spineless castor demonstrated highest stem diameter (4.35 cm) in TRC + 1 % KNO_3 + SA @ 40 mg/L under no water deficit. NIAB castor 2023 reached (4.01 cm) under controlled conditions (no drought) in same treatment. NIAB castor 2023 demonstrated better stem diameter (2.04 cm) in TRC + hydro priming under control condition as compared to NIAB spineless castor which demonstrated lower stem diameter (1.64 cm). Under early water deficit, NIAB castor 2023 reached stem diameter (2.85 cm) by seed priming with TRC + 1% KNO_3 + SA @ 40 mg/L. However, under the same treatment, stem diameter (1.83 cm) was observed in the NIAB spineless castor. Under no water deficit, seed priming of TRC+ 1% KNO_3 gave stem dimeter (3.03 cm) in NIAB castor 2023 against 3.41 cm in NIAB Spineless castor in the same treatment. In early water deficit under the same treatment, NIAB spineless castor showed lower stem diameter (1.76 cm) compared to the NIAB Castor 2023 (2.67 cm). NIAB spineless castor, under TRC + salicylic acid SA @ 40 mg/L showed (1.60 cm) under control condition and TRC + hydro priming under water deficit condition showed (1.61 cm) with same letters as they did not differ significantly as shown in Table 4. However, under early water deficit, NIAB Castor 2023 revealed maximum stem diameter (2.85 cm) in plots where castor seed testa was removed at caruncle and primed with 1% KNO3 and 40 mg per liter of SA solution. It was statistically and significantly greater than NIAB spineless castor in the same priming treated castor plants whereas the shortest stem diameter was observed in untreated seeds of NIAB castor 2023 (0.19 cm) under early water deficit.

Interactive effect of seed priming and early water deficit on number of branches plant^{-1} in castor cultivars

NIAB spineless castor showed higher number of branches (7.59) in TRC + 1 % KNO3 + SA @ 40 mg/L employed to plots which were statistically followed by same treatment in NIAB castor 2023 (7.27) under controlled condition (no drought). NIAB Spineless castor showed the least branches per plant (1.15) in untreated seed under early water deficit (Table 5). However, it was interesting to note that for untreated seeds number of branches per plant for NIAB spineless castor could not differ significantly from early water deficit employed plot. In early water deficit, NIAB castor 2023 reached higher numbers of branches (6.61) by seed priming with TRC + 1% KNO3 + SA @ 40 mg/L as compared to the same treatment, which was observed to have fewer number of branches (4.45) in NIAB spineless castor. Under early water deficit, seed priming TRC+ 1% KNO3 showed a higher number of branches (5.45) in NIAB spineless castor. While, under the same treatment, NIAB castor 2023 showed a low number of branches (5.07). For each testa removal at caruncle TRC (3.02) under the control condition, and TRC + salicylic acid SA @ 40 mg/L (2.91) in early water deficit had similar letters in NIAB spineless castor as shown in Table 5. Among early water deficit employed plots of castor plants, NIAB spineless castor cultivar whose testa was removed at caruncle and treated with 1% KNO3 produced significantly maximum number of branches per plant (5.45) whereas the same cultivar also produced least branches per plant when sown untreated (1.15).

Interactive effect of seed priming and early water deficit on spikes per plant in castor cultivars

NIAB spineless castor produced more spikes per plant (6.98) in plots where TRC + 1 % KNO_3 + SA @ 40mg/L were applied as compared to NIAB- castor 2023 in the same treatment which reached (6.25) under controlled condition (no drought). It was also interestingly observed that under early water deficit, same cultivar produced 6.83 spikes per plant statistically like plots where castor plants were grown without early water deficit showing its possible potential under early water deficit. NIAB castor 2023 produced lowest number of spikes per plant (1.35) of untreated seed in early water deficit. NIAB spineless castor could not bring significant variation in control and early water deficit conditions for same tested treatment. However, both were significantly different and higher than NIAB castor 2023 in corresponding similar treatments as shown in Table 6. In early water deficit NIAB spineless castor reached the highest spikes per plant (6.83) with TRC + 1% KNO3 + SA @ 40 mg/L treatment as compared to NIAB Castor 2023 for the same treatment with less spikes per plant (5.97). Seed priming of TRC+ 1% KNO3 showed higher spikes per plant (5.48) observed in NIAB spineless castor in early water deficit. While NIAB castor 2023 showed less spikes per plant (4.53) under early water deficit. Untreated seeds of NIAB castor 2023 showed spikes per plant (2.01) and under the same treatment, NIAB spineless castor showed spikes per plant (1.95) having same letters under no water deficit. Similarly, testa removal at caruncle TRC showed (1.03) spikes per plant in NIAB castor 2023. TRC + hydro priming showed (4.96) in NIAB spineless castor under no water deficit condition, in the same treatment in early water deficit, NIAB spineless castor showed (4.95) spikes per plant having same letters. TRC + 1% KNO3 gave spikes per plant (5.64) under no water deficit, in same treatment in early water deficit, (5.48) in NIAB spineless castor was recorded with same letters. Under no early water deficit, NIAB spineless castor produced higher number of capsules per plant (514.40) in plots where castor seeds were primed with TRC + 1% KNO3 + SA @ 40 mg/L.

Table 2 Interactive effect of priming and early water deficit on emergence (%) in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	52.62 k	45.00 m	56.62 j	47.50 lm
Testa removal at caruncle (TRC)	62.65 i	55.00 jk	66.37 h	55.48 j
TRC + salicylic acid (SA) @ 40 mg/L	73.90 f	60.82 i	77.90 e	70.00 g
TRC + Hydro priming	87.32 d	65.00 hi	85.00 d	76.75 e
TRC + 1% KNO3	88.05 cd	71.13 fg	96.12 b	88.50 c
TRC + 1% KNO3 + SA @ 40 mg/L	94.27 b	72.82 f	99.94 a	91.00 c

(HSD value at 0.05 α = 3.059)

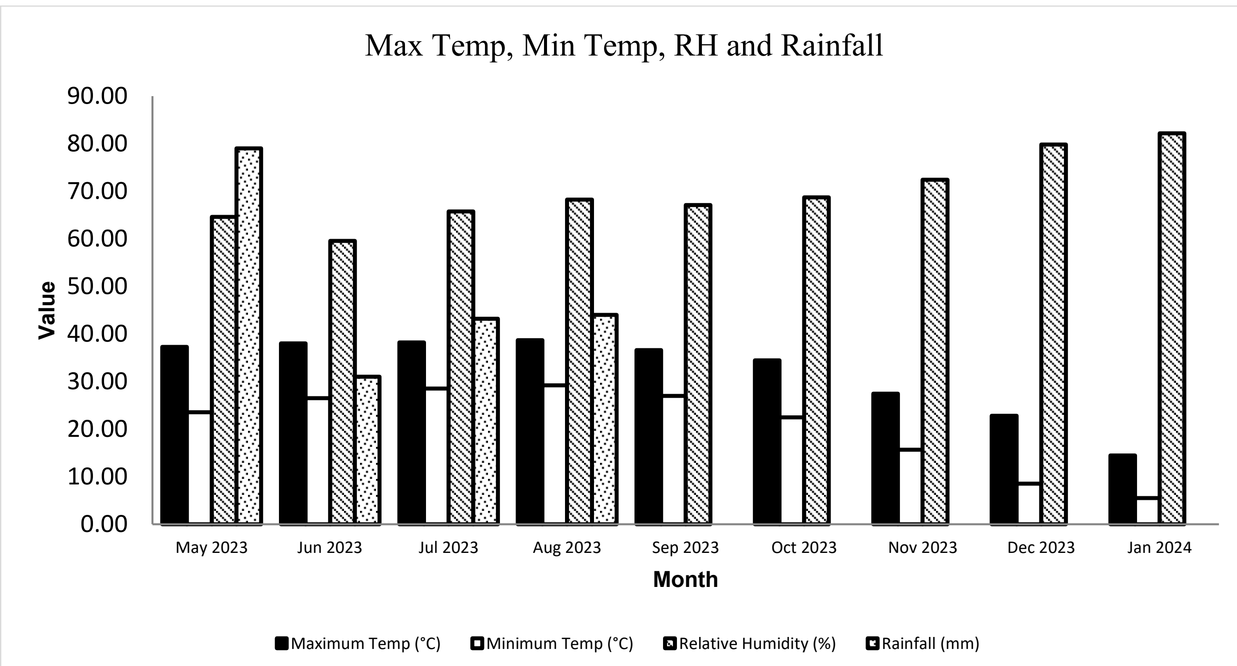

Fig. 1 Climatic variables during castor crop season (May 2023 to January 2024)

Table 3 Interactive effect of seed priming and early water deficit on plant height (cm) in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	165.20 d	108.58 f	167.52 d	148.20 e
Testa removal at caruncle (TRC)	173.26 cd	116.60 f	174.33 cd	159.28 de
TRC + Salicylic acid (SA) @ 40 mg/L	210.22 a	124.42 f	184.56 c	179.33 cd
TRC + Hydro priming	194.38 bc	137.33 ef	189.12 b	169.04 d
TRC + 1% KNO3	191.16 bc	146.53 e	196.33 b	175.02 cd
TRC + 1% KNO3 + SA @ 40 mg/L	185.19 bc	126.54 f	193.23 bc	176.06 cd

(HSD value 0.05α = 11.59)

Table 4 Interactive effect of seed priming and early water deficit on stem diameter (cm) in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	0.95 q	0.19 t	0.61 r	0.36 s
Testa removal at caruncle (TRC)	1.83 i	1.02 p	1.43 m	1.33 n
TRC + salicylic acid (SA) @ 40 mg/L	1.90 h	1.73 j	1.60 kl	1.57 l
TRC + Hydro priming	2.04 g	1.19 o	1.64 k	1.61 kl
TRC + 1% KNO3	3.03 d	2.67 f	3.41 c	1.76 j
TRC + 1% KNO3 + SA @ 40 mg/L	4.01 b	2.85 e	4.35 a	1.83 i

(HSD value 0.05α = 0.051), Means sharing similar letters do not differ significantly from each other at 5% probability level

Table 5 Interactive effect of seed priming and early water deficit on number of branches plant^{-1} on castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	2.16 t	1.58 r	1.26 u	1.15 u
Testa removal at caruncle (TRC)	2.71 p	2.33 q	3.02 o	1.98 s
Salicylic acid (SA) @ 40 mg/L	4.85 h	3.26 n	4.10 j	2.91 o
TRC + Hydro priming	4.18 j	3.81 l	3.94 k	3.51 m
TRC + 1% KNO3	6.05 d	5.07 g	5.74 e	5.45 f
TRC + 1% KNO3 + SA @ 40 mg/L	7.27 b	6.61 c	7.59 a	4.45 i

(HSD value 0.05α = 0.132)

Interactive effect of seed priming and early water deficit on Numbers of Capsules plant^{-1} in castor cultivars

However, it was also observed that NIAB castor 2023 also showed no significant variation for number of capsules per plant (511.31) in the above-mentioned treatment. It was followed by plots where NIAB castor 2023 was primed with TRC + 1% KNO3 (494.11) which were significantly different from rest of the tested treatments. In early water deficit NIAB spineless castor produced highest numbers of capsules (471.23) in seed priming with TRC + 1 % KNO3 + SA @ 40mg/L treatment. However, under the same treatment NIAB castor 2023 showed significantly lower numbers of capsules (451.38). Seed priming TRC+ 1% KNO3 showed higher numbers of capsules (431.14) in NIAB castor 2023 in early water deficit compared with NIAB spineless castor (421.17) as shown in Table 7. Testa removal at caruncle remained relatively consistent across cultivars under early water deficit. Likewise, TRC + SA @ 40 mg / L when applied under normal irrigation exhibited negligible differences across the cultivars. Likewise early water deficit-imposed plots demonstrated minimal variation for capsules per plant across the cultivars. NIAB Castor 2023 and NIAB spineless did not change appreciably for capsules per plant in plots which had early water deficit in untreated seeds. Among early water deficit-imposed plots, significantly tallest castor plants (176.06 cm), maximum number of spikelets and capsules per plant were observed in plots where testa were removed at caruncle of NIAB castor spineless seeds and primed with 1% KNO3 and 40 mg per liter salicylic acid solution.

Table 6 Interactive effect of seed priming and early water deficit on spikes per plant in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	2.01 m	1.35 o	1.95 m	1.71 n
Testa removal at caruncle (TRC)	3.01 k	1.03 p	3.70 j	2.35 l
Salicylic acid (SA) @ 40 mg/L	3.60 j	2.47 l	4.52 g	4.04 i
TRC + Hydro priming	4.83 f	4.30 h	4.96 ef	4.95 ef
TRC + 1% KNO3	5.02 e	4.53 g	5.64 d	5.48 d
TRC + 1% KNO3 + SA @ 40 mg/L	6.25 b	5.97 c	6.98 a	6.83 a

(HSD value 0.05α = 0.156)

Table 7 Interactive effect of seed priming and early water deficit on numbers of capsules plant^{-1} in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	352.41 m	322.66 o	364.25 k	323.26 o
Testa removal at caruncle (TRC)	358.34 l	341.22 n	368.32 k	345.48 n
TRC + salicylic acid (SA) @ 40 mg/L	399.59 h	381.96 i	402.51 h	381.10 ij
TRC + Hydro priming	399.77 h	380.37 ij	400.86 h	376.55 j
TRC + 1% KNO3	494.11 b	431.14 f	487.02 c	421.17 g
TRC + 1% KNO3 + SA @ 40 mg/L	511.31 a	451.38 e	514.40 a	471.23 d

(HSD value 0.05α = 0.037). Means sharing similar letters do not differ significantly from each other at 5% probability level

Interactive effect of seed priming and early water deficit on spike length (cm) in castor cultivars

NIAB spineless castor produced taller (18.57cm) spikes because of TRC + 1 % KNO3 + SA @ 40mg/L which was statistically followed by NIAB-castor 2023 (18.08cm) under controlled condition (no drought). Tallest castor spikes were obtained in plots where testa were removed at caruncle and primed with integrated use of KNO3 @ 1% and SA @ 40 mg per liter irrespective of the cultivar under study (17.03 cm and 16.97 cm) while the shortest spikes were observed when NIAB-Castor 2023 seeds were sown non-treated (7.07 cm). In early water deficit, NIAB castor 2023 reached longest spikes (17.03 cm) because of seed priming with TRC + 1 % KNO3 + SA @ 40mg/L treatment as compared to the same treatment imposed to NIAB spineless castor which showed shorter spikes (16.97cm). Seed priming TRC+ 1% KNO3 showed longer spikes (16.55cm) in NIAB spineless castor in early water deficit when compared with NIAB castor 2023 (16.07cm) (Table 8).

Interactive effect of seed priming and early water deficit on 100 seed weight in castor cultivars

NIAB castor 2023 produced significantly (25.52 g) heaviest castor seeds in plots were TRC + 1 % KNO3 + SA @ 40mg/L were applied to seeds sown in plots receiving normal irrigation. It was significantly followed by seeds weighing 25.04 g in NIAB spineless castor in normal irrigated plots. While the lightest castor seeds (8.03 g) were noticed in NIAB-castor 2023 as shown in Table 9. In early water deficit, NIAB spineless castor reached heavier 100 seeds (23.70 g) when seeds primed with TRC + 1 % KNO3 + SA @ 40mg/L as compared to NIAB spineless castor (23.26 g). Seed priming TRC+ 1% KNO3 showed heavier 100 seeds (22.91 g) for NIAB spineless castor in early water deficit-imposed plots compared to NIAB castor 2023 with lowest 100 seed weight (22.41 g) as shown in Table 9. Significantly heaviest 100 seeds (23.70 g) were obtained in case of NIAB castor 2023 in plots treated with TRC + 1 % KNO3 + SA @ 40mg/L which was followed by NIAB spineless (23.26 g).

Interactive effect of seed priming and early water deficit on seed yield of castor cultivars

NIAB castor 2023 gave higher seed yield (3894.2 kg ha^{-1}) when seeds were primed with TRC + 1% KNO3 + SA @ 40 mg/L which remained statistically unchanged to TRC + 1% KNO3 (3871.5 kg ha^{-1}) under no early water deficit. NIAB castor 2023 showed the lowest (3415.9 kg ha^{-1}) yield (untreated seed) under early water deficit condition as shown in Table 10 which again could not reach significance level with early water deficit imposed on NIAB Spineless (3470.2 kg ha^{-1}). Among early water deficit imposed plots, NIAB castor 2023 reached higher seed yield (3749 kg ha^{-1}) in seed priming with TRC + 1 % KNO3 + SA @ 40mg/L and under the same treatment NIAB spineless castor also showed no meaningful differences for seed yield (3745 kg ha^{-1}). While under no early water deficit irrespective of cultivar grown, plots where castor seeds were sown and treated with TRC + 1% KNO3 and SA @ 40 mg per liter exhibited highest seed yield (Table 10). Seed yield highest percentage (9.1%) was observed in NIAB spineless castor which was treated by TRC +1% KNO3 + salicylic acid 40 mg/L under control condition followed by NIAB castor 2023 (8.88 %) in same treatment. The lowest seed yield percentage increase was observed over control (1.5 %) in NIAB spineless castor in which testa was removed at caruncle under drought condition. Under early drought, NIAB spineless castor and NIAB castor 2023 when treated with 1% KNO3 and 40 mg per liter SA for seeds whose testa were removed at caruncle before sowing exhibited more than 6% increment in seed yield of castor over untreated control. However, under normal irrigation in the above treatment this increment across cultivars used was around 9% (Fig. 2).

Economic analysis

Total fixed cost has been given in Table 11, while the net benefits and benefit cost ratio (BCR) of castor cultivars are represented in Table 12, 13, 14 and 15 as influenced by early water deficit and seed priming treatments. The maximum net benefits (146691/- PKR per hectare) were obtained from plots where seed priming was done with TRC + 1% KNO3 + SA @

40 mg/L in NIAB - castor 2023 under water deficit with maximum BCR 1.59. Whereas under early water deficit imposed plots the minimum net benefits (125540/- PKR per hectare) were recorded in untreated seed with minimum BCR 1.36. Under early water deficit conditions higher net benefits of Rs. 145191 per hectare were observed in NIAB castor 2023 with BCR (1.55) in TRC + 1% KNO3 + SA @ 40 mg/L as compared to TRC + 1% KNO3 within same genotype where the net benefits were Rs. 144881 per hectare. We conclude that under non-limited irrigation higher economic returns may be achieved through salicylic acid priming at lower concentration in castor bean with latest genotype (i.e. NIAB castor 2023). Whereas same treatment combination also performed better under early stage of water shortage scenario. Parameters like stem diameter, branches per plant, spike length and 100 seed weight were relatively better in NIAB castor 2023 variety in some treatments. Whereas, emergence percentage, plant height, spikes per plant and capsules per plant were better in some treatments in NIAB spineless castor. However, seed yield was at par among cultivars tested. Benefit cost ratio was relatively better for NIAB castor 2023 over NIAB spineless castor.

Table 8 Interactive effect of seed priming and early water deficit on spike length (cm) in castor cultivars

Seed priming	NIAB castor2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	8.93 s	7.07 w	10.06 q	7.50 v
Testa removal at caruncle (TRC)	9.47 r	8.17 u	10.66 p	8.51 t
TRC + salicylic acid (SA) @ 40 mg/L	14.15 k	12.23 o	14.98 i	13.12 m
TRC + Hydro priming	14.50 j	13.65 l	15.35 h	12.86 n
TRC + 1% KNO3	17.88 c	16.07 g	17.66 d	16.55 f
TRC + 1% KNO3 + SA @ 40 mg/L	18.08 b	17.03 e	18.57 a	16.97 e

(HSD value 0.05α = 0.156). Means sharing similar letters do not differ significantly from each other at 5% probability level

Table 9 Interactive effect of seed priming and early water deficit on 100 seed weight (g) in castor cultivars

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	8.61 w	8.03 x	11.01 r	10.40 t
Testa removal at caruncle (TRC)	9.71 u	9.23 v	11.50 q	10.85 s
Salicylic acid (SA) @ 40 mg/L	14.74 k	12.23 p	13.23 n	12.73 o
TRC + Hydro priming	15.47 i	14.36 l	15.05 j	13.62 m
TRC + 1% KNO3	24.02 d	22.41 h	24.61 c	22.91 g
TRC + 1% KNO3 + SA @ 40 mg/L	25.52 a	23.70 e	25.04 b	23.26 f

(HSD value 0.05α = 0.130)

Table 10 Interactive effect of priming and early water deficit on seed yield (kg ha 1) in castor genotypes

Seed priming	NIAB castor 2023		NIAB spineless castor	
	Control (No drought)	Early water deficit (Skip irrigation)	Control (No drought)	Early water deficit (Skip irrigation)
Untreated seed	3646.4 e	3415.9 h	3512.7 g	3470.2 h
Testa removal at caruncle (TRC)	3745.4 e	3503.8 gh	3569.1 f	3520.6 g
Salicylic acid (SA) @ 40 mg/L	3791.5 b	3589.8 f	3608.6 e	3595.7 f
TRC + Hydro priming	3818.1 b	3690.6 d	3640.2 e	3637.3 e
TRC + 1% KNO3	3871.2 a	3744.5 c	3744.8 c	3733.1 c
TRC + 1% KNO3 + SA @ 40 mg/L	3894.5 a	3749 c	3866.7 a	3745 c

(HSD value 0.05α = 42.24). Means sharing similar letters do not differ significantly from each other at 5% probability level

Table 11 Total fixed cost

Sr. No.	Input operation	Unit	Frequency/ amount	Cost (PKR/ acre)	Cost (PKR/ ha)
1	Land preparation	Hour	2 ploughings	1500	3706
2	Seed	Kg ha^{-1}	15 Kg	1820	4497
3	Sowing	Labour	4 women	2000	4942
4	Irrigation	Hour	4	4000	9884

5	Fertilizer	No.	1 bag DAP	9000	22239
6	Weed removal	Labour	4	2000	4942
7	Harvesting	Labour	4	2000	4942
8	Threshing	Labour	2	1000	2471
9	Land rent	Month	6	15000	37065
Total				38320/-	94688/-

Note: Total fixed cost for normal (no drought) treatment was PKR 94688/- per hectare, because one irrigation was skipped at flowering i.e. 94688-2500=92188/- (as 1000 PKR was the cost of one irrigation per acre and 2500 PKR for 1 hectare). Hence total fixed cost for skip irrigation was 92188/- PKR per hectare.

Table 12 Benefit cost ratio of NIAB castor 2023 under normal irrigation

Treatments	S.Y. Maunds/ acre	S.P.	F.C.	V.C.	T.C.	N.B.	B.C.R.
				PKR ha^{-1}			
			NIAB- CASTOR 2023 (NORMAL)				
Untreated seed	36.89	232407	94688	0	94688	137719	1.45
Testa removal at caruncle (TRC)	37.8	238140	94688	0	94688	143452	1.52
TRC + salicylic acid (SA) @ 40 mg/L	38.36	241668	94688	5	94693	146975	1.55
TRC + Hydro priming	37.34	235242	94688	0	94688	140554	1.48
TRC + 1% KNO3	39.17	246771	94688	75	94763	152009	1.60
TRC + 1% KNO3 + SA @ 40 mg/L	39.4	248220	94688	80	94768	153452	1.62

S.Y. = Seed yield; F.C. = Fixed cost; N.B. = Net benefit; S.P. = Seed price @ 6300 PKR per 40 kg castor seed; T.C. = Total cost; V.C. = Variable cost; B.C. R. = Benefit cost ratio

Table 13 Benefit cost ratio of NIAB castor 2023 under early water deficit

Treatments	S.Y. maunds/ acre	S.P.	F.C.	V.C.	T.C.	N.B.	B.C.R.
				PKR ha^{-1}			
		NIAB-CASTOR 2023			(Early water deficit)		
Untreated seed	34.56	217728	92188	0	92188	125540	1.36
Testa removal at caruncle (TRC)	35.45	223335	92188	0	92188	131147	1.43
TRC + salicylic acid (SA) @ 40 mg/L	36.32	228816	92188	5	92193	136623	1.48
TRC + Hydro priming	36.9	232470	92188	0	92188	140282	1.52
TRC + 1% KNO3	37.88	238644	92188	75	92263	146381	1.59
TRC + 1% KNO3 + SA @ 40 mg/L	37.93	238959	92188	80	92268	146691	1.59

S.Y. = Seed yield; F.C. = Fixed cost; N.B. = Net benefit; S.P. = Seed price @ 6300 PKR per 40 kg castor seed; T.C. = Total cost; V.C. = Variable cost; B.C.R. = Benefit cost ratio

Discussion

Increase in germination could be owing to pre-sowing salicylic acid treatment to the seeds promoting enzyme activation and higher emergence (Saha et al., 2022). The emergence % may have been enhanced by salicylic acid seed priming. Plots where SA was primed with castor seeds 40 mg/L showed better emergence (74.94%) (Raza et al., 2023). Here it is also important to mention the role of testa removal from caruncle for castor seeds which significantly enhanced emergence percentage to even above 90% in some treatments. More plant height of NIAB castor-2023 cultivar than NIAB spineless due to SA application may be attributed to the likeliness of greater intrinsic sensitivity to SA mediated signaling pathways. Castor seed priming with salicylic acid 0.5 mM increased the plant height in common beans (Sadeghipour & Aghaei, 2012). However, early water deficit conditions can significantly reduce the plant height due to loss of water which is necessary for plant growth and development (Bhattacharya et al., 2021). NIAB castor-2023 variety showing relatively better stem diameter than NIAB spineless under early water deficit can be likely related to drought tolerance character, improved root water acquisition, water use efficiency and sustained allocation of assimilates to stem tissues under stress. 43% and 20% more stem diameter in okra was observed when seeds were primed with salicylic acid 50 mg/Land 100 mg/L, respectively (Raza et al., 2023). Foliar salicylic acid application significantly improved stem diameter in sunflowers (Noreen et al., 2017). Salicylic acid increases stem diameter which may by associated with improved cell wall development and lignification through SA facilitated regulation of growth-related genes and peroxidase activity potentially promoting stem thickening and vascular development under stress (Elsisi et al., 2024).

Different salicylic acid priming treatments resulted in increased branches per plant in NIAB-GOLD under both normal and drought conditions (Raza et al., 2023). More branches per plant (7.65 and 8.33) under normal and drought conditions were obtained in N-2020 (NIAB Castor 2023). External salicylic acid application sole and in combination with gibberellic acid significantly increased branch formation in canola (Ijaz et al., 2019). Increase in branch formation could probably be due to more cell division because of positive influence of salicylic acid. Salicylic acid can increase number of spikes by altering the hormonal balance and stress responses in plants. Higher spikes per plant (9.25) were counted in seed priming with 120 mg/L salicylic acid (Raza et al., 2023). Salicylic acid can encourage growth and developmental activities, including blooming and spike production. More capsules per plant were counted in 40 mg/L salicylic acid in N-2020 (NIAB Castor 2023) under normal irrigation succeeded by 630.0 in 80 mg/L SA in N-2020 (NIAB Castor 2023) under normal irrigation. Reduced number of per plant capsules (490) was observed in hydro priming of NIAB-GOLD under drought (Raza et al., 2023).

More per plant capsules (18%) were noticed in priming seeds with salicylic acid @ 200 mg/L in linseed cultivars (Mohammad et al., 2020). Higher per plant capsules number obtained from higher main and sub-branches of the plant. Oilseed crop yields can be enhanced by salicylic acid, which increases spikes per plant by balancing hormones, photosynthesis, and stress tolerance (Mutlu et al., 2009). Priming with salicylic acid was hindered by drought, which shortened the spikes, fostered longer spikes in wheat crops in both normal and drought conditions (Ulfat et al., 2017).

Bandurska and Stroinski (2005) found that applying salicylic acid to barley crops increased spike length. Seed priming with salicylic acid resulted in heavier 100-seeds in cowpea under both normal and drought conditions (Pak Mehr et al., 2011) and in sunflower (Noreen & Ashraf, 2010). Gaining in weight of 100 seeds could be because of SA priming, which resulted in higher ion uptake, cell division, and cell elongation. Drought reduced the grain yield in castor bean while SA priming improved the grain yield as compared to control (Abasi et al., 2018). Seed priming with salicylic acid proved to be effective methodology to improve the final seed yield of castor bean crop under both normal and drought conditions (Raza et al., 2023). Salicylic acid promotive effects could have increased seed yield due to cell elongation and better sink source relation (Alam et al., 2021). In both normal irrigation and drought conditions during blooming, the yield of NIAB castor 2023 was greater than that of NIAB spineless castor though not significantly higher. Both normal and drought situations saw an improvement in crop performance after applying salicylic acid and KN03. It is possible to enhance castor bean emergence, yield, and components associated with yield by using salicylic acid, KNO3, and hydro priming.

Table 14 Benefit cost ratio of NIAB spineless castor under normal irrigation

Treatments	.Y. maunds/ acre	S.P.	F.C.	V.C.	T.C.	N.B.	B.C.R.
			PKR ha^{-1}				
			NIAB- Spineless castor (Normal)				
Untreated seed	35.45	223335	94688	0	94688	128647	1.36
Testa removal at caruncle (TRC)	36.11	227493	94688	0	94688	132805	1.40
TRC + salicylic acid (SA) @ 40 mg/L	36.51	230013	94688	5	94693	135320	1.43
TRC + Hydro priming	37.16	234108	94688	0	94688	139420	1.47
TRC + 1% KNO3	38.11	240093	94688	75	94763	145330	1.53
TRC + 1% KNO3 + SA @ 40 mg/L	38.63	243369	94688	80	94768	148601	1.57

S.Y. = Seed yield; F.C. = Fixed cost; N.B. = Net benefit; S.P. = Seed price @ 6300 PKR per 40 kg castor seed; T.C. = Total cost; V.C. = Variable cost; B.C.R. = Benefit cost ratio

Table 15 Benefit cost ratio of NIAB spineless castor under early water deficit

Treatments	.Y. maunds/ acre	S.P.	F.C.	V.C.	T.C.	N.B.	B.C.R.
			PKR ha^{-1}				
			NIAB-Spineless castor (Early water deficit)				
Untreated seed	35.41	223083	92188	0	92188	130895	1.42
Testa removal at caruncle (TRC)	35.62	224406	92188	0	92188	132218	1.43
TRC + salicylic acid (SA) @ 40 mg/L	36.38	229194	92188	5	92193	137001	1.49
TRC + Hydro priming	36.8	231840	92188	0	92188	139652	1.51
TRC + 1% KNO3	37.77	237951	92188	75	92263	145688	1.58
TRC + 1% KNO3 + SA @ 40 mg/L	37.89	238707	92188	80	92268	146439	1.59

S.Y. = Seed yield; F.C. = Fixed cost; N.B. = Net benefit; S.P. = Seed price @ 6300 PKR per 40 kg castor seed; T.C. = Total cost; V.C. = Variable cost; B.C.R. = Benefit cost ratio

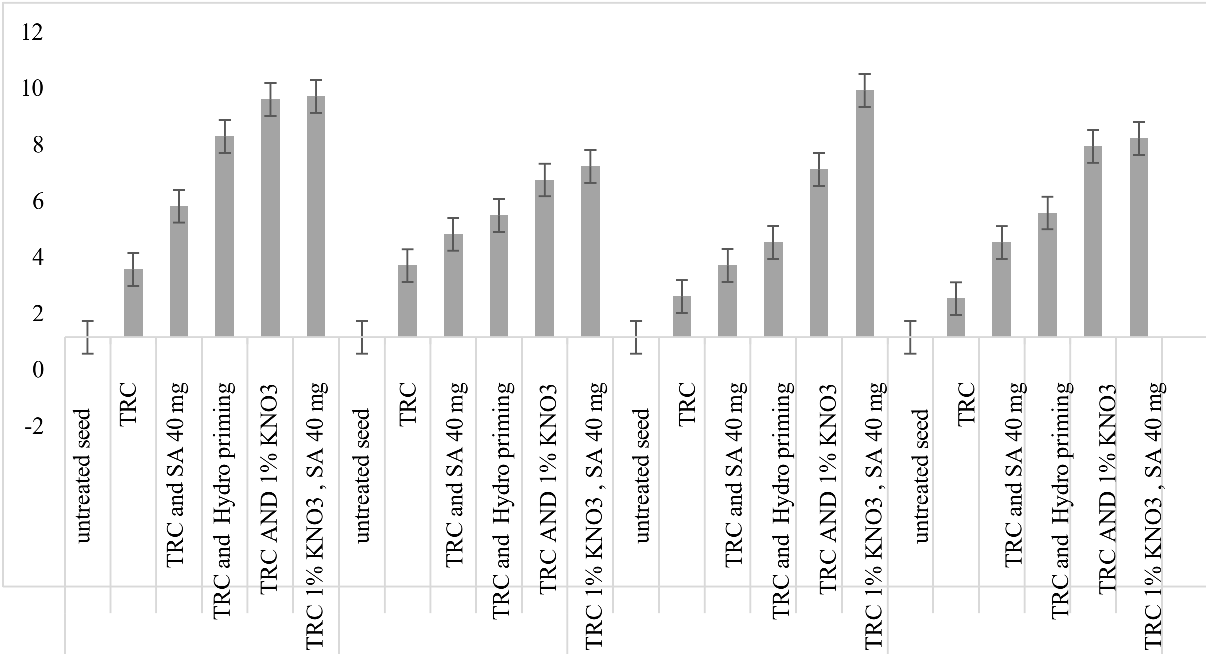

Fig. 2 Percent increase in seed yield (kg ha^{-1}) over untreated control. N: Normal irrigation D: Early water deficit

Conclusion

Under limited water supply at early-stage farmers can get better castor seed yield and improved returns if testa is removed at caruncle and primed with 1% KNO3 and salicylic acid @ 40 mg per liter by sowing NIAB castor 2023 cultivar. If farmers do not have NIAB castor 2023, they can also use NIAB spineless castor for obtaining good yield and income.

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