Heliyon 11 (2025) e42320

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Optimizing boron application methods and dosages to enhance jute (*Corchorus olitorius*) seed yield and quality under sub-tropical climate

Tapan Kumar [a,*], Pritthee Mallick Tama [b], Syed Aflatun Kabir Hemel [a], Ranjit Kumar Ghosh [a], Md Imran Ali [a], Abdullah Al-Bakky [a], Abdul Alim [a]

[a] *Bangladesh Jute Research Institute, Manik Mia Avenue, Dhaka, 1207, Bangladesh*
[b] *Biotechnology and Genetic Engineering Discipline, Khulna University, Khulna, 9208, Bangladesh*

A R T I C L E I N F O

Keywords:
Boron
Corchorus olitorius seed
Foliar application of boron
Principal component analysis
Seed yield

A B S T R A C T

Bangladesh, despite being a top raw jute producer, struggles with inadequate jute seed quantity and quality due to some unforeseen circumstances. Boron is a key micronutrient for enhancing crop seed yield and quality. However, research on its effects on jute (*Corchorus olitorius*) seed production in Bangladesh remains limited, highlighting a significant knowledge gap. Therefore, a two-year field study was conducted at the Bangladesh Jute Research Institute, Regional Station in Faridpur to examine the effects of various boron application methods and doses on *Corchorus olitorius* seed production. The experiment included ten treatments combining three boron doses (2.0, 3.0, and 4.0 kg/ha) with three different application methods: (1) full dose as basal application, (2) full dose as foliar spray in two equal split and (3) haft the dose as basal application with the remaining half as foliar spray in two equal splits. An additional treatment without boron served as the control. The experiment, using the jute variety BJRI Tossa Pat 8, was conducted in a randomized complete block design to account for environmental variability and enhance treatment comparison. The study revealed that, independent of application methods and doses, boron application significantly improved seed yield and germination percentage compared to treatments without boron. Foliar application of boron at 3.0 kg/ha significantly enhanced yield contributing characters, including the number of capsules/plant, capsule length, and 1000-seed weights, compared to control and basal treatments. Additionally, boron application consistently improved seed yield and germination percentage across all methods and doses. The 3.0 kg/ha foliar treatment, applied half at 20–25 days after sowing and the remainder at the first flowering stage, yielded the highest results for *Corchorus olitorius*. Principal component analysis indicated that the number of seeds per capsule, capsule length, and seed yield were the main contributors. So, 3.0 kg/ha foliar boron treatment, applied half at 20–25 days after sowing and the remainder at the first flowering stage is recommended for late jute seed production to achieve optimum seed yield and net profit.

* Corresponding author.
E-mail addresses: tapanpstus@gmail.com, tapan@bjri.gov.bd (T. Kumar).

https://doi.org/10.1016/j.heliyon.2025.e42320
Received 11 July 2024; Received in revised form 22 January 2025; Accepted 27 January 2025
Available online 30 January 2025

1. Introduction

Jute is usually referred to as 'golden fibre' throughout most of the world and is one of the main fibre crops, along with cotton [1]. Jute is the second most common bast fibre after cotton in terms of availability, production, consumption, and utilization globally [2]. It is vital to replace ecologically damaging synthetic materials with natural, reusable, and biodegradable ones since the usage of synthetic items may lead to an increase in pollution that harms both living things and the environment. Since jute fibre possesses practically all these qualities, it is well-known around the world for being environmentally friendly. In 2021, India led as the top producer of jute in the Asia Pacific region with an output of 1.72 million metric tons. Bangladesh came in second with 1.68 million metric tons of output [3] and receives foreign exchange from the export of jute and its derivatives to other nations [4]. Jute has been a key element of Bengali culture since the beginning, notably in some regions of West Bengal and the southwest part of Bangladesh [5]. Jute production in Bangladesh is important from an economic, industrial, agricultural, and economic standpoint [6] since it has the potential to provide significant foreign exchange earnings for the country [4].

In Bangladesh, jute is mostly farmed for its fibre rather than its seeds. Typically, farmers produce seeds by retaining a portion of the March–April planted fibre crops. Due to its protracted stay in the field, the lingering part of the fibre crop is frequently damaged by natural disasters, become physiologically weak, and yields a low quantity of poor-quality seeds [7]. Furthermore, farmers frequently produce vegetables or Aman rice when jute seeds ought to be planted. Therefore, farmers are not persuaded to switch to jute seed from the staple crops, which deters farmers from growing more jute seed. Bangladesh needs roughly 5000–5500 tons of seed to produce the amount of jute [7]. Quality jute seed was not produced with as much care; therefore, it was typically scarce when it should have been sown [2,7]. Approximately 15 %–20 % of the quality jute seeds that are needed are provided through institutional organizations; the remaining quality seeds need to be collected [7]. The production of seeds must be boosted to close the gap. The seed yield, for instance, depends on certain yield-contributing characteristics, such as plant height, the number of branches per plant, the number of capsules per plant, capsule length, the number of seeds per capsule, etc., which should be maximized to achieve the highest yield [5]. Effective nutrient management of an improved variety itself 30–50 % more yield along with standard agricultural practices [8].

The effective use of crop nutrients is known as nutrient management, which aims to increase productivity while preserving the environment. The main idea underlying nutrient management is to balance the inputs of soil nutrients with the needs of the crops. Fertilizers are supplementary materials that are given to crops to boost productivity. Efficient fertilizer application is paramount for minimizing waste and optimizing nutrient utilization [9].

Plant nutrients, essential for growth and health, include seventeen elements such as carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, chlorine, boron, zinc, manganese, iron, copper, molybdenum, and nickel [10]. The roles of boron on cell wall integrity and expansion, splitting cells, fruit and seed formation, sugar transport, and hormone synthesis are primarily responsible for its necessity [11]. Boron deficiency impairs flowering and pollen tube production, resulting in reduced yield and quality features and this deficiency can be alleviated by applying boron to the soil and by foliar applications [12]. Low boron levels are more likely to affect sexual reproduction in plants than vegetative growth [9]. Giving emphasise on these fact, it is imperative to execute optimal boron fertilization using appropriate methods during the developmental stages of jute seeds. This strategic approach is essential for enhancing jute seed production. Several studies have investigated the impact of boron fertilization on yield and related traits in various crops. Yadav et al. (2016) examined its effects on mustard (*Brassica juncea* L.) growth, yield, and quality [13]. Khuong et al. (2022) determined optimal boron levels for enhancing growth, production, and oil content in black sesame [14]. Al-Amery et al. (2011) and Asad et al. (2003) explored the response of open-pollinated sunflowers (*Helianthus annuus* L.) to boron [15,16]. Arredondo & Bonomelli, (2023) assessed cherry trees' reactions to varying boron concentrations by analyzing growth, biomass, photosynthesis, and morphology [17]. Choudhary et al. (2020) studied the effects of high boron levels on essential oil crops, *Mentha arvensis* and *Cymbopogon flexuosus* [18]. Silva et al. (2018) evaluated foliar boron fertilization, with and without sorbitol, on cowpea growth,

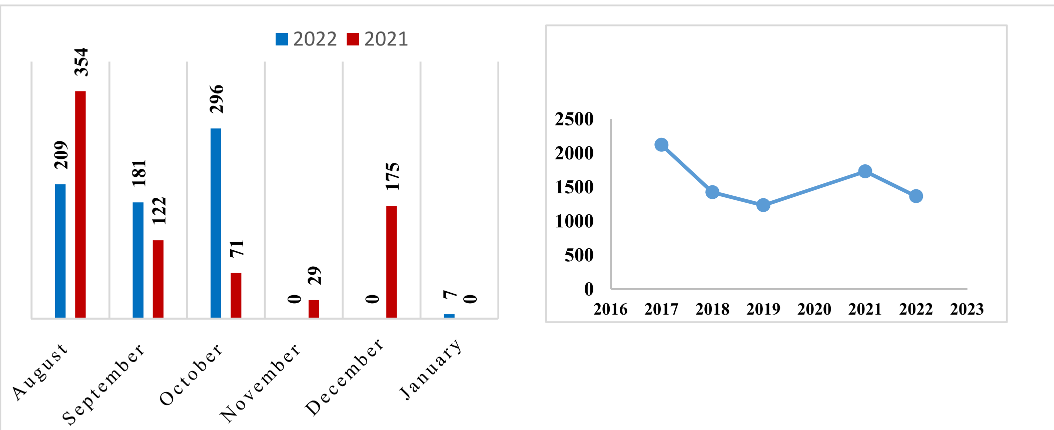

Fig. 1. Monthly average rainfall during the cropping season (year 2021–2022) (left) and yearly average rainfall (year 2017–2022) (right) of the experimental site.

nutritional status, and boron uptake [19].

