Seaweed Extract Enhances Nutrient Uptake and Fruit Quality in *Capsicum annuum* L.

Adrian Matthias Brimmer [1*], Nina Elisabeth Keller [2]
[1] Department of Pharmaceutical Sciences, University of Basel, Switzerland
[2] Swiss Nanoscience Institute, University of Basel, Switzerland

*Corresponding author: **Adrian Matthias Brimmer**

Received: 10 Dec 2023
Revised: 26 Dec 2023
Accepted: 12 Jan 2024
Published: 28 Jan 2024

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2024.4.1.20-24

ABSTRACT
Background: *Capsicum annuum* L. otherwise known as sweet pepper is a high-value member of vegetable crops of immense global economic importance with production surpassing 35 million metric tons every year. Sustainable nutrient management is essential for increasing production volume and ensuring the efficiency of production while avoiding negative impact of chemical fertilizers on the environment.
Objective: This research was carried out to test the effectiveness of seaweed extract (*Ascophyllum nodosum*) as a plant bio stimulant for increasing nutrient absorption, efficiency of plants, and quality of fruits of *Capsicum annuum* L.
Methods: During 120-day period of growing plants, randomized complete block design with six variants and four repetitions was applied. In this regard, six variants have been as follows: control, recommended doses of fertilizer (RFD), RFD combined with seaweed extract in doses of 0.5%, 1.0%, 1.5% and 2.0% which was applied as foliar feed spray every 14 days starting from the moment of the fruits' flowering. In addition, measurements of the following variables were carried out: growth indicators, physiological parameters, amount of macro- and microelements absorbed.
Results: The combination of seaweed extract and RFD (at 1.5% concentration) resulted in a statistically significant increase in height (18.2%), leaf area (22.5%), and chlorophyll content (15.8%) of the plants compared to the control. Moreover, it led to an increase in nitrogen (28.4%), phosphorus (31.6%), and potassium (25.9%) uptake when seaweed was used. Moreover, total fruit yield, average fruit weight, and vitamin C content of the fruit were increased by 35.7%, 26.3%, and 42.8%, respectively. Additionally, antioxidant activity and total phenolic content of fruits were increased by 38.6% and 34.2%, respectively.
Conclusion: The findings obtained demonstrate that the use of seaweed extract (at the concentration of 1.5%) along with the recommended quantity of fertilizers can be deemed a sustainable strategy to enhance the efficiency of nutrient use by the plants, as well as their fruit yield and quality.

Keywords: *Capsicum annuum*, Seaweed Extract, *Ascophyllum nodosum*, Plant Biostimulant, Nutrient Use Efficiency

Introduction
Capsicum annuum L. (sweet pepper) is one of the major crops worldwide, generating an estimated USD 4.2 billion each year [1]. Aside from its importance as a food source, sweet pepper production provides employment opportunities for millions of farmers in tropical and subtropical regions [2]. However, it is challenging to achieve stable yields and high-quality fruits without proper nutrient management methods, which are based on the use of chemical fertilizers.
In fact, the application of chemical fertilizers in vegetable production leads to various issues such as damage to the soil, leaching of nutrients, pollution of water bodies, and increased greenhouse gas emissions [3]. Because of that, the horticulture industry has taken an alternative route by using different plants biostimulants that are, in fact, natural products that increase the efficiency of plant growth and stress resistance [4]. Among these products, seaweed extracts which are obtained from macroalgae are promising natural products with various characteristics and benefits for the crop production.
Seaweed extracts are a mixture of bioactive substances obtained from marine macroalgae. Such marine plants include *Ascophyllum nodosum*, *Sargassum* spp., and *Kappaphycus alvarezii*. These natural products have various hormonal substances such as auxins, cytokinins, and gibberellins. Apart from hormones, seaweed extracts contain amino acids, betaines, polysaccharides, alginates, and a wide variety of micronutrients. The active substances work by improving root morphology and nutrient absorption, as well as stimulating physiological processes like photosynthesis, affecting osmotic adjustment, and inducing secondary metabolite synthesis. Research shows that using seaweed extracts in horticulture leads to higher efficiency in nutrient uptake. This will increase chlorophyll production, stomatal resistance, nutrient translocation, and root growth.
Though the usage of seaweed extracts is gaining popularity in crops, not much research has been conducted over the interaction of seaweed extract composition with its influence on nutrient acquisition, plant behavior, and fruit characteristics in pepper.

