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EFFECT OF SEAWEED EXTRACT AND BORON APPLICATION ON GROWTH AND YIELD OF OKRA (*ABELMOSCHUS ESCULENTUS* L.)

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Abstract

Okra (*Abelmoschus esculentus* L.) is an important vegetable crop valued for its nutritional and economic significance. Optimal nutrient management, including micronutrients and natural bio stimulants, plays a key role in enhancing growth and yield. Seaweed extracts and boron have been reported to improve plant physiological processes and yield components in various crops. Therefore, this study aimed to evaluate the effects of foliar-applied seaweed extract and boron on the growth, yield, and related attributes of okra under field conditions in Peshawar, Pakistan. A field trial was conducted at the Horticulture Research Farm, University of Agriculture, Peshawar, following a Randomized Complete Block Design (RCBD) with three replications. The results indicated that the application of seaweed extract at a concentration of 40 mL L^{-1} produced the maximum plant height (220.92 cm), highest number of pods per plant (39.26), longest pods (13.94 cm), widest pod diameter (16.73 mm), heaviest pods (13.69 g), highest fresh pod yield (23.61 t ha^{-1}), and the earliest flowering (41.08 days) and first pod harvest (46.25 days). Similarly, boron applied at 0.6% improved plant height (219.92 cm), pod number per plant (37.73), pod length (13.12 cm), enhanced pod diameter (15.42 mm), average pod weight (13.02 g), and fresh pod yield (22.11 t ha^{-1}), while shortening the period to first flowering (44.58 days) and initial harvesting (49.58 days). Overall, the results demonstrated that foliar application of seaweed extract at 40 mL L^{-1} in combination with 0.6% boron significantly improved vegetative growth and yield attributes of okra. Therefore, this treatment is suggested as an effective practice for okra cultivation under the agro-climatic conditions of Peshawar.

Keywords: Boron, Seaweed Extract, Foliar Application, Benefit Cost Ratio, Okra.

INTRODUCTION

Okra, classified under Malvaceae family with the scientific name *Abelmoschus esculentus*, also goes by the common name "Lady's Finger." The origins of okra are rooted in Ethiopia; however, it was cultivated across a variety of countries such as Sudan, Egypt, and Nigeria (Naheed *et al*., 2013). Okra goes by many different names across different cultures of the world. Some of these common names include "Ochro" in many languages of the world, "Okoro" in West Africa, "Okra Crop" in Nigeria, "Quimgombo" in Sudan, "Gombo" in West Africa and Malaysia, "Kopi" in Malaysia, and "Bamia" in Arab Countries. In America, okra's common name in regions such as Southern America is "Gumbo"; in Pakistan, okra's local name is "Bhindi." Okra was cultivated in Bangladesh, Iran, Japan, Afghanistan, Pakistan, (Benjawan *et al*., 2007).

Pakistan contributes 8.6% of the world's total okra production (Canton, 2021). Okra was grown on about 25802 hectares of land in Pakistan, with an annual production of 279987 tonnes. Okra was grown on 2126 hectares of land in Khyber-Pakhtunkhwa, with 15559 tonnes produced there annually (MINNFSR, 2021). Okra is especially valuable in human diets because of its nutritional significance. Scientific evidence indicates that okra pods are rich in essential vitamins, including vitamin A (36 µg per 100 g), vitamin K (53 µg per 100 g), and vitamin C (21 mg per 100 g) as reported by the USDA (2019).

Significant concentrations of calcium (82 mg/100g), magnesium (57 mg/100g), iron (0.6 mg/100g), and potassium (299 mg/100g) are present in the mineral composition (Falade *et al.,* 2020). Together, these nutrients support many facets of human health, especially cardiovascular regulation, bone health, and immune function. Furthermore, okra has important antioxidants like polyphenols and flavonoids which possess strong anti-free radical properties (Arapitsas, 2008). The distinctive mucilage of the vegetable, which is rich in polysaccharides, has demonstrated potential health advantages such as lowering cholesterol and promoting gastrointestinal health (Lengsfeld *et al.*, 2004).

Okra needs well-drained, fertile soils with a pH of 6.0–6.8, which is slightly acidic to neutral, and warm temperatures between 25 and 35°C for the best growth (Kumar *et al.,* 2010). Although the crop has a moderate tolerance for drought, it greatly benefits from steady soil moisture in order to maximize yields and preserve pod quality. Okra is especially well-suited for smallholder farmers in tropical and subtropical areas due to its adaptable characteristics and comparatively low input needs.