However, hardly any research has been done to establish the optimum boron application rate and method for enhancing the yield-contributing characteristics and seed yield of jute (*Corchorus olitorius*). In Bangladesh, the high demand for jute seeds necessitates substantial imports, highlighting a need for increased domestic seed production. Given boron's role in enhancing seed yield and crop resilience, this study explores various application methods and doses to optimize jute seed yield in a cost-effective manner. It is hypothesized that specific boron doses and application methods will significantly improve yield-contributing traits and overall seed yield, with certain methods proving more economically advantageous for farmers. The aim of this study is to enhance jute seed production by identifying the most effective boron dose and application method for jute crops. Additionally, this research seeks to identify the key yield-contributing traits that account for the observed variance in production outcomes. Furthermore, the study will explore the most economical approaches to utilizing boron, an essential plant nutrient for jute seed production. This will ultimately contribute to addressing the shortage of high-quality jute seed in Bangladesh.

2. Methods

2.1. Experimental site and soil

The experiment was carried out at medium high land of Jute Research Regional Station, Faridpur, Bangladesh (Supplementary Fig. 1). The experimental location was under sub-tropical climatic condition located at 23°59′ north latitude and 89°82′ east longitude, and 12 m (m) above mean sea level. The average annual rainfall in the specified location from 2017 to 2022 amounted to 1576.2 mm (mm) (Fig. 1). The yearly average temperature experienced by the site for 2021 and 2022 were 27.6° Celsius (C) and 26.7 °C, respectively (Fig. 2). The calcareous dark grey soil from the Low Ganges River Floodplain's Agroecological Zone (AEZ 12) distinguished the soil at the experiment site. The soil within this Agroecological Zone (AEZ) was categorized as 'silt loam' with a notable presence of clay content [20]. Given the soil's critical limits, the soil's nutritional status ranged from very low to medium (Table 1).

2.2. Layout and crop husbandry utilized in the experiment

The experiment was carried out from August 25, 2021 to January 2022 as well as from August 27, 2022 to January 2023 respectively, covering the jute seed seasons of both years. Using a randomized complete block design and a 3 m (m) × 2.1 m unit plot size, a field experiment with ten treatments and three replications was set up. With a line-to-line distance of 30 cm (cm), a plot-to-plot distance of 60 cm, and a replication to replication distance of 1 m, seeds were sown using a continuous line approach maintaining direction north to south. The preferred cultivar for *Corchorus olitorius* was BJRI Tossa pat-8, a high-yielding jute cultivar released by the Bangladesh Jute Research Institute (BJRI). During land preparation, a power tiller was used to repeatedly plow and cross-plow the ground. The soil was laddered for levelling and breaking up the colds. To get the plot ready for seeding, weeds and stubbles were collected and removed. Before planting, seeds were uniformly treated with Provax 200 @ 5 g per kilogram (gm/kg) to prevent soil-borne diseases. With a wheel hoe, a furrow was carved to a depth of about 5 cm (cm), into which seed was sown and which was then completely covered with soil. To keep the land free of weeds and maintain an ideal population, weeding and thinning were done at 23 and 43 days after sowing (DAS). Paste control measures and ample irrigation was offered when it was necessary.

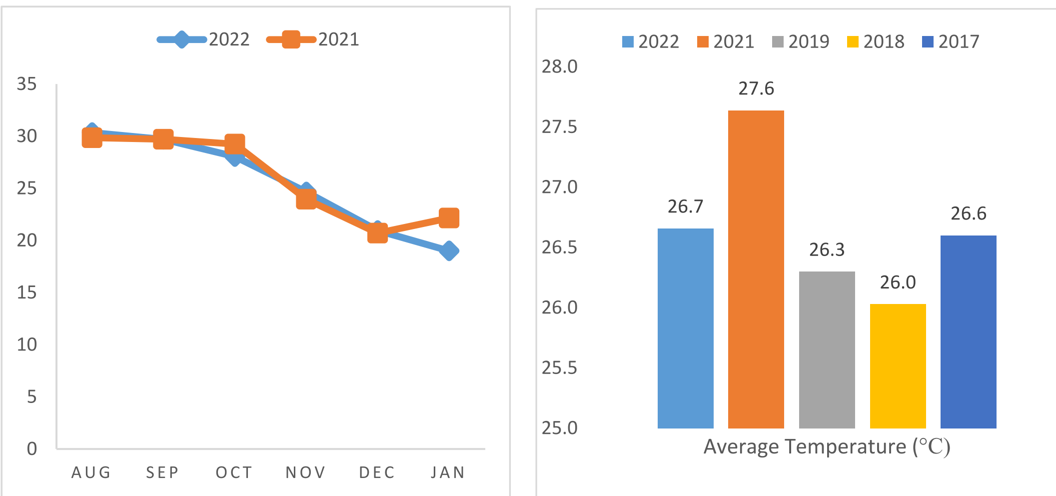

Fig. 2. Monthly average temperatures during the cropping season (year 2021–2022) (left) and yearly average temperatures (year 2017–2022) (right) of the experimental site.

Table 1
Physicochemical characteristics of the soil of the experimental site (year 2021 and 2022).

Parameters	Soil Test Value		Interpretation[a]	
	2021	2022	2021	2022
pH	7.4	7.5	Basic in nature	Basic in nature
% Organic matter	1.32	1.2	Low	Low
Total N (Kjeldahl)	0.12	0.09	Low	Low
Available P (Olsen method)	12.37 mg/g	13.01 mg/g	Low	Low
NH4OAc exchangeable K	0.2 mg/100 g	0.2 mg/100 g	Moderate	Moderate
CaCl2 extractable S	4.5 μg/g	4.0 μg/g	Very Low	Very Low
Zinc (Zn)	0.52 μg/g	0.65 μg/g	Low	Low
Boron (B)	0.14 μg/g	0.19 μg/g	Very low	Low

[a] Interpretation based on Fertilizer Recommendation Guide, (2018).

2.3. Fertilization and treatment implementation

The crop received an appropriate quantity of urea, diammonium phosphate (DAP), muriate of potash (MoP), and gypsum as a source of nitrogen, phosphorus, potassium, and sulfur. Ten boron fertilization treatments were generated, each with a different dose of boron (2 kg per hectare (kg/ha), 3 kg/ha, and 4 kg/ha), three application methods (basal, foliar, and basal + foliar), and a control treatment with no boron application (Table 2). Usually, farmers refrain from applying boron, yet the prescribed dose for *Corchorus olitorius* seed production stands at 3 kg/ha, as stipulated by the Fertilizer Recommendation Guide (FRG), 2018 [21]. Therefore, this dose, along with a reduced (2 kg/ha) and an augmented (4 kg/ha) dose, was chosen for treatment. On the other hand, basal application represents the traditional practice of fertilizer application where boron is applied to the soil before planting ensuring nutrient availability during early crop development. Foliar spray is the approach to address the need for mid-season nutrient correction or supplementation, targeting immediate uptake by the plant during critical growth stages. And combined basal and foliar application is a combination approach preferred to investigate whether a synergistic effect could be achieved by integrating both methods. A control treatment without boron is essential for benchmarking the effects of boron fertilization and understanding its impact compared to untreated plots. So ten treatments were formulated combining those doses and application methods to systematically investigate the effects of boron application on *Chorcorus olitorius* seed production while accounting for practical constraints, variability in farming practices, and economic considerations. The details of the treatment combinations as shown in Table 2 provides a comprehensive framework for understanding the interaction between boron doses and application methods.

All the diammonium phosphate (44 kg/ha), muriate of potash (60 kg/ha), gypsum (72 kg/ha), and half of the urea (108 kg/ha) were used during the final land preparation. The additional urea was distributed equally as top dressing at 25 days after sowing (DAS) and 45 DAS. The source of boron used was Solubor, which had 18 % boron content. Due to the Solubor's small quantity for the basal application, it was combined with ground-up dry soil to boost the quantity and aid in spreading it out evenly around the plot. For foliar application, the necessary amount of Solubor for each plot was diluted using water and sprayed with a hand sprayer over the foliage therein. Before spraying each plot, the sprayer was thoroughly rinsed with new water to remove any remaining adherent boron from the prior plot.

2.4. Crop harvesting and data collection

When 80 % of the capsules were mature and dark grey in color, the crop was harvested by severing the base with a sickle. To collect

Table 2
Details of the treatments employed in the experiment.

Methods	Treatments	Description
–	T_1	No Boron (control)
Method-1 (Basal application)	T_2	2.0 kg/ha boron (7.00 g/plot Solubor)- basal application
	T_3	3.0 kg/ha boron (11.00 g/plot Solubor)- basal application
	T_4	4.0 kg/ha boron (14.00 g/plot Solubor)- basal application
Method-2 (Foliar application in two equal splits)	T_5	2.0 kg/ha boron (7.00 g/plot Solubor)- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)
	T_6	3.0 kg/ha boron (11.00 g/plot Solubor)- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)
	T_7	4.0 kg/ha boron (14.00 g/plot Solubor)- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)
Method-3 (Half portion basal application and the rest half portion as a foliar spray in two equal splits)	T_8	2.0 kg/ha boron (7.00 g/plot Solubor) - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray
	T_9	3.0 kg/ha boron (11.00 g/plot Solubor) - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray
	T_{10}	4.0 kg/ha boron (14.00 g/plot Solubor) – half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray

information on average plant height, base diameter, the number of branches/plant, the number of capsules/plant, and the capsule's length, ten plants were randomly chosen from each plot. Each plot's plants were kept apart on the threshing floor, sun-dried, and then pounded with a bamboo stick to release the seed from the pod. Individually harvested and dried seeds from each plot were used for storage and data collecting on 1000- seed weights, seed production, and germination rate. To determine germination percentage (%), the methodology outlined by Ref. [22] was adopted. In each test, one hundred (100) normal seeds from every treatment combination were placed in a Petri dish on soaked blotting paper with distilled water. Three petri dishes were employed for each test. These dishes were then positioned in a germinator set at 30 °C under dark conditions for a duration of 4 days. Seedlings were tallied daily until the completion of germination on the fourth day. A seed was considered germinated if the seed coat ruptured and the radicle reached a length of up to 2 mm. The calculation of germination percentage followed the formula [23]:

Germination (%) = (Number of seeds germinated/Number of seeds placed on Petri dish) × 100.

The plant's height was measured using a measuring tape, and the base diameter was determined with slide calipers. The following formulae were used to compute the net benefit in BDT (taka) obtained over control treatment:

1. $Y_I = Y_B - Y_C$

Y_I = Yield increase (kg/ha) over control (no boron) due to application of boron; Y_B = Jute seed yield (kg/ha) due to application of boron; Y_C = Jute seed yield (kg/ha) without applying boron (control)

2. Net benefit in (taka/ha) obtained by farmers over control : $(Y_I \times P_S) - (R_B \times P_B)$

P_s = Selling price of jute seed (taka/kg); R_B = Application rate of boron (kg/ha) × P_B= Purchasing price of boron (Solubor) (taka/kg)

2.5. Statistical analysis

The data were analyzed using R 4.3.1 [24] through analysis of variance (ANOVA) following a randomized complete block design. Significant treatment effect ($p \leq 0.05$) were further examined through multiple mean comparisons using the Least Significant Difference (LSD) method at 5 %. Principal Component Analysis (PCA) was conducted using JMP 17 software.

Table 3
Comparative effect of different methods and doses of boron treatment on yield contributing characters (pooled) of *Corchorus olitorius* seed.

Treatments	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
	Plant Height (M)	Base Diameter (mm)	No. of Branches/ plant	No. of Capsule/ plant	Capsule Length (cm)	No. of Seeds/ Capsule	1000 Seed's weight (gm)
T1: No Boron (control)	1.41bc	6.74 ab	3.19 ab	10.03a	5.78d	166.48c	1.55b
T2: 2.0 kg/ha boron- basal application	1.46 ab	7.33a	3.31 ab	15.27d	6.89bc	196.28 ab	1.97a
T3: 3.0 kg/ha boron- basal application	1.43bc	6.76 ab	3.12 ab	14.53de	6.98bc	188.77bc	1.94a
T4: 4.0 kg/ha boron- basal application	1.51a	6.83 ab	3.37 ab	14.37de	6.80bc	197.62 ab	1.94a
T5: 2.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	1.46 ab	6.56 ab	3.12 ab	12.70e	7.13 ab	191.73 ab	1.98a
T6: 3.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	1.37c	6.05b	2.84b	17.88c	7.44a	213.50a	1.98a
T7: 4.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	1.49 ab	6.77 ab	3.39 ab	23.17a	6.89bc	209.91 ab	1.98a
T8: 2.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	1.45 ab	6.72 ab	3.07 ab	15.47d	6.73c	194.58 ab	2.00a
T9: 3.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	1.42bc	6.61 ab	3.19 ab	19.18bc	6.97bc	194.44 ab	2.01a
T10: 4.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	1.44abc	6.73 ab	3.51a	20.39b	7.02bc	196.95 ab	2.01a
% CV	2.92	6.87	10.95	8.39	3.01	6.68	3.49
Significance Level	NS	NS	NS	***	***	*	***

* Indicates a 5 % level of significance** indicates a 1 % level of significance and*** indicates a 0.1 % level of significance; *CV* = coefficient of variation. Pooled value = average value of two years.

3. Result

3.1. Effect of boron on yield contributing characters of *Corchorus olitorius*

Plant height, base diameter, and the number of branches/plant were all shown to be statistically insignificant, however, the application of boron significantly ($p < 0.001$) increased the number of capsules/plant in comparison to the control (Table 3). The highest number of capsules (23.17) was recorded with T7 (4.0 kg/ha boron -the half at 20–25 DAS and the rest half at the first flowering stage as a foliar spray), while the lowest (10.03) was observed in the (T1: no boron) control treatment (Table 3). Treatments involving foliar application of boron tended to produce more capsules per plant compared to basal applications (Table 3).

Capsule length also varied significantly ($p < 0.001$), with T6 (3.0 kg/ha boron foliar spray) producing the longest capsules (7.44 cm), and T1 (control) having the shortest capsules (5.78 cm). Capsule length also significantly respond to boron treatments ($p < 0.001$). The shortest capsules were recorded in the control treatment (T1), with an average length of 5.78 cm, while the longest capsules were found in T6 (3.0 kg/ha boron foliar spray), which reached an average of 7.44 cm. Other treatments involved in foliar application of boron such as T7 (4.0 kg/ha foliar spray) and T5 (2.0 kg/ha foliar spray) also produced relatively longer capsules 6.89 cm and 7.13 cm, respectively (Table 3).

Boron treatments significantly increased the number of seeds/capsule ($p < 0.05$). Based on pooled value, treatment T6 (3.0 kg/ha boron foliar spray) produced highest number of seeds/capsule which was average 213.50 seeds/capsule. Other treatment related to boron foliar application such as T5, T7, T8, T9 and T10 are also statistically similar to treatment T6 (3.0 kg/ha boron foliar spray) On the other hand, control treatment T1 (no boron) produced lowest number of seed/capsule i.e. 166.48 number of seed/capsule (Table 3).

Significant differences observed in the 1000-seed weight ($p < 0.001$), where treatments with boron application resulted in higher seed weights compared to the control. The lowest 1000-seed weight was recorded in the control treatment T1 (no boron) with 1.55 g, while the highest seed weight were observed in treatments T9 (3.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray) and T10 (4.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray), in both treatments the weight was 2.01 g. Foliar application treatments consistently produced heavier seeds than the basal application treatments, indicated the efficacy of foliar boron application in enhancing seed development and weight (Table 3).

3.2. The effect of boron application on seed yield

The application of boron had a significant impact on the seed yield in both years and in the pooled seed yield. The lowest seed yield was consistently obtained in both years from the control treatment T1, which did not receive any boron. In 2021, the seed yield for T1 was 457.67 kg/ha, which decreased further to 419.92 kg/ha in 2022, resulting in a pooled yield of 438.80 kg/ha. The highest seed yield was observed in T6 (3.0 kg/ha boron applied as a foliar spray) among the boron treatments, which produced 615.82 kg/ha in 2021 and 531.23 kg/ha in 2022, with a pooled yield of 573.53 kg/ha. This was closely followed by T7 (4.0 kg/ha boron foliar spray), which recorded seed yields of 591.15 kg/ha in 2021 and 534.02 kg/ha in 2022, leading to a pooled value of 562.59 kg/ha. The split application method (half basal and half foliar at various growth stages) also showcased a positive effect on seed yield. T10 (4.0 kg/ha boron applied as half basal and the rest in two foliar sprays) produced seed yields of 597.35 kg/ha in 2021 and 523.59 kg/ha in 2022,

Table 4
Effect of different methods and doses of boron treatment on yield and germination of *Corchorus olitorius* seed in 2021, 2022 and pooled.

Treatments	Seed yield (kg/ha)			% germination		
	2021	2022	Pooled	2021	2022	Pooled
T1: No Boron (control)	457.67f	419.92d	438.80d	85.33b	85.00b	85.17b
T2: 2.0 kg/ha boron- basal application	548.68d	456.06cd	502.37c	92.00a	92.00a	92.00a
T3: 3.0 kg/ha boron- basal application	540.74d	484.61bc	512.68bc	94.67a	96.33a	95.67a
T4: 4.0 kg/ha boron- basal application	504.23e	495.81abc	500.02c	95.67a	92.33a	94.00a
T5: 2.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	582.54bc	482.47bc	532.50b	91.00a	93.67a	92.33a
T6: 3.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	615.82a	531.23a	573.53a	91.00a	93.33a	92.16a
T7: 4.0 kg/ha boron- foliar spray (the half at 20–25 DAS and the rest half at the first flowering stage)	591.15 ab	534.02a	562.59a	92.67a	95.33a	94.00a
T8: 2.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	555.56d	485.37bc	520.46bc	92.67a	93.33a	93.00a
T9: 3.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	592.06 ab	522.45 ab	557.26a	92.00a	91.67a	91.83a
T10: 4.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray	597.35 ab	523.59 ab	560.47a	96.33a	93.33a	94.83a
% CV	3.99	5.21	2.49	5.53	3.36	2.48
Significance Level	***	**	***	*	*	**

* Indicates a 5 % level of significance ** indicates a 1 % level of significance and *** indicates a 0.1 % level of significance; *CV* = coefficient of variation, Pooled value = average value of two years.

with a pooled yield of 560.47 kg/ha, which was significantly higher than the control. In general, treatments involving foliar applications (T5–T10) showed better seed yield results compared to treatments with only basal application (T2-T4), indicating the efficacy of foliar application over basal application. The trend of lower seed yields in 2022 compared to 2021 was observed across most treatments, which could be attributed to environmental factors such as rainfall distribution, temperature fluctuations during the second growing season (Table 4).

As a result of the boron application, there was a significant yield advantage over the control treatment (Fig. 3). The magnitude of the seed yield advantage varied according to the treatments.

Based on pooled data the T6 treatment (3.0 kg/ha boron applied as a foliar spray) had the highest yield advantage, 134.73 kg/ha (30.70 %) over the control treatment, followed by 121.67 kg/ha (27.73 %) in the T10 (4.0 kg/ha boron - half as basal and ¼ th at 20–25 DAS and rest ¼ th at 40–45 DAS as foliar spray) treatment and 118.46 kg/ha (27.00 %) in the T9 treatment. The T4 treatment (4.0 kg/ha boron-basal application), on the other hand, had the lowest yield advantage of 61.22 kg/ha (13.95 %) over the control treatment (Fig. 3).

3.3. The effect of boron application on germination percentage

The germination percentage was also significantly affected by boron treatments. In both years, the lowest germination rates were observed in the control treatment (T1) with values of 85.33 % in 2021 and 85.00 % in 2022, resulting in a pooled average of 85.17 %. This indicates a remarkable decrease in seed quality and viability in the absence of boron application. The highest germination rate was observed in T3 (3.0 kg/ha boron basal application), with germination rates of 94.67 % in 2021 and 96.33 % in 2022, resulting in a pooled value of 95.67 %. Based on pooled average germination percentage all the boron treatments outperformed the control treatment with no boron and was statistically similar. The germination percentage exhibited lower variation between the two years compared to seed yield, which suggests that while environmental conditions might have influenced overall yield performance, seed quality (as indicated by germination) was more directly affected by the boron treatments (Table 4).

3.4. Benefit of boron application

Boron application on the *Corchorus olitorius* seed crop provided a net benefit to all boron treatments (Fig. 4). On the basis of pooled net benefit, treatment T6 provided the highest net benefit (22945 taka/ha) and the lowest net benefit found in the T4 treatment with a benefit of 8244.40 taka/ha. Method-2 was the most effective in both years, followed by method-3, and method-1 comparing at the same level of boron application. Among all the boron doses, applying at the rate of 3 kg/ha provided more net benefit in all application method (Fig. 4).

3.5. Principal component analysis (PCA)

Table 5 presents the variance % and eigenvalues of PCA analysis. In 2021, PC1 explained 42.97 % of the entire variance, PC2 explained 22.44 %, and PC3 explained 12.99 %. In 2022, PC1 explained 61.69 % of the total variance, PC2 explained 22.33 %, and PC3 explained 8.63 %. In 2021 and 2022, PC1, PC2, and PC3 accounted for 78.40 % and 92.65 % of the total variation, respectively. According to the Kaiser guidelines [25], eigenvalues greater than 1.0 are recognized as the descriptor of the variance in data collection.

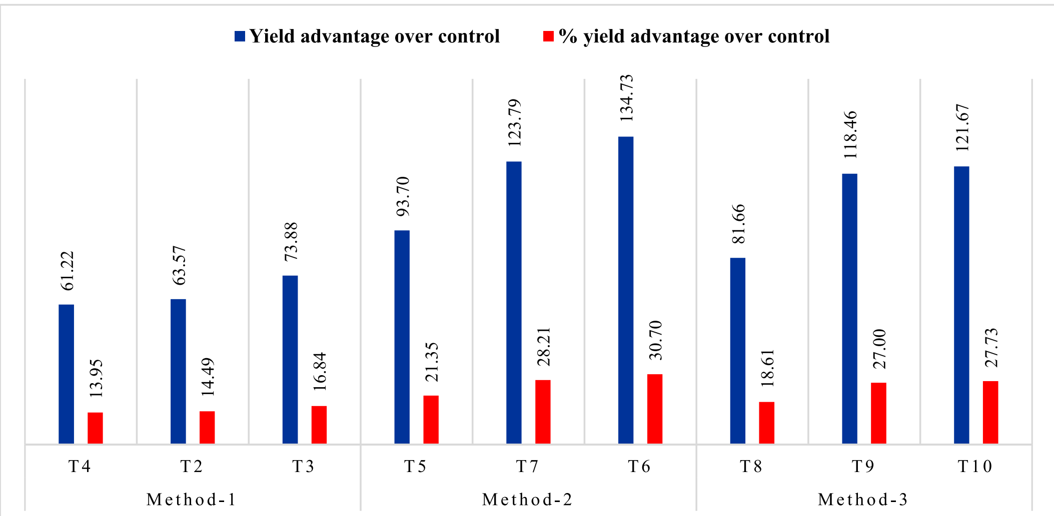

Fig. 3. Yield advantages and yield advantages percentage (%) due to different application methods of born over control treatment. (Based on pooled data).

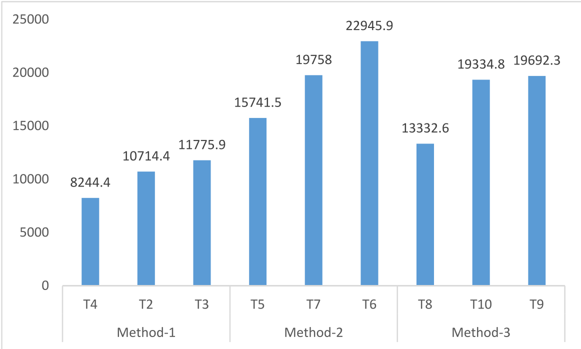

Fig. 4. Net benefit obtained due to boron application in different doses and methods (based on pooled data).

Table 5
The eigenvalues and the percentage of variance for the parameters of Principal Component Analysis (PCA).

Principal components	Years	Eigenvalue	Percentage	Cumulative Percentage
PC1	2021	3.86	42.97	42.97
	2022	5.55	61.69	61.69
PC2	2021	2.02	22.44	65.41
	2022	2.01	22.32	84.02
PC3	2021	1.17	12.99	78.40
	2022	0.77	8.62	92.64

PC1 = Principal Component 1, PC2 = Principal Component 2 and PC3 = Principal Component 3.

PC1 (3.87), PC2 (2.02), and PC3 (1.17) all had eigenvalues that were greater than 1.0 in 2021; but, in 2022, PC1 (5.55) and PC2 (2.01) had eigenvalues that were higher than 1.0.

Fig. 5 presents PCA graphs for the studied parameters on the application of boron. There were three groups in 2021. The first one included the number of seeds/capsule, capsule length, and seed yield. The second one consisted of plant height, the 1000- seed weights, the number of capsules/plant, and the germination percentage. And the last one included the number of branches/plant and base diameter. In 2022, there were also three groups: i. the number of seeds/capsule, capsule length, and the seed yield, ii. Plant height, 1000- seed weights, the number of capsules/plant, the germination percentage, and the number of branches/plant, and iii. Only base diameter.

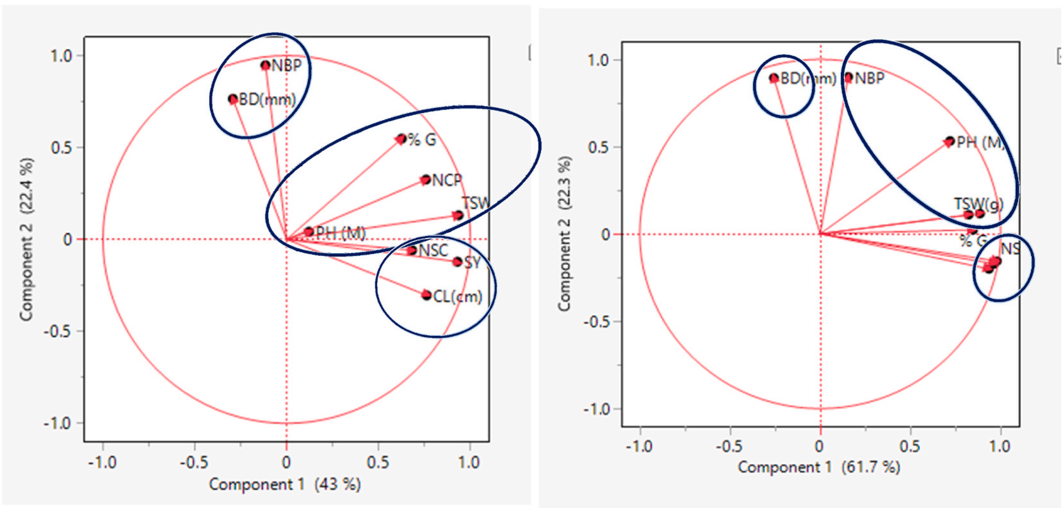

Fig. 5. PCA graph of boron application for investigated parameters of the year 2021 (left) and 2022 (right).
PH = Plant Height, BD = Base Diameter, NBP = Number of Branch/Plant, NCP = Number of Capsule/Plant, CL = Capsule length, NSC = Number of Seed/Capsule, TSW = Thousand Seed Weight, SY = Seed Yield, %G = Germination Percentage.

4. Discussion

In our experiment, plant height, base diameter, and the number of branches/plant showed no statistically significant response to varying methods and doses of boron application. However, previous studies on crops like cotton, tomato, soybean and summer tomato [26–29] have demonstrated significant effects of boron on these traits. The non-significant effect of boron on plant height, base diameter, and branch number of *Corchorus olitorius* may be due to the fact that these traits are primarily controlled by genetic factors and influenced more significantly by macro-nutrients [30,31]. As a micronutrient, boron mainly affects reproductive and cellular processes [32,33], which means its influence on structural growth may not be as prominent as its role in promoting reproductive functions like flower and seed development of *Corchorus olitorius*. The variation in boron's effects between *Corchorus olitorius* seed crop and other crops on non-significant traits suggests species-specific responses, requiring further detailed research.

Our experiment also revealed that the number of capsules/plant and capsule length were significantly influenced by boron application. This result partially aligns with findings by Ali et al. (2015), who reported that combined foliar applications of zinc and boron improved summer tomato growth and fruit yield [34]. Similarly, Abdel-Motagally and El-Zohri, (2018) observed that boron increased spike length in wheat (*Triticum aestivum* L.) [35]. This significant increase suggests that boron plays a pivotal role in reproductive development, likely enhancing flower fertility and capsule formation [36]. These findings align with boron's established function in promoting reproductive processes and seed setting in plants. Additionally, Haque (2024) noted that while boron has limited effects on structural traits like plant height and stem diameter, it is crucial for reproductive functions such as flowering and fruit set in crops like maize [37].

The research demonstrated that the application of boron significantly increased the number of seeds/capsule and the 1000-seed weights. Previous studies support this, with Long and Peng, (2023) showing that boron enhances seed numbers in fruits by improving pollen viability, stimulating pollen tube growth, and increasing fertilization efficiency, which promotes better seed setting and pod development [30]. Additionally, boron aids hormonal balance, enhancing flower retention and seed formation. Lei et al. (2009) further confirmed that boron greatly improves silique formation, seed setting, and seed yield in mustard, especially in boron-deficient soils [38]. The observed increase in seed numbers per capsule, capsule length, and 1000-seed weights aligns with findings by Refs. [13,39] and is partially consistent with [18], who reported similar results in separate mustard studies. Likewise, Ahmad et al. (2009) demonstrated that boron application improves seed formation and enhances grain development in various rice cultivars [9].

The results of this study regarding the effect of boron on yield-contributing traits of *Corchorus olitorius* seeds align with findings from various other studies conducted on different crops. Rab and Haq (2012) found that borax significantly increased the number of branches, flowers per cluster, and fruits per plant in tomatoes [40]. This aligns with Zheng et al. (2019), who observed that foliar boron application boosted reproductive growth and seed yields in *Moringa oleifera* [41]. Similar results were noted by Ref. [42] in soybeans. Foliar boron treatments also enhanced cotton yield and 1000-seed weights in studies by Refs. [43,44].

The application of boron significantly increased seed production over both years of the study. Specifically, the yield of *Corchorus olitorius* seeds improved with varying boron dosages compared to yields obtained without boron application. Generally, the concentration of boron in floral structures, such as the flowers, stamen, and pistil, rises with increased boron availability, enhancing flower formation, continuity, germination, pollen tube development, and overall seed and fruit development [9,45–48]. Moreover, the observed improvements in seed production may be attributed to the increased levels of organic matter and nutrients in the soil resulting from boron application. Naznin et al. (2020) demonstrated that the application of boron in black gram production led to elevated soil levels of organic matter, nitrogen, phosphorus, potassium, and boron post-harvest [49]. Supporting this, Mumivand et al. (2021) and Yadav et al. (2016) reported that boron application enhanced yield-contributing traits and seed yields in mustard and *Satureja khuzistanica*, respectively [13,50]. Additionally, Halim et al. (2023) found that a combination treatment of zinc and boron increased mustard seed production [51]. Öktem (2022) similarly reported that combined soil and foliar boron treatment maximized grain production in lentils [52]. Furthermore, Maqbool et al. (2018) highlighted that applying boron optimized the growth, yield, and seed protein content of mungbean, particularly under both normal and water-stressed conditions [53]. Soylu et al. (2004) found that applications of boron significantly increased the grain yields of *Triticum durum* Desf. across all genotypes compared to the control [54].

The addition of boron significantly improved seed germination rates over both years of the study, with the highest germination percentage achieved through combined basal and foliar applications. Similar findings were reported by Ref. [55] in their research on *Parthenium argentatum* seeds. This study underscores the importance of boron in enhancing seed germination and quality, as supported by Ref. [56]. Boron contributes to the structural integrity of cell walls by facilitating pectin formation, which is essential for cell division and elongation. Additionally, it supports root system development and enhances the uptake and transport of essential nutrients, collectively leading to increased germination rates and improved seedling vigor [30,57,58]. These cumulative effects can elucidate the enhanced seed yield and germination percentage observed in *Corchorus olitorius*, as these factors are critical determinants of crop seed yield and quality.

The study indicated that a foliar application of 3 kg/ha of boron resulted in the highest seed yield. Boron can be applied through soil for root absorption or via foliar spray, though literature presents mixed results regarding foliar boron application. For instance, positive outcomes have been observed in almonds [59], while other studies reported no significant differences between basal and foliar sprays [60]. Positive effects of foliar boron application have also been reported for wheat, potato, and barley [61–63]. In distinct investigations, Dey et al. (2023) and Sabry et al. (2023) independently showcased that the foliar application of boron resulted in an increase in sesame seed yield [64,65]. In dry soil conditions, root uptake is often limited, making foliar application a more effective method to fulfill boron needs [58]. Given the typically dry conditions during *Corchorus olitorius* seed production in the study region, foliar application proved more effective than soil application for meeting the plant's boron requirements.

The study emphasizes that the application of boron at optimal rates substantially increases farmers' net benefits by significantly improving the seed yield of *Corchorus olitorius* over both years. Sarker et al. (2007) similarly observed that foliar boron application provided superior economic returns compared to soil application for crops such as wheat, potato, and mustard [66]. Hussain et al. (2012) also demonstrated that optimal boron levels maximize net financial gains in rice farming [67]. Priyanka et al. (2022) found that the benefit-cost ratio and net return improved when boron and plant growth regulators were applied at recommended rates [68].

Excessive boron, however, can be harmful to plants, as shown by Refs. [69,70], and [71], who noted its toxic effects on agronomic crops. Thus, applying boron at optimal levels is crucial to maximizing economic benefits and avoiding yield losses due to deficiencies or toxicities [46,72]. A balanced approach ensures that crops receive the necessary nutrients without exceeding tolerance thresholds.

5. Conclusion

The field experiment aimed to evaluate the cumulative effects of different doses and application methods of boron on the seed production of *Corchorus olitorius*. The results demonstrated that all boron treatments significantly enhanced seed yield for late-season jute seed production compared to the control. Among the treatments, a foliar application of boron at 3 kg/ha applied in two splits, half at 20–25 DAS and the remainder at the first flowering stage consistently outperformed all other treatments across both years. Based on these findings, this dose and application method are recommended for optimizing *Corchorus olitorius* seed production in subtropical regions of Bangladesh.

CRediT authorship contribution statement

Tapan Kumar: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pritthee Mallick Tama:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Syed Aflatun Kabir Hemel:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation. **Ranjit Kumar Ghosh:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Md Imran Ali:** Writing – review & editing, Validation, Resources, Funding acquisition. **Abdullah Al-Bakky:** Writing – review & editing, Resources, Funding acquisition. **Abdul Alim:** Writing – review & editing, Visualization, Validation, Resources, Funding acquisition.

Consent to participate

Not applicable.

Ethics approval

Not applicable.

Consent for publication

Not applicable.

Data availability

The analyzed datasets will be made available on reasonable request. For requesting data, please write to the corresponding author.

Code availability

Not applicable.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article. The study's design, data analysis, publishing choice, and article preparation were all done independently from the funders.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Tapan Kumar reports administrative support was provided by Bangladesh Jute Research Institute. Tapan Kumar reports a relationship with Bangladesh Jute Research Institute that includes: employment.

Acknowledgment

We are grateful to the reputable professionals at the Jute Research Regional Station, Faridpur.

Bangladesh, for their kind collaboration and technical support during the study. The Soil Science Department under The Agronomy Division of Bangladesh Jute Research Institute and their instructing support throughout the study's period are also deserving of our gratitude.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2025.e42320.

References

[1] M.I. Ali, S. Monira, T. Kumar, S.N. Islam, S.A. Kabir Hemel, M.A. Islam, Assessment of optimal sowing time for seed production of Bjri Deshi Pat-10 under the Ganges tidal floodplain of Bangladesh, Trop. Agrobiodiver. 4 (2) (2023) 48–52. https://www.researchgate.net/publication/380824085.

[2] M. Al-Mamun, C. Saha, M. Mostofa, A. Miah, M. Hossain, Identification of suitable varieties for seed production of jute in non-traditional areas of Bangladesh, Bangladesh J. Plant Breed Genet. 30 (1) (2017) 33–38. https://www.banglajol.info/index.php/BJPBG/article/view/36531/24610.

[3] Statista, Jute Production in the Asia-Pacific Region in 2021, by Country, Statista, 2023. Retrieved from, https://www.statista.com/statistics/679345/asia-pacific-jute-production-by-country/.

[4] S. Akter, M.N. Sadekin, N. Islam, Jute and jute products of Bangladesh: Contributions and challenges, Asian Bus. Rev. 10 (3) (2020) 143–152, https://doi.org/10.18034/abr.v10i3.480.

[5] S. Rahman, M.M.H. Kazal, I.A. Begum, M.J. Alam, Exploring the future potential of jute in Bangladesh, Agriculture 7 (12) (2017) 96, https://doi.org/10.3390/agriculture7120096.

[6] D. Gupta, P. Sahu, R. Banerjee, Forecasting jute production in major contributing countries in the world, J. Nat. Fibers 6 (2) (2009) 127–137, https://doi.org/10.1080/15440470902931436.

[7] M.M. Islam, M.N. Uddin, Research and development advances of jute seed in Bangladesh: a review, Hayat: Saudi J. Sci. 4 (2) (2019) 52–68. https://www.researchgate.net/publication/332250075.

[8] M.M. Islam, A.T.M.M. Alam, Agronomic research and advancement in jute crop in Bangladesh (Sub-theme paper), in: Souvenir: 11th Conference on Advances in Agronomic Research under Changing Environment in Bangladesh, Bangladesh Agricultural Research Institute, 2012. Joydebpur, Gazipur-1701, Bangladesh, https://www.researchgate.net/publication/322266396.

[9] W. Ahmad, A. Niaz, S. Kanwal, Rahmatullah, M.K. Rasheed, Role of boron in plant growth: a review, J. Agric. Res. 47 (3) (2009) 329–338. Retrieved from, https://www.researchgate.net/publication/235674754_Role_of_boron_in_plant_growth_a_review.

[10] P.H. Brown, F.-J. Zhao, A. Dobermann, What is a plant nutrient? Changing definitions to advance science and innovation in plant nutrition, Plant Soil 476 (1–2) (2022) 11–23, https://doi.org/10.1007/s11104-021-05171-w.

[11] S.M. Mousavi, T. Raiesi, Essentiality of boron in higher plants, in: S.M. Mousavi, T. Raiesi (Eds.), Boron in Plants and Agriculture, Elsevier, 2022, pp. 1–28. https://shop.elsevier.com/books/boron-in-plants-and-agriculture/aftab/978-0-323-90857-3.

[12] M.M.H. Khan, N. Ahmed, U. Ghafoor, M. Ali, M.A. Ali, M. Irfan, S. Maqsood, S. Khan, S.H. Abdel-Hafez, R. Ali, S.M.B. Asdaq, N.M. Alabdallah, A.T.K. Zuan, S. Danish, R. Datta, Synchronization of boron application methods and rates is an environmentally friendly approach to improve quality attributes of *Mangifera indica L.* on a sustainable basis, Saudi J. Biol. Sci. 29 (3) (2022) 1869–1880, https://doi.org/10.1016/j.sjbs.2021.10.036.

[13] S. Yadav, S. Singh, O. Kumar, Effect of boron on yield attributes, seed yield, and oil content of mustard (*Brassica juncea L.*) on an Inceptisol, J. Indian Soc. Soil Sci. 64 (3) (2016) 291–296, https://doi.org/10.5958/0974-0228.2016.00041.4.

[14] N.Q. Khuong, L.V. Thuc, N.T.B. Tran, T.N. Huu, J.-I. Sakagami, Foliar application of boron positively affects the growth, yield, and oil content of sesame (*Sesamum indicum L.*), Open Agri. 7 (1) (2022) 30–38, https://doi.org/10.1515/opag-2022-0067.

[15] M. Al-Amery, J. Hamza, M. Fuller, Effect of boron foliar application on reproductive growth of sunflower (*Helianthus annuus L.*), Int. J. Agron. 230712 (2011), https://doi.org/10.1155/2011/230712.

[16] A. Asad, F. Blamey, D. Edwards, Effects of boron foliar applications on vegetative and reproductive growth of sunflower, Ann. Bot. 92 (4) (2003) 565–570, https://doi.org/10.1093/aob/mcg179.

[17] G. Arredondo, C. Bonomelli, Effect of three boron concentrations in soil on growth and physiology in sweet cherry trees, Plants 12 (6) (2023) 1240, https://doi.org/10.3390/plants12061240.

[18] S. Choudhary, A. Zehra, M. Naeem, M.M.A. Khan, T. Aftab, Effects of boron toxicity on growth, oxidative damage, antioxidant enzymes, and essential oil fingerprinting in *Mentha arvensis* and *Cymbopogon flexuosus*, Chem. Biol. Technol. Agri. 7 (2020) 1–11, https://doi.org/10.1186/s40538-019-0175-y.

[19] S.L.O. Silva, R. de Mello Prado, G.P. da Silva, G.B. da Silva Júnior, M.L. Rossi, L.C. González, Effects of boron omission and foliar fertilization on nutrition efficiency and production of cowpea, Hortscience 53 (11) (2018) 1683–1688, https://doi.org/10.21273/HORTSCI13154-18.

[20] M.H. Rahman, A.Z.M. Moslehuddin, D.K. Saha, I.U. Ahmed, K. Egashira, Mineralogy of soils from different agroecological regions of Bangladesh: region 12-low Ganges River Floodplain, Clay Sci. 12 (2005) 321–326. https://www.jstage.jst.go.jp/article/jcssjclayscience1960/12/6/12_6_321/_pdf.

[21] Fertilizer recommendation Guide. https://moa.portal.gov.bd/sites/default/files/files/moa.portal.gov.bd/page/9d1b92d4_1793_43af_9425_0ed49f27b8d0/FRG-2018%20%28English%29.pdf, 2018.

[22] M.N. Uddin, S.M. Ali, M.A. Sadat, M.A.H. Chowdhury, I.J. Mumu, M.Z. Tareq, Mid-storage seed hardening: a mechanical method to maintain seed viability during long-term jute seed preservation, Plant Sci. Today 8 (1) (2021) 79–88, https://doi.org/10.14719/pst.2021.8.1.916.

[23] V. Krishnasamy, D.V. Seshu, Germination after accelerated ageing and associated characters in rice varieties, Seed Sci. Technol. 18 (1990) 147–156. https://www.semanticscholar.org/paper/Germination-after-accelerated-ageing-and-associated-Krishnasamy-Seshu/29bc57d9a8b05e1db5618272a7bf6a214c0a5ba7.

[24] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, 2023. https://www.r-project.org/.

[25] H.F. Kaiser, The application of electronic computers to factor analysis, Educ. Psychol. Meas. 20 (1) (1960) 141–151, https://doi.org/10.1177/001316446002000116.

[26] E. Karademir, C. Karademir, Effect of different boron applications on cotton yield components and fiber quality properties, Cercetări Agron. Moldova 52 (2020) 341–352, https://doi.org/10.46909/cerce-2019-0033.

[27] M.S. Rahman, M.R. Hossain, A. Hossain, M.I. Khan, Impact of foliar boron application on the growth and yield of summer tomato, J. Agroforestr. Environ. 16 (2023) 58–63, https://doi.org/10.55706/jae1608.

[28] S. Das, S.K. Paul, M.R. Rahman, S. Roy, F.M.J. Uddin, M.H. Rashid, Growth and yield response of soybean to sulfur and boron application, J. Bangladesh Agric. Univ. 20 (1) (2022) 12–19, https://doi.org/10.5455/JBAU.100644.

[29] M. Sanjida, J. Howlader, M.R. Akon, T. Ahmed, Effects of varieties and boron on growth and yield of summer tomato, Asian J. Crop, Soil Sci. Plant Nutr. 4 (1) (2020) 141–149, https://doi.org/10.18801/ajcsp.040120.18.

[30] Y. Long, J. Peng, Interaction between boron and other elements in plants, Genes 14 (1) (2023) 130, https://doi.org/10.3390/genes14010130.

[31] F. Shireen, M.A. Nawaz, C. Chen, Q. Zhang, Z. Zheng, H. Sohail, J. Sun, H. Cao, Y. Huang, Z. Bie, Boron: functions and approaches to enhance its availability in plants for sustainable agriculture, Int. J. Mol. Sci. 19 (7) (2018) 1856, https://doi.org/10.3390/ijms19071856.

[32] H.E. Goldbach, Q. Yu, R. Wingender, M. Schulz, M. Wimmer, P. Findeklee, F. Baluška, Rapid response reactions of roots to boron deprivation, J. Plant Nutr. Soil Sci. 164 (2001) 173–181, https://doi.org/10.1002/1522-2624(200104)164:2<173::AID-JPLN173>3.0.CO;2-F.

[33] K. Miwa, T. Fujiwara, Boron transport in plants: Co-ordinated regulation of transporters, Ann. Bot. 105 (2010) 1103–1108, https://doi.org/10.1093/aob/mcq044.

[34] M. Ali, H. Mehraj, A. Jamal Uddin, Effects of foliar application of zinc and boron on growth and yield of summer tomato, J. Biol. Agri. Res. 6 (1) (2015) 512–517, https://doi.org/10.18801/jbar.060115.61.

[35] F. Abdel-Motagally, M. El-Zohri, Improvement of wheat yield grown under drought stress by boron foliar application at different growth stages, J. Biol. Agri. Res. 17 (2) (2018) 178–185, https://doi.org/10.1016/j.jssas.2016.03.005.

[36] G.L. Pereira, J.A. Siqueira, W. Batista-Silva, F.B. Cardoso, A. Nunes-Nesi, W.L. Araújo, Boron: more than an essential element for land plants? Front. Plant Sci. 11 (2021) 610307 https://doi.org/10.3389/fpls.2020.610307.

[37] M.A. Haque, Boron impact on maize growth and yield: a review, Int. J. Plant Soil Sci. 36 (6) (2024) 353–363, https://doi.org/10.9734/ijpss/2024/v36i64637.

[38] S. Lei, W. Yun-Hua, N. Fu-Zhao, L. Jian-Wei, M. Jin-Ling, X. Fang-Sen, Inheritance of boron efficiency in oilseed rape, Pedosphere 19 (2009) 403–408, https://doi.org/10.1016/S1002-0160(09)60132-6.

[39] M.A. Masum, M.N.H. Miah, M.N. Islam, M.S. Hossain, P. Mandal, A.P. Chowdhury, Effect of boron fertilization on yield and yield attributes of mustard (var. BARI Sarisha-14), J. Biosci. Agri. Res. 20 (2) (2019) 1717–1723, https://doi.org/10.18801/jbar.200219.209.

[40] A. Rab, I.-u. Haq, Foliar application of calcium chloride and borax influences plant growth, yield, and quality of tomato (*Lycopersicon esculentum* Mill.) fruit, Turk. J. Agric. For. 36 (6) (2012) 695–701, https://doi.org/10.3906/tar-1112-7.

[41] Y. Zheng, J. Wu, X. Peng, Y. Zhang, Field-grown *Moringa oleifera* response to boron fertilization: yield component, chemical composition of seed-oil, and physiology, Ind. Crop. Prod. 138 (2019) 111449, https://doi.org/10.1016/j.indcrop.2019.06.012.

[42] M.K. Schön, D.G. Blevins, Foliar boron applications increase the final number of branches and pods on branches of field-grown soybeans, Plant Physiol. 92 (3) (1990) 602–607, https://doi.org/10.1104/pp.92.3.602.

[43] M. Yaseen, W. Ahmed, M. Shahbaz, Role of foliar feeding of micronutrients in yield maximization of cotton in Punjab, Turk. J. Agric. For. 37 (4) (2013) 420–426, https://doi.org/10.3906/tar-1206-56.

[44] M. Azeem, Y. Shoujun, M. Qasim, M.W. Abbasi, N. Ahmed, T. Hanif, M.Y. Adnan, R. Ahmed, Foliar enrichment of potassium and boron overcomes salinity barriers to improve growth and yield potential of cotton (*Gossypium hirsutum* L.), J. Plant Nutr. 44 (3) (2021) 438–454, https://doi.org/10.1080/01904167.2020.1845365.

[45] S. Day, M. Aasim, Role of boron in growth and development of plant: deficiency and toxicity perspective, in: T. Aftab, K.R. Hakeem (Eds.), Plant Micronutrients, Springer, 2020, pp. 1–14, https://doi.org/10.1007/978-3-030-49856-6_19.

[46] H. Bariya, S. Bagtharia, A. Patel, Boron: a promising nutrient for increasing growth and yield of plants, in: M. Hawkesford, S. Kopriva, L. De Kok (Eds.), Nutrient Use Efficiency in Plants, Plant Ecophysiology, vol. 10, Springer, 2014, pp. 47–62, https://doi.org/10.1007/978-3-319-10635-9_6.

[47] A.L. De Silva, W. Kämper, H.M. Wallace, S.M. Ogbourne, S. Hosseini Bai, J. Nichols, S.J. Trueman, Boron effects on fruit set, yield, quality, and paternity of *Macadamia*, Agronomy 12 (3) (2022) 684, https://doi.org/10.3390/agronomy12030684.

[48] S.K. Kohli, H. Kaur, K. Khanna, R. Kaur, Boron in plants: uptake, deficiency, and biological potential, Plant Growth Regul. 100 (2023) 267–282, https://doi.org/10.1007/s10725-022-00844-7.

[49] F. Naznin, M.A. Hossain, M.A. Khan, M.A. Islam, A.K.M.H. Rahman, Effect of boron on growth, yield, and nutrient accumulation in black gram, Agriculturists 18 (2) (2020) 34–43. Retrieved from, https://www.researchgate.net/publication/350799499_Effect_of_Boron_on_Growth_Yield_and_Nutrient_Accumulation_in_Black_Gram.

[50] H. Mumivand, P. Khanizadeh, M.R. Morshedloo, K. Żuk-Gołaszewska, T. Horaczek, H.M. Kalaji, Improvement of growth, yield, seed production, and phytochemical properties of *Satureja khuzistanica* by foliar application of boron and zinc, Plants 10 (11) (2021) 2469, https://doi.org/10.3390/plants10112469.

[51] A. Halim, S.K. Paul, M.A.R. Sarkar, M.H. Rashid, S. Perveen, M.L. Mia, M.S. Islam, A.K.M.M. Islam, Field assessment of two micronutrients (zinc and boron) on the seed yield and oil content of *Mustard*, Seeds 2 (2023) 127–137, https://doi.org/10.3390/seeds2010010.

[52] A.G. Öktem, Effects of different boron applications on seed yield and some agronomical characteristics of red lentil, Turkish J. Field Crops 27 (1) (2022) 112–118, https://doi.org/10.17557/tjfc.1106779.

[53] R. Maqbool, W. Ali, M.A. Nadeem, T. Abbas, Boron application in clay-loam soil for improved growth, yield, and protein contents of mungbean in water-stressed conditions, Sains Malays. 47 (1) (2018) 51–58, https://doi.org/10.17576/jsm-2018-4701-06.

[54] S. Soylu, A. Topal, B. Sade, N. Akgün, S. Gezgin, M. Babaoglu, Yield and yield attributes of durum wheat genotypes as affected by boron application in boron-deficient calcareous soils: an evaluation of major Turkish genotypes for boron efficiency, J. Plant Nutr. 27 (6) (2004) 1077–1106, https://doi.org/10.1081/PLN-120037537.

[55] H. Zhu, G. Bañuelos, Influence of salinity and boron on germination, seedling growth, and transplanting mortality of *Guayule*: a combined growth chamber and greenhouse study, Ind. Crop. Prod. 92 (2016) 236–243, https://doi.org/10.1016/j.indcrop.2016.07.027.

[56] A. Archana, P. Verma, N. Pandey, Impact of inadequate concentration of boron in seed storage proteins content in oilseed crops, IntechOpen 11 (2021) 175–188, https://doi.org/10.5772/intechopen.95873.

[57] S. Mandloi, J. Bangre, S. Chicham, Important functions of boron in crop production and how to manage it, Zenodo 2 (2023) 232–237, https://doi.org/10.5281/zenodo.7893405.

[58] Q. Atique-Ur-Rehman, R. Qamar, A. Hussain, H. Sardar, N. Sarwar, H.M.R. Javeed, A. Maqbool, M. Hussain, Soil applied boron (B) improves growth, yield, and fiber quality traits of *Cotton* grown on calcareous saline soil, PLoS One 15 (5) (2020) e0231805, https://doi.org/10.1371/journal.pone.0231805.

[59] A.M. Nyomora, P.H. Brown, B. Krueger, Rate and time of boron application increase almond productivity and tissue boron concentration, Hortscience 34 (2) (1999) 242–245, https://doi.org/10.21273/HORTSCI.34.2.242.

[60] M. Arrobas, A. Ribeiro, D. Barreales, E.L. Pereira, M.Â. Rodrigues, Soil and foliar nitrogen and boron fertilization of almond trees grown under rainfed conditions, Eur. J. Agron. 106 (2019) 39, https://doi.org/10.1016/j.eja.2019.02.014.

[61] M.A. Saleem, M. Tahir, T. Ahmad, M. Tahir, Foliar application of boron improved the yield and quality of wheat (*Triticum aestivum* L.) in a calcareous field, Soil Environ. 39 (2020) 59–66, https://doi.org/10.25252/SE/20/132047.

[62] M.A. Ewais, L.A. Abd El-Rahman, D.A. Sayed, Effect of foliar application of boron and potassium sources on yield and quality of potato (*Solanum tuberosum* L.), Middle East J. Appl. Sci. 10 (1) (2020) 120–137, https://doi.org/10.36632/mejas/2020.10.1.15.

[63] S. Ahmad, T. Raza, S. Imran, N. Khan, W. Ashiq, T. Flynn, Foliar application of boron improves the growth and yield in barley (*Hordeum vulgare* L.), Bull. Univ. Agric. Sci. Vet. Med. Cluj-Napoca. Food Sci. Technol. 78 (2021) 11–17, https://doi.org/10.15835/buasvmcn-fst:2021.0013.

[64] A. Dey, M. Begum, M.S. Kabiraj, M.H. Rashid, S.K. Paul, Influence of foliar application of boron on the growth, yield, and quality of sesame (cv. BARI Til-4), Turkish J. Agri. Forestr. Sci. Technol. 11 (12) (2023) 2356–2364, https://doi.org/10.24925/turjaf.v11i12.2356-2364.6326.

[65] N.A. Sabry, W.A.T. Fahdawi, M.A. Hamed, Investigating sowing date and foliar application of boron effects on some growth and yield parameters of sesame (*Sesamum indicum* L.), IOP Conf. Ser. Earth Environ. Sci. 1158 (2023) 062029, https://doi.org/10.1088/1755-1315/1158/6/062029.

[66] D. Sarker, B. Mandal, M.C. Kundu, Increasing use efficiency of boron fertilisers by rescheduling the time and methods of application for crops in India, Plant Soil 301 (2007) 77–85, https://doi.org/10.1007/s11104-007-9423-1.

[67] M. Hussain, M.A. Khan, M.B. Khan, M. Farooq, S. Farooq, Boron application improves growth, yield and net economic return of rice, Rice Sci. 19 (3) (2012) 259–262, https://doi.org/10.1016/S1672-6308(12)60049-3.

[68] G. Priyanka, B.M. Krishna, H.S. Kumar, R.S. Kumar, J. Dawson, Effect of boron application and plant growth regulator on growth and yield of maize (*Zea mays* L.), Pharm. Innov. 11 (3) (2022) 1679–1682. Retrieved from, https://www.thepharmajournal.com/archives/2022/vol11issue3/PartV/11-3-122-192.pdf.

[69] R. Kastori, I. Maksimovic, M. Kraljevic-Balalic, B. Kobiljski, Physiological and genetic basis of plant tolerance to excess boron, Zbornik Matice Srpske za Prirodne Nauke 114 (2008) 41–51, https://doi.org/10.2298/ZMSPN0814041K.
[70] M.K. Souri, M. Hatamian, Aminochelates in plant nutrition: a review, J. Plant Nutr. 42 (2019) 67–78, https://doi.org/10.1080/01904167.2018.1549671.
[71] K. Khalaj, N. Ahmadi, M.K. Souri, Improvement of postharvest quality of Asian pear fruits by foliar application of boron and calcium, Horticulturae 3 (1) (2016) 15, https://doi.org/10.3390/horticulturae3010015.
[72] M. Öztürk, S. Sakcali, S. Gucel, Boron and plants, in: M. Ashraf, M. Öztürk, M. Ahmad (Eds.), Plant Adaptation and Phytoremediation, Springer, 2010, pp. 231–240, https://doi.org/10.1007/978-90-481-9370-7_13.