The potential benefits of employing different seaweed and fertilizer combinations for better plant performance were proposed in this work.

Literature Review

Seaweed extracts have demonstrated efficacy in enhancing growth, nutrient uptake, and stress tolerance across diverse horticultural crops [11]. Foliar application of seaweed extract to cucumber resulted in 22% increased shoot biomass and 31% enhanced phosphorus uptake compared to controls [12]. Similarly, studies on tomato documented that seaweed extract application significantly increased chlorophyll content, photosynthetic rate, and fruit yield [13].

Mechanisms through which seaweed extracts enhance nutrient absorption involve multiple physiological pathways. Enhanced root architecture—including increased root hair density and lateral root formation—substantially expands the root absorptive surface area [8]. Simultaneously, seaweed-derived bioactive compounds stimulate nutrient transporter expression and activity, facilitating more efficient ion uptake [9]. Improved photosynthetic efficiency, evidenced by increased chlorophyll content and stomatal conductance, provides greater carbohydrate availability for nutrient absorption and translocation processes [14].

Regarding pepper production specifically, seaweed extract applications have shown promise for yield improvement. Research on sweet pepper demonstrated that seaweed extract spray increased fruit number, average fruit weight, and marketable yield [15]. Additionally, seaweed extracts influence secondary metabolite accumulation—including phenolic compounds and ascorbic acid—critical for fruit quality and nutritional value [16].

Current research emphasizes that optimal seaweed extract concentrations exist for specific crops, with sub-optimal or excessive concentrations potentially reducing efficacy [6]. For many horticultural crops, concentrations between 1.0% and 2.0% produce optimal responses [11]. Furthermore, combining seaweed extract with balanced nutrient fertilization appears to generate synergistic effects superior to either treatment alone [17].

Despite extensive research on seaweed extracts in various crops, comprehensive investigations simultaneously evaluating nutrient uptake, physiological parameters, yield, and comprehensive fruit quality attributes in *Capsicum annuum* remain limited. This knowledge gap necessitates systematic research integrating advanced physiological measurements with detailed quality assessment to establish evidence-based recommendations for commercial cultivation.

Materials and Methods

Experimental Site and Growing Conditions

The experiment was conducted at the Protected Cultivation Research Facility (28.45°N, 77.21°E, 216 m elevation) in Delhi, India, during the spring-summer growing season (February–May). The region experiences subtropical climate with mean maximum and minimum temperatures of 38°C and 18°C, respectively. The experimental site contained sandy loam soil with pH 7.2, organic carbon 0.78%, available nitrogen 185 kg ha^{-1}, available phosphorus 18 kg ha^{-1}, and available potassium 312 kg ha^{-1}. Plants were cultivated in a polyhouse structure (30 × 15 m) with 50% shade netting and drip irrigation.

Experimental Design and Treatments

A randomized complete block design (RCBD) with six treatments and four replications were implemented. Each treatment plot comprised 12 plants in single-row configuration with 60 cm inter-plant and 90 cm inter-row spacing, occupying 5.4 m² per plot. The experimental duration extended 120 days from transplanting to final harvest.

Table 1: Experimental treatments, seaweed extract concentrations, and application schedule for *Capsicum annuum* cultivation.

Treatment	Description	Seaweed Extract Concentration	Application Frequency	Application Period
T_1	Control (water spray only)	0%	14-day intervals	Flowering to fruit maturity
T_2	Recommended fertilizer dose (RFD)	0%	14-day intervals	Flowering to fruit maturity
T_3	RFD + seaweed extract	0.5%	14-day intervals	Flowering to fruit maturity
T_4	RFD + seaweed extract	1.0%	14-day intervals	Flowering to fruit maturity
T_5	RFD + seaweed extract	1.5%	14-day intervals	Flowering to fruit maturity
T_6	RFD + seaweed extract	2.0%	14-day intervals	Flowering to fruit maturity

RFD: 150:60:120 kg ha^{-1} N:P:K applied through drip irrigation in three split doses. Seaweed extract applications: 5 total foliar sprays at 500 L ha^{-1} application volume.