The agriculture industry is under pressure to maintain low production costs in a globalized economy while overcoming new and concurrent challenges. The goal is to increase productivity to feed the world's expanding population while reducing environmental impact and protecting natural resources for coming generations (Jagermeyr, 2020).

Using organic plant stimulants is a creative and eco-friendly approach. This approach ensures steady yields under challenging soil and environmental conditions while reducing dependency on chemical inputs, particularly synthetic fertilizers (Calvo and Nelson, 2014). Seaweed extracts have gained popularity recently as a class of biostimulants that can be used in the agricultural industry These extracts, which come from brown algae/seaweed like Macrocystis pyrifera, Ecklonia maxima, and Aschophyllum nodosum, are known to contain trace metals like potassium, sodium, iron, copper, and manganese in addition to growth-promoting hormones. Studies have examined their use in a variety of crops to increase agricultural production and stress resistance while several researchers have reported that seaweed extracts contribute to prolonging the postharvest longevity of agricultural commodities (Battacharyya et al., 2015; Gupta *et al*., 2011; Sivasankari *et al*., 2006).

Consequently, the use of seaweed-based biostimulants has gained considerable attention as an effective strategy for enhancing crop productivity, particularly in horticultural crops. that are agronomically important, trees, flowers, and vegetables. According to Dhargalkar and Pereira (2005), seaweed extract is an effective fertilizer for these crops. Over 15 million metric tons annually Seaweed is used to make and process products. These products serve as bio-fertilizers to increase crop growth and productivity, as well as essential nutrients and biostimulants (Sabir *et al.,* 2014).

Seaweed extracts, which come in liquid or soluble powder form, are widely used in horticultural crops. By mixing them with irrigation water and using drip irrigation, they can be applied to plant roots (El-Kader *et al.,* 2010). A study demonstrates that foliar application of plant extracts significantly enhances potato growth, physiological traits, and yield, highlighting an environmental-friendly alternative to artificial inputs (Mubashir *et al.,* 2023). For optimal effectiveness, seaweed extracts must be applied to foliage at the right time. The best time to apply seaweed extracts is in the morning, when the stomata on the leaves are open. Furthermore, the effectiveness of seaweed extracts is significantly influenced by the crops' developmental stage (Fornes *et al.,* 2002).

In a similar vein, plants require both macro and micronutrients, such as calcium, boron, manganese, iron, zinc, copper, and molybdenum, to grow and function properly. Although macronutrients are more crucial for plant growth and development, micronutrients are still required for the best possible growth (Younas *et al.,* 2020). Crop yield and quality have increased because of the application of micronutrients in agriculture (Younas *et al.* 2020; Tavakoli *et al.,* 2014). Micronutrients for vegetable crops have gained popularity recently because of their beneficial effects on nutrition as well as their capacity to increase yield and profitability.

A thorough understanding of micronutrients is crucial to meeting the growing demand for vegetable production (Sidhu *et al.,* 2019). Because micronutrients increase crop quality, yield, and shelf life, their use as foliar applications are growing in popularity. Furthermore, foliar spraying crops with micronutrients fixes nutritional deficiencies (Rahman, 2020).

In micronutrients boron is also important and it's necessary for the formation of pollen, as well as for the pollination and formation of flowers in plants. In the meristematic region, boron is crucial for the growth and development of new plant cells. Furthermore, the formation of cell walls and the growth of fruits and seeds depend on boron. All things considered, boron's role in numerous physiological functions emphasizes how important it is for promoting plant development and reproduction. Because it helps plants absorb nitrogen, improves calcium solubility and metabolism, and increases its mobility, boron is essential. Additionally, it is involved in different kind of physiological processes like photosynthetic activities, transport and carbohydrate metabolism, synthesis of nucleic acids, and water absorption in plants and vegetable crops.

Foliar application of seaweed extract and boron, individually or in combination, enhances growth, yield, and yield components of okra. This study provides the first comparative evaluation of combined seaweed extract and boron application on okra growth and yield under local field conditions in Peshawar. This study is aimed to assess the impact of different concentrations of seaweed extract on the vegetative growth and yield performance of okra, to determine the impact of foliar-applied boron on okra growth, yield, and pod quality, and to identify the optimal dose combination of seaweed extract and boron for maximizing okra productivity.

MATERIALS AND METHODS

The study was carried out in the summer season of 2023 at the Horticulture Research Farm, University of Agriculture, Peshawar. The experiment was designed to investigate the influence of boron and seaweed extract applications on the growth characteristics and yield performance of okra

(*A. esculentus* L.). The study comprised 16 treatment combinations arranged in a Randomized Complete Block Design (RCBD) with three replications, totaling 48 experimental units. Two factors were investigated: boron applied at four concentrations (0, 0.3, 0.6, and 0.9%) and seaweed extract applied at four levels (0-, 20-, 30-, and 40-mlL^{-1}). Both treatments were applied foliarly at designated growth stages.

Treatments

Seaweed extract

A commercially prepared seaweed extract, SeaMaxx® (formulated from *Ascophyllum nodosum* and marketed by Swat Agrochemicals), was used at 0, 20, 30, and 40 mlL^{-1}. The extract was applied as a foliar spray at two growth stages (20 and 40 days after sowing). No extraction procedure was needed as the product was ready-to-use.

Boron (Solubor®)

Solubor® (disodium octaborate tetrahydrate, $Na_2B_8O_{13}\cdot 4H_2O$), containing 20% boron, was used for foliar application at 0, 0.3, 0.6, and 0.9% concentrations. The required amount of Solubor was dissolved in water to prepare the spray solution. Applications were made at the same two growth stages as the seaweed extract.

Soil analysis of experimental field

To determine the physico-chemical properties of the experimental site, soil samples were collected and analyzed at the Soil Science Laboratory, University of Agriculture, Peshawar. The results obtained from the soil analysis are presented in Table 1.

Table 1. Analysis of the experimental soil

Soil Analysis	Value
Soil Texture	Silt loam
pH	7.8
Electric Conductivity (Dsm^{-1})	0.32

Measurement of plant parameters

At the conclusion of the experiment, five plants were randomly selected from each treatment, and their heights were measured using a measuring tape, followed by calculation of the mean plant height. Chlorophyll content was assessed in the top, middle, and lower leaves of the selected plants using a SPAD meter. For each leaf, three readings were taken, and the average was computed. Similarly, the mean of the replication data was recorded for each treatment. The number of days from sowing until 50% of the plants began flowering was recorded as the days to first flowering, and the mean value was calculated for each treatment.

Likewise, the days from sowing to the first harvest were recorded for the selected plants, and the average was determined. Each harvesting event was considered a single picking, and the total number of pods per plant was calculated by summing the pods harvested across all pickings, followed by calculation of the mean. For each treatment, five plants were selected from all replications to measure the weight of a single pod using an electronic balance, and the average pod weight was calculated. Pod length was measured with a measuring tape, and the mean length was computed for each treatment across all replications. Fresh pod yield was then determined using the following formula: Yield ha^{-1} (tons) = $\frac{\text{Yield per plot(kg)} \times 10000\text{m}^2}{\text{Plot area (m}^2) \times 1000}$

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Benefit cost ratio analysis

A cost analysis was conducted to evaluate the economic feasibility of the treatments involving seaweed extract and boron applications. As mentioned earlier, a detailed cost and return analysis was done, as recommended by Alma et al., (1989). To illustrate, Benefit Cost Ratio (BCR) calculation is as follows:

$$\text{Benefit cost ratio} = \frac{\text{Net returen per hectare}}{\text{Total cost of production per hectare}}$$

Statistical analysis:

During the course of research, the data gathered with respect to all the studied parameters was analyzed with the help of the ANOVA procedure. Similarly, the means were compared and checked statistically using the LSD test and software STATISTIX 8.1 (Steel and Torrie, 1997).

RESULTS AND DISCUSSION

Plant height (cm)

Foliar application of seaweed extract and boron significantly influenced the plant height of okra (Table 1). The tallest plants (220.92 cm) were observed in those treated with 40 mL L^{-1} seaweed extract, followed by 203.83 cm in plants receiving 30 mL L^{-1}, while the control plants were the shortest (179.25 cm). In the boron treatments, the maximum plant height (219.92 cm) occurred at 0.6% boron, followed by 205.50 cm at 0.9%, whereas untreated plants exhibited the lowest height (174.92 cm).

The combined application of seaweed extract and boron, however, did not result in a statistically significant increase. These results align with Kumar *et al*. (2018), who reported that foliar application of seaweed extract markedly improved okra plant height, attributing this effect to the presence of natural growth regulators, minerals, and bioactive compounds that enhance cell elongation and division. Similarly, Khan et al. (2020) demonstrated that seaweed extracts promoted plant height and overall vigor in various vegetable crops, including okra, likely by improving nutrient uptake and physiological efficiency.

The present findings regarding boron application are consistent with those of Akhtar et al. (2009), who reported that foliar application of boron positively influenced okra growth and significantly increased plant height. This may be due to boron's essential role in cell wall synthesis, meristem activity, and sugar transport, which collectively contribute to improved plant growth. The agreement between the present findings and earlier studies strengthens the evidence that both seaweed extract and boron, when applied foliar can effectively improve okra plant height by enhancing physiological and metabolic processes.

Chlorophyll content (SPAD)

The chlorophyll content of okra, as presented in Table 2 was significantly influenced by both seaweed extract (SWE) and boron applications. The highest chlorophyll content (63.93) was observed in plants treated with 40 mL L^{-1} SWE, followed by 58.08 in those receiving 30 mL L^{-1}, while the untreated plants exhibited the lowest value (44.37). Regarding boron treatments, the maximum chlorophyll content (58.41) occurred at 0.6% boron, with the second highest value (54.98) recorded at 0.9%, and the control plants showing the lowest content (51.13).

However, the combined application of SWE and boron did not produce a statistically significant effect. Previous studies have demonstrated that fresh seaweed extracts from *Gracilaria edulis* and *Kappaphycus alvarezii* markedly enhance the growth and yield of crops such as tomato, okra, and French bean. Specifically, seaweed applications significantly improved growth attributes, including plant height, chlorophyll index (SPAD) in French beans, and primary branches per plant and chlorophyll index in tomatoes (Layek *et al.*, 2023).

When Aschophyllum nodosum extract was applied exogenously, the amount of chlorophyll-a rose under both drought and control conditions. Chlorophyll-a content was highest in plants treated with a high dose of Ascophyllum nodosum extract (0.3%) and lowest in control plants (Ali *et al.*, 2022). As the rate of boron application increased, total chlorophyll, chlorophyll a and b, and total soluble sugars all increased significantly; the greatest increase was at 200 mg L^{-1} boron concentration rate. In comparison to the control, the majority of rice genotypes showed a significant increase in chlorophyll, boron, amylose, and nitrate reductase activity (Kumar *et al.*, 2015).

Days to First Flowering

As shown in Table 1, the results for mean values concerning days to first flowering for plants that have been sprayed with SWE and for which data is available show that when they were sprayed with 40 mlL-1, they had minimum values for days to first blossom (41.08), and when sprayed with 30 mlL^{-1}, they had 43.42 for the same parameter. At the same time, for the control plants, they had maximum values for days to first blossom (53.0). When it came to plant data concerning values for 0.6% boron, they had minimum values for days to first blossom (44.58), and for 0.9% boron, they had 46.33 for the same parameter.

However, their combined application did not produce a statistically significant effect. Earlier flowering observed with SWE application (Table 1) is consistent with its reported hormonal effects, particularly the presence of cytokinin, auxins, and gibberellins, which promote floral initiation (Khan *et al.*, 2020; Ali *et al.*, 2022). In comparison to the control group, a tiny foliar application of seaweed extracts improved pea flower initiation (Aliko, 2017). In addition to lowering fruit drop in fruit crops, foliar application of different nutrients such as potassium, calcium, and boron was effective in improving fruit set, retention, yield attributes, and quality (Bons and Sharma, 2023). In a similar vein, Singh *et al.* (2015) assessed the impact of foliar boron spraying on okra and found that it significantly shortened the time it took for okra plants to flower early.

Days to First Harvest

Table 1 shows that the application of seaweed extract at 40 mL L^{-1} resulted in the shortest duration to first pod harvest (46.25 days), followed by 48.33 days in plants treated with 30 mL L^{-1}, whereas the control plants required the longest period (58.08 days). Similarly, among the boron treatments, plants receiving 0.6% boron reached the first picking in the minimum number of days (49.58 days), while the plants that recorded the next maximum days were those that were sprayed with 0.9% boron (51.25).

While the control plants recorded the maximum days to first pod picking (53.42). However, their combined application did not produce a statistically significant effect.

Seaweed extract foliar spraying has demonstrated a notable improvement in the flower-to-fruit ratio, leading to an early harvest of larger fruits (Stasio *et al.*, 2017). By enhancing nutrient efficiency and reproductive growth, foliar boron application can shorten the time until harvest. According to Pandey and Gupta (2013), foliar sprays (such as 0.2–0.5% borax) accelerated flowering and curd formation, cutting the harvest time by 5–10 days, while boron deficiencies delay the maturity of crops like tomatoes and cauliflower. Similarly, under ideal boron conditions, Brown and Shelp (1997) showed that boron improves pollen viability and fruit set, cutting the time from flowering to harvest in vegetables like peppers and beans by 7–14 days. The importance of boron in accelerating crop maturity is supported by these studies.

Number of pods plant^{-1}

As shown in Table 1, the number of pods per plant was significantly influenced by seaweed extract (SWE) application. Plants treated with 40 mL L^{-1} SWE produced the highest number of pods per plant (39.26), followed by 35.93 pods in plants treated with 30 mL L^{-1}, while the control plants produced the fewest pods (30.13). Similarly, boron application affected pod production, with the maximum number of pods per plant (37.73) observed at 0.6% boron, followed by 35.09 pods at 0.9%, and the lowest count (31.78) in untreated plants. The combined application of SWE and boron, however, did not result in a statistically significant increase.

These findings are supported by Nawar and Ibraheim (2014), who reported that application of 10–15% algae extract significantly enhanced pod number, total yield per plant, and overall yield components compared to untreated controls. More pods or fruits per plant are eventually produced when there is sufficient boron available to support pollination, pollen tube formation, and fruit set. In tomatoes, the same outcome was noted. In an experiment conducted on tomato plants, Singh *et al.* (2016) assessed how foliar boron application affected yield and quality metrics, such as the quantity of fruits produced per plant.

Single pod length (cm)

Date related to single pod length (cm) indicated in Table 2 and plant treated with SWE the maximum pod length (13.94 cm) was recorded when sprinkled with seaweed solution at a concentration of 40 mlL^{-1}, then followed by (13.20 cm) when sprinkled at 30 mlL-1, while minimum pod length (9.21cm) was recorded for control plants. However, with regard to boron at a concentration of 0.6%, it was recorded that the highest pod length was 13.12 cm, followed by 12.24 cm when the concentration was 0.9%, while the minimum pod length of 10.86 cm was recorded for control plants. Nevertheless, the combined application failed to elicit a statistically significant response.

Jayasinghe *et al*. (2016) found the same results, indicating that chilli plants were producing pods that were longer and of higher quality. The pod length of cluster bean and okra plants was considerably increased by applying 20% seaweed liquid extract (Thirumaran *et al*., 2009). According to a study on lima beans by Chakrabarti *et al*. (2015), foliar boron application greatly enhanced pod length and yield. Longer, more consistent pods are the result of improved cell division in the developing pods, which is facilitated by boron. Better vascular tissue function and increased nutrient availability were credited with the increased growth, which allowed sugars to be transported to developing pods more effectively. For leguminous crops, where successful fertilization directly impacts pod development, this is especially crucial. Longer pods may result indirectly from foliar boron applications, which can help ensure improved fruit set (Marschner, 2012).

Single pod weight (g)

1 indicates that the highest single pod weight (13.69 g) was achieved with foliar application of seaweed extract at 40 mL L^{-1}, followed by 12.28 g in plants treated with 30 mL L^{-1}, while the control plants produced the lowest pod weight (9.82 g). Similarly, among the boron treatments, 0.6% boron resulted in the maximum single pod weight (13.02 g), followed by 11.89 g at 0.9% boron, whereas the control plants exhibited the minimum value (10.50 g). Nevertheless, the combined application failed to elicit a statistically significant response. Khan et *al.* (2009) looked into how seaweed extract affected strawberry plants. In comparison to the control group, the researchers discovered that foliar application of seaweed extract considerably improved the yield and quality parameters, including fruit weight. When seaweed was applied topically to pears, Colavita *et al*. (2010) also noticed a comparable increase in fruit weight. Zinc and boron may have improved the way minerals were used by plants, which may have been crucial in improving photosynthetic activity, metabolic processes, and eventually the supply of assimilates to sinks. Narayanamma *et al.* (2009) reported the same outcomes in bitter gourd. The findings of our study are corroborated by Islam *et al*. (2017), who noted that because of the influence of zinc and boron, pod weight of mung bean crop was increased significantly.

Pod fresh yield (tons/ha^{-1})

Table 2 shows that fresh pod yield (t ha^{-1}) was highest in plants treated with seaweed extract at 40 mL L^{-1}, producing 23.61 t ha^{-1}, followed by 20.99 t ha^{-1} in plants receiving 30 mL L^{-1}, while the control plants yielded the lowest (15.03 t ha^{-1}). Similarly, boron application influenced fresh pod yield, with 0.6% boron resulting in the maximum yield (22.11 t ha^{-1}), followed by 20.09 t ha^{-1} at 0.9%, and the lowest yield observed in untreated plants (16.85 t ha^{-1}). However, the combined application of seaweed extract and boron did not produce a statistically significant increase in fresh pod yield.

The interaction between boron levels and seaweed extract concentrations exhibited a marked influence on the fresh yield of okra. Fresh yield values showed a progressive increase with rising levels of seaweed extract across all boron treatments. In the absence of seaweed extract (0 mlL^{-1}), the lowest yield (12.50 t ha^{-1}) was recorded under the control treatment (Boron 0%), while the highest yield in this group (17.83 t ha^{-1}) was observed with 0.3% boron application. The incorporation of 20 mlL^{-1} extract of seaweed output in a substantial improvement, with yields ranging from 15.60 to 20.63 t ha^{-1}. While the decline in yield at 0.9% boron suggests possible toxicity at high doses.

At 30 mlL^{-1} seaweed extract, fresh yield further increased, with the maximum value (23.53 t ha^{-1}) achieved in plants treated with 0.3% boron, while the control group recorded 20.37 t ha^{-1}. The trend persisted at 40 mlL^{-1}, where the overall highest fresh yield (26.43 t ha^{-1}) was obtained under 0.3% boron, followed by 24.33 t ha^{-1} with 0.9% boron and 22.80 t ha^{-1} with 0% boron. These findings indicate that the combined application of moderate boron concentration (0.3%) and high seaweed extract dose (40 mlL^{-1}) produced the most favorable results.

Zodape *et al.* (2008) investigated how okra's nutrition and quality were affected by seaweed extract liquid fertilizers sprayed at varying concentrations. They found that the plant sprayed with LSE exhibited a notable improvement in growth and yield metrics. Similar outcomes were observed by Zahid (1999) when seaweed was applied foliarly and as manure. According to the data collected, Okra foliar application of seaweed extract during the two tested seasons significantly increased the number of pod plants-1 and total yield (g) per plant. According to Perveen and Rehman (2002), applying Mn, B, and Zn enhanced okra yield. The findings are corroborated by Medhi and Kakati (1994), who showed that zinc and boron have a synergistic effect on growth and yield by having a substantial impact on respiration, morphological activity, photosynthesis, and nitrogen metabolism. The foliar application of boron increased the marketable yield of beans (Abou El-Yazied et al., 2012).

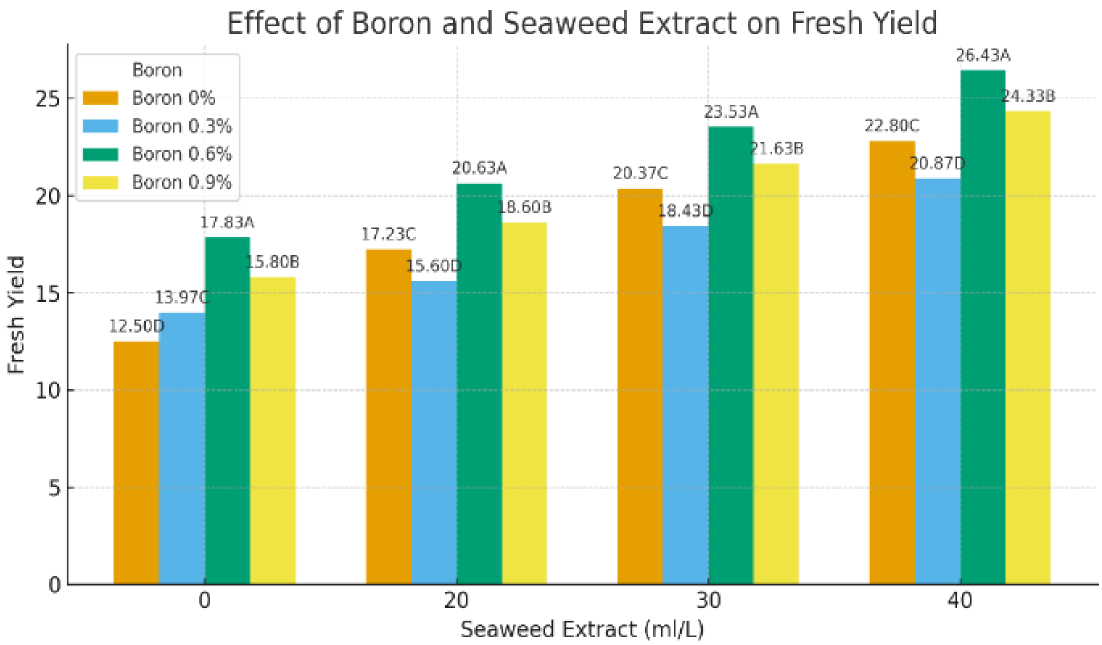

Figure 1. Effect of various concentrations of seaweed extract (SWE) and boron on fresh pod yield of okra yield of okra. Different letters above bars indicate significant differences at $p \leq 0.01$ according to LSD test.

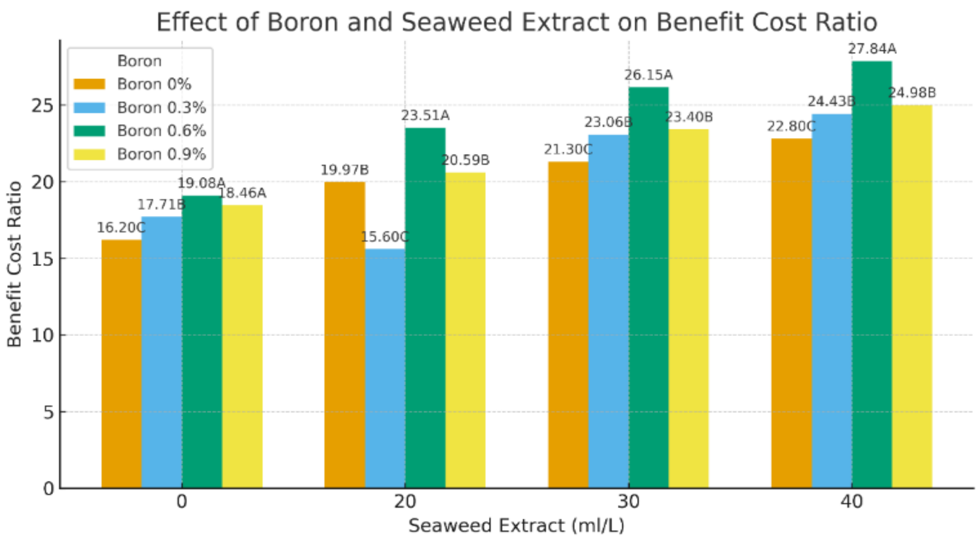

Figure 2. Effect of varying concentrations of seaweed extract (SWE) and boron on the benefit–cost ratio (BCR) of okra. Different letters above bars indicate significant differences at $p \leq 0.01$ according to LSD test.

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Benefit–Cost Ratio (BCR) for Fresh Pod Yield of Okra

The BCR results presented in the last column of Table 3.1 indicate that seaweed extract application significantly influenced economic returns. The highest BCR (25.01) was observed in plants treated with 40 mL L^{-1} seaweed extract, followed by 23.48 in those receiving 30 mL L^{-1}, while the control plants recorded the lowest BCR (18.81). Similarly, boron treatments affected the BCR, with 0.6% boron producing the maximum value (24.94), followed by 22.01 at 0.9% boron, and the minimum BCR (19.69) in untreated plants. The interaction of boron and seaweed extract (ANE) concentrations significantly influenced the benefit-cost ratio (BCR) of okra production (Figure 2). In the absence of seaweed extract (0 mlL^{-1}), the BCR.

The interaction between SWE*Boron was found to be not significant ranged from 16.20 under control conditions (Boron 0%) to 22.26 with 0.9% boron application, indicating that boron supplementation alone can enhance economic returns. The application of 20 mlL^{-1} seaweed extract increased BCR across all boron levels, with the highest value (23.51) obtained at 0.3% boron, compared to 18.46 in the untreated control. While higher BCR for SWE vs. boron (25.01 vs. 24.94) likely reflects lower cost of SWE per unit yield.

At 30 mlL^{-1} seaweed extract, the BCR peaked at 26.15 with 0.3% boron, followed closely by 23.40 at 0.6% boron, while the lowest value at this level (21.30) was recorded in the control. Further increase to 40 mlL^{-1} seaweed extract resulted in the maximum BCR (27.84) with 0.3% boron, whereas the control recorded 22.80. This demonstrates that the combination of moderate boron application (0.3%) and high seaweed extract concentration (40 mlL^{-1}) optimizes economic profitability. The observed improvement in BCR may be attributed to enhanced crop yield and marketable produce quality under combined boron and seaweed extract application, leading to higher gross returns relative to production costs. Boron plays a vital role in reproductive growth and nutrient translocation (Shireen *et al.,* 2018), while seaweed extract acts as a biostimulant that improves nutrient uptake efficiency and stress tolerance (Ali *et al*., 2022; Khan *et al*., 2020). These findings suggest that adopting this integrated nutrient management strategy can substantially increase economic returns in okra cultivation.

High production costs resulted from the foliar application of biostimulants on tomato fields. However, compared to the cost-benefit ratio of untreated plants, the improved yields brought about by the biostimulant application resulted in higher gross returns, which in turn led to improved net returns (Colla, 2017). Foliar application of boron had an impact on okra yield attributes and yield plant-1. Fruit weight, fruit length, and the number of fruit plants per plant all significantly increased with a high B:C ratio. This could be because of boron's involvement in active photosynthesis, which eventually contributes to an increase in fruit weight and quantity (Kumar and Sen, 2005).

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Table 2. Effects of seaweed extract (SWE) and boron on okra growth, yield, and economics.

Treatment	PH (cm)	CC (SPAD)	DTFF	DTFH	NPPP	SPL (cm)	SPW (g)	Yield (t ha^{-1})	BCR
SWE Levels (mlL^{-1}) Control (0)	179.25D	44.37D	53.00A	58.08A	30.13D	9.21C	9.82D	15.03D	18.81D
SWE 20	192.58C	51.63C	48.58B	53.50B	33.11C	11.29B	11.03C	18.02C	20.63C
SWE 30	203.83B	58.08B	43.42C	48.33C	35.93B	13.20A	12.28B	20.99B	23.48B
SWE 40	220.92A	63.93A	41.08CD	46.25D	39.26A	13.94A	13.69A	23.61A	25.01A
Boron Levels (%) Control (0)	174.92D	51.13D	48.08A	53.42A	31.78D	10.86D	10.50C	16.85D	19.69D
Boron 0.3	196.25C	53.48C	47.08A	51.92B	33.83C	11.43C	11.41B	18.59C	21.29C
Boron 0.6	219.92A	58.41A	44.58B	49.58C	37.73A	13.12A	13.02A	22.11A	24.94A
Boron 0.9	205.50B	54.98B	46.33A	51.25B	35.09B	12.24B	11.89B	20.09B	22.01B
LSD at $P \leq 0.01$	8.87	3.21	2.01	1.98	2.10	0.78	1	1.02	1.2
CV %	3.95	5.06	3.85	3.43	5.43	5.86	8.1	4.7	4.9

Where, PH=Plant Height, SPAD = leaf greenness (chlorophyll index), DTFF=Days to First Flowering, DTFH=First Days to Harvest, NPPP=No. of pods plant-1, SPL=Single length of pod, SPW=Single weight of pod. The interaction between SWE*Boron was found to be not significant.

CONCLUSION

Seaweed extract significantly improved the growth and yield of okra (cv. Swat Green), with the best results obtained at 40 ml L^{-1} applied twice. Increasing boron levels reduced growth and yield, although 0.6% foliar boron improved most parameters. The combination of boron and seaweed extract showed no significant effect on any measured characteristic. Through this study, it is suggested that for optimal okra growth and yield, apply seaweed extract foliarly at 40 ml L^{-1} twice, 20 days apart after sowing, and apply 0.6% boron as a foliar spray twice at the same interval to enhance yield and quality. Similarly, application of boron beyond 0.6% is not recommended, as higher concentrations may induce phytotoxicity and adversely affect plant growth and yield. Further research is recommended to evaluate the impact of higher seaweed extract concentrations on okra and other vegetable crops.

AUTHORS' CONTRIBUTION

All authors contributed equally.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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