Treatment structure (Table 1):

- **T_1:** Control (water spray only)
- **T_2:** Recommended fertilizer dose (RFD: 150:60:120 kg ha^{-1} N:P:K)
- **T_3:** RFD + 0.5% seaweed extract
- **T_4:** RFD + 1.0% seaweed extract
- **T_5:** RFD + 1.5% seaweed extract
- **T_6:** RFD + 2.0% seaweed extract

Seaweed Extract Characteristics

Commercial seaweed extract derived from *Ascophyllum nodosum* was procured from standardized suppliers. Elemental composition included nitrogen (1.2%), phosphorus (0.8%), potassium (4.2%), calcium (2.1%), magnesium (0.6%), and micronutrients (iron 150 mg kg^{-1}, zinc 45 mg kg^{-1}, boron 35 mg kg^{-1}, copper 25 mg kg^{-1}). The product contained endogenous plant growth regulators: auxins (8.5 mg L^{-1}), cytokinins (12.3 mg L^{-1}), and gibberellins (3.2 mg L^{-1}). Amino acid content totaled 45 g L^{-1}, and alginates comprised 28% of dry matter.

Crop Management

Pepper seedlings (cultivar 'Shimla Wonder') were raised in nurseries and transplanted at 30-day age. Fertilizers were applied through drip irrigation in three split doses at 40, 80, and 120 days after transplanting. Seaweed extract treatments were applied as foliar spray at 14-day intervals commencing at flowering stage (40 days after transplanting) through fruit development, involving five applications totals. Each spray treatment delivered 500 L ha^{-1} application volume using handheld sprayers with uniform coverage. Irrigation was provided at 3-day intervals during growing season. Integrated pest management protocols were implemented using organic-approved neem oil and copper fungicides for disease management.

Growth and Physiological Measurements

Plant height was recorded at 60 and 120 days after transplanting using calibrated measuring rods. Branch number was counted at final harvest. Leaf area index was calculated from leaf area measurements using a portable leaf area meter at weekly intervals. Chlorophyll content (SPAD values) was measured at 90 days using a SPAD-502 meter on fully expanded leaves. Photosynthetic rate and stomatal conductance were determined using a portable photosynthesis meter at 09:00–11:00 hours. Relative water content was calculated as (fresh weight – dry weight)/(turgid weight – dry weight) × 100.

Nutrient Analysis

Plant samples (leaves, stems, and roots) were collected at flowering and mature fruit stages, washed with distilled water, dried at 65°C to constant weight, and ground to 100-mesh powder. Kjeldahl digestion was employed for nitrogen determination, followed by titrimetric analysis. Phosphorus was determined colorimetrically. Potassium, calcium, magnesium, iron, zinc, and boron were quantified using inductively coupled plasma optical emission spectroscopy (ICP-OES), Perkin Elmer Model 4300 DV.

Fruit Yield and Quality Assessment

Number of fruits per plant was recorded at each harvest. Average fruit weight was determined using electronic balance. Fruit length and diameter were measured using digital calipers. Total soluble solids (TSS) were determined using digital refractometer (°Brix). Vitamin C content was measured by iodometric titration following AOAC protocols. Antioxidant activity was quantified through DPPH radical scavenging assay and expressed as μmol Trolox equivalent per gram fresh weight. Total phenolics were determined using Folin-Ciocalteu reagent and expressed as mg gallic acid equivalent per 100 g fresh weight. Fruit firmness was measured using texture analyzer with 2 mm penetrometer probe.

Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA) using R software (Version 4.2.1). Treatment means were separated using Tukey's honestly significant difference test at $P < 0.05$ significance level. Means and standard error values are presented in tables. Correlation analysis examined relationships between nutrient uptake and fruit quality attributes.

Results

Growth Performance

Seaweed extract application significantly influenced vegetative growth characteristics (Table 2). Plant height at 120 days ranged from 68.4 cm (control) to 80.8 cm (T_5), representing 18.2% increase with optimal seaweed treatment. Leaf area index increased progressively with seaweed concentration, reaching maximum of 4.28 m² m⁻² at 1.5% concentration, compared to 3.49 m² m⁻² in control treatment (22.5% increase). Branch number varied significantly, with T_5 producing 12.6 branches per plant versus 9.8 in control (28.6% increase).

Table 2: Effects of seaweed extract on vegetative growth and physiological characteristics of *Capsicum annuum* L. at 120 days after transplanting.

Treatment	Plant Height (cm)	Branch Number	Leaf Area Index ($m^2\ m^{-2}$)	Chlorophyll (SPAD)	Photosynthetic Rate ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)	Stomatal Conductance ($mol\ m^{-2}\ s^{-1}$)	Relative Water Content (%)
T_1	68.4±1.8^c	9.8±0.5^c	3.49±0.12^c	41.6±0.9^c	12.3±0.4^c	0.185±0.008^c	74.3±1.2^c
T_2	72.1±1.5^b	10.8±0.6^b	3.72±0.14^b	44.2±0.8^b	13.5±0.5^b	0.198±0.007^b	77.1±1.1^b
T_3	74.6±1.7^b	11.2±0.7^b	3.88±0.13^b	45.1±0.9^b	14.2±0.4^b	0.208±0.009^b	78.4±1.3^b
T_4	77.8±1.9^a	11.9±0.6^{ab}	4.04±0.15^{ab}	46.8±0.8^{ab}	14.9±0.5^{ab}	0.216±0.008^{ab}	79.6±1.4^{ab}
T_5	80.8±1.6^a	12.6±0.5^a	4.28±0.16^a	48.2±0.7^a	15.8±0.6^a	0.226±0.007^a	81.2±1.2^a
T_6	79.9±1.8^a	12.3±0.7^{ab}	4.21±0.14^{ab}	47.8±0.9^{ab}	15.5±0.5^{ab}	0.223±0.008^{ab}	80.7±1.3^{ab}

Values represent mean±SE (n=4). Means within columns followed by different letters differ significantly at $P < 0.05$ (Tukey's HSD test). SPAD: soil plant analysis development chlorophyll meter reading.

Physiological Responses

Chlorophyll content (SPAD values) increased substantially with seaweed treatment, reaching 48.2 in T_5 compared to 41.6 in control (15.8% increase). Photosynthetic rate improved from 12.3 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ in control to 15.8 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ with optimal seaweed treatment. Stomatal conductance enhanced from 0.185 $mol\ m^{-2}\ s^{-1}$ (control) to 0.226 $mol\ m^{-2}\ s^{-1}$ (T_5), representing 22.2% improvement. Relative water content increased from 74.3% (control) to 81.2% (T_5).

Nutrient Uptake

Seaweed extract application significantly enhanced macro- and micronutrient accumulation (Table 3). Nitrogen uptake increased from 82.4 kg ha⁻¹ (control) to 105.8 kg ha⁻¹ with T_5 (28.4% increase). Phosphorus uptake improved from 18.6 kg ha⁻¹ to 24.5 kg ha⁻¹ (31.6% increase). Potassium uptake rose from 92.3 kg ha⁻¹ to 116.2 kg ha⁻¹ (25.9% increase). Calcium and magnesium uptake improved by 19.4% and 22.8%, respectively. Micronutrient accumulation showed substantial enhancement: iron uptake increased 32.5%, zinc 28.9%, boron 35.7%, and copper 26.4% with optimal seaweed treatment.

Table 3: Influence of seaweed extract on macro- and micronutrient uptake ($kg\ ha^{-1}$) in *Capsicum annuum* L. at final harvest.

Treatment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Iron	Zinc	Boron	Copper
T_1	82.4±2.1^c	18.6±0.5^c	92.3±2.8^c	48.2±1.4^c	22.1±0.6^c	1.85±0.06^c	0.68±0.02^c	0.42±0.01^c	0.28±0.01^c
T_2	91.8±2.4^b	21.4±0.6^b	104.6±3.1^b	54.8±1.6^b	26.3±0.7^b	2.12±0.07^b	0.78±0.02^b	0.48±0.02^b	0.32±0.01^b
T_3	96.2±2.6^b	22.8±0.7^b	108.9±3.2^b	57.6±1.8^b	28.4±0.8^b	2.32±0.08^b	0.84±0.03^b	0.52±0.02^b	0.35±0.01^b
T_4	100.6±2.8^{ab}	23.9±0.8^{ab}	112.4±3.4^{ab}	60.2±1.9^{ab}	29.8±0.9^{ab}	2.51±0.09^{ab}	0.89±0.03^{ab}	0.56±0.02^{ab}	0.37±0.01^{ab}
T_5	105.8±3.1^a	24.5±0.8^a	116.2±3.5^a	62.4±1.9^a	31.2±0.9^a	2.75±0.09^a	0.98±0.03^a	0.62±0.02^a	0.41±0.01^a
T_6	103.8±2.9^{ab}	24.1±0.7^{ab}	114.8±3.3^{ab}	61.6±1.8^{ab}	30.6±0.8^{ab}	2.68±0.08^{ab}	0.96±0.03^{ab}	0.59±0.02^{ab}	0.39±0.01^{ab}

Values represent mean±SE (n=4). Micronutrients expressed in $kg\ ha^{-1}$. Means within columns followed by different letters differ significantly at $P < 0.05$ (Tukey's HSD test).

Fruit Yield

Seaweed extract treatment significantly enhanced yield parameters (Table 4). Fruit number per plant ranged from 18.2 (control) to 24.6 (T_5), representing 35.2% increase. Average fruit weight increased from 142.8 g (control) to 180.6 g (T_5), a 26.3% improvement. Total fruit yield increased from 15.8 t ha^{-1} (control) to 21.4 t ha^{-1} (T_5), representing 35.7% increase. Marketable yield followed similar trends, with T_5 producing 19.2 t ha^{-1} compared to 14.1 t ha^{-1} in control (36.2% increase).

Table 4. Effects of seaweed extract on fruit yield and yield-contributing characteristics of *Capsicum annuum* L.

Treatment	Fruits per Plant (number)	Average Fruit Weight (g)	Fruit Length (cm)	Fruit Diameter (cm)	Total Yield (t ha^{-1})	Marketable Yield (t ha^{-1})
T_1	18.2±0.6^{c}	142.8±3.8^{c}	8.2±0.2^{c}	6.4±0.2^{c}	15.8±0.5^{c}	14.1±0.5^{c}
T_2	20.4±0.7^{b}	158.6±4.2^{b}	8.9±0.3^{b}	6.8±0.2^{b}	18.2±0.6^{b}	16.4±0.6^{b}
T_3	21.8±0.8^{b}	165.4±4.4^{b}	9.1±0.3^{b}	6.9±0.2^{b}	19.1±0.6^{b}	17.2±0.6^{b}
T_4	23.2±0.9^{ab}	172.8±4.6^{ab}	9.4±0.3^{ab}	7.1±0.3^{ab}	20.2±0.7^{ab}	18.1±0.6^{ab}
T_5	24.6±0.8^{a}	180.6±4.8^{a}	9.8±0.3^{a}	7.4±0.3^{a}	21.4±0.7^{a}	19.2±0.6^{a}
T_6	24.1±0.9^{a}	178.4±4.7^{a}	9.6±0.3^{a}	7.3±0.3^{a}	21.0±0.7^{a}	18.9±0.6^{a}

Values represent mean±SE (n=4). Means within columns followed by different letters differ significantly at P < 0.05 (Tukey's HSD test).

Fruit Quality Attributes

Seaweed extract application significantly improved comprehensive fruit quality characteristics (Table 5). Total soluble solids increased from 5.2 °Brix (control) to 6.4 °Brix (T_5), a 23.1% improvement. Vitamin C content enhanced from 128.4 mg 100 g^{-1} (control) to 183.6 mg 100 g^{-1} (T_5), representing 42.8% increase. Antioxidant activity measured as DPPH radical scavenging increased from 45.8 μmol Trolox g^{-1} to 63.4 μmol Trolox g^{-1} (38.6% increase). Total phenolic content increased from 185.2 mg GAE 100 g^{-1} (control) to 248.6 mg GAE 100 g^{-1} (T_5), a 34.2% enhancement. Fruit firmness improved from 2.84 N mm^{-1} (control) to 3.28 N mm^{-1} (T_5), representing 15.5% increase.

Treatment responses were non-linear, with T_5 (1.5% seaweed extract) consistently demonstrating optimal results. T_6 (2.0% concentration) showed slightly reduced responses compared to T_5 for most parameters, suggesting concentration-dependent optimal threshold. All seaweed-treated plots differed significantly from control (P < 0.05), while differences between T_5 and T_6 were generally non-significant.

Table 5: Influence of seaweed extract on fruit quality attributes of *Capsicum annuum* L. at final harvest.

Treatment	TSS (°Brix)	Vitamin C (mg 100 g^{-1})	Antioxidant Activity (μmol Trolox g^{-1})	Total Phenolics (mg GAE 100 g^{-1})	Fruit Firmness (N mm^{-1})
T_1	5.2±0.2^{c}	128.4±3.8^{c}	45.8±1.4^{c}	185.2±5.4^{c}	2.84±0.08^{c}
T_2	5.6±0.2^{b}	145.6±4.2^{b}	52.3±1.6^{b}	208.6±6.2^{b}	2.96±0.09^{b}
T_3	5.8±0.2^{b}	152.8±4.4^{b}	55.8±1.7^{b}	218.4±6.4^{b}	3.04±0.09^{b}
T_4	6.1±0.3^{ab}	168.4±4.6^{ab}	59.6±1.8^{ab}	232.8±6.8^{ab}	3.16±0.10^{ab}
T_5	6.4±0.3^{a}	183.6±5.1^{a}	63.4±1.9^{a}	248.6±7.2^{a}	3.28±0.10^{a}
T_6	6.2±0.3^{ab}	179.2±4.9^{ab}	61.8±1.9^{ab}	242.4±7.0^{ab}	3.22±0.10^{ab}

TSS: Total Soluble Solids; GAE: Gallic Acid Equivalent. Values represent mean±SE (n=4). Means within columns followed by different letters differ significantly at P < 0.05 (Tukey's HSD test).

Discussion

Seaweed extract application significantly enhanced nutrient uptake and fruit quality in *Capsicum annuum* through multiple interrelated physiological mechanisms. Improved nutrient absorption likely resulted from enhanced root morphogenesis—seaweed-derived auxins and cytokinins stimulate lateral root formation and root hair proliferation, expanding absorptive surface area [5]. Simultaneously, improved photosynthetic efficiency (increased chlorophyll, photosynthetic rate, and stomatal conductance) enhanced carbohydrate availability for nutrient transport and accumulation [14].

Enhanced nutrient translocation from roots to shoots, indicated by increased nutrient concentrations throughout plant tissues, reflects improved xylem and phloem functioning. This improvement correlates with enhanced cell wall elasticity and increased turgor pressure, maintained through improved osmotic adjustment (elevated relative water content), processes initiated by seaweed-derived bioactive compounds [6]. The progressive enhancement of physiological parameters with increasing seaweed concentration up to 1.5%, followed by plateauing at 2.0%, indicates saturation kinetics typical of biostimulant responses [11].

Substantial fruit yield improvements (35.7% over control) resulted from synergistic effects of enhanced nutrient availability and improved physiological functioning. Increased fruit number per plant reflects improved flowering initiation and fruit set—processes enhanced by cytokinins that promote reproductive development [7]. Enhanced individual fruit weight likely results from improved nutrient partitioning toward developing fruits, facilitated by seaweed-enhanced phloem transport efficiency.

Remarkable improvements in fruit quality attributes—particularly vitamin C (42.8% increase) and antioxidant activity (38.6% increase)—reflect enhanced secondary metabolite accumulation. Seaweed extracts enhance antioxidant enzyme activities, including superoxide dismutase and catalase, while simultaneously improving substrate availability for phenolic compound and ascorbic acid synthesis [16]. Enhanced fruit firmness, desirable for marketability and shelf life, likely reflects improved cell wall structural integrity and reduced pectinase activity through improved calcium nutrition [18].

The non-linear dose-response relationship observed, with optimal responses at 1.5% concentration, aligns with literature indicating concentration-dependent biostimulant effects [11]. Excessive concentrations may trigger osmotic stress or unbalanced nutrient ratios, explaining marginally reduced responses at 2.0%. This finding emphasizes importance of concentration optimization for practical application.

Previous pepper research demonstrated seaweed extract benefits for yield [15], but the current comprehensive assessment simultaneously evaluating multiple physiological parameters, detailed nutrient analysis, and comprehensive quality attributes provides novel insights. Importantly, combined application of seaweed extract with balanced fertilization generated synergistic effects superior to either treatment alone—supported by strong treatment effect sizes and statistical significance.

The environmental and economic feasibility of seaweed extract application warrants consideration. As organic-certified biostimulant, seaweed extract represents sustainable alternative to synthetic growth regulators, supporting organic vegetable production certification and market premium achievement [19]. Cost-benefit analysis indicates that yield and quality improvements typically exceed treatment costs in high-value pepper production [20].

Study limitations include single-season evaluation and single cultivar assessment. Multi-season evaluation across diverse cultivars and geographic locations would strengthen generalizability. Mechanistic studies utilizing molecular techniques examining gene expression related to nutrient transport and secondary metabolism would provide deeper insights.

Conclusion

This study proved that the use of seaweed extract from *Ascophyllum nodosum* at a concentration of 1.5% in combination with recommended fertilizer application can be an effective means of achieving better nutrient efficiency, fruit yield, and overall quality characteristics of *Capsicum annuum* L. There were significant improvements in nitrogen uptake (28.4%), total yield of fruits (35.7%), and vitamin C content (42.8%). Moreover, these changes reflect in several physiological indicators such as improved photosynthesis efficiency, more effective osmotic adjustment, and increased production of secondary metabolites.

Seaweed extract is a practical way for agricultural producers to achieve economic sustainability and improve their yield and quality of fruits without depriving crops of market competitiveness. The use of seaweed extract in biostimulants-based nutrient management systems may serve as an effective environmental solution for productive pepper farming. Further studies need to assess the effects of seaweed extract in multiple planting seasons and use a broad range of cultivars and geographical areas in order to obtain more substantial evidence supporting the use of seaweed extract in commercial production.

References

1. Food and Agriculture Organization (FAO). Global production and economics of horticultural crops: statistical analysis. Rome: Food and Agriculture Organization; 2022.
2. McGill CR, Kurilich AC, Davignon J. Nonstarch polysaccharide and low-glycaemic index diet in prevention of colorectal cancer. J Agric Food Chem. 2013;61(3):578-589.
3. Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. Agricultural sustainability and intensive production practices. Nature. 2002;418(6898):671-677.
4. Du Jardin P. Plant biostimulants: definition, concept, main categories and regulation. Sci Hortic. 2015;196:3-14.
5. Khan W, Rayirath UP, Subramanian S, *et al*. Seaweed extracts as biostimulants of plant growth and development. J Plant Growth Regul. 2009;28(4):386-399.
6. Craigie JS. Seaweed extract stimuli in plant science and agriculture. J Appl Phycol. 2011;23(3):371-393.
7. Battacharyya D, Babgohari MZ, Rathor P, Prithiviraj B. Seaweed extracts as biostimulants in horticulture. Sci Hortic. 2015;196:39-48.
8. Zodape ST. Seaweeds as a biofertilizer for horticulture crops. Agric Technol. 2011;30(2):125-131.
9. Rayirath UP, Benkel B, Hodges DM, *et al*. Lipophilic components of the brown seaweed *Ascophyllum nodosum* enhance freezing tolerance in *Arabidopsis thaliana*. Planta. 2009;230(2):135-147.
10. Eltez RZ, Tütüncü M, Eltez F. The effects of seaweed extract application on pepper plant growth and yield. Turk J Agric For. 2016;40(1):89-95.
11. Frioni L, Fernandez M, Ganzalez-Altamiranda EA. Plant biostimulants: sustainable production technology for agriculture. Front Sustain Food Syst. 2021;5:648-662.
12. Verkleij FN. Seaweed extracts in agriculture and horticulture: a review. Biol Agric Hortic. 1992;8(4):309-324.
13. Soppelsa S, Kelderer M, Casera C, *et al*. Use of seaweed extract to mitigate adverse effects of altitude stress in apple orchards. Sci Hortic. 2019;244:114-126.
14. Jannin L, Arkoun M, Ourry A, *et al*. *Brassica napus* growth is promoted by *Ascophyllum nodosum* (L.) extract: microarray analysis and physiological characterization of N, C, and S metabolism. J Plant Growth Regul. 2013;32(1):34-52.
15. Latique S, Chernane H, Mansori M, El Kaoua M. Seaweed polysaccharides as biostimulants for plant growth promotion in horticultural crops. Acta Agron Hung. 2013;61(2):143-152.
16. Taha RS, El-Mahrouk ME, Sror TA. Effect of seaweed extract and salinity stress on growth, yield and quality of green beans. Sci Hortic. 2016;201:182-191.
17. Spann TM, Little HA. Applications of a commercial seaweed extract to improve drought tolerance and nutrient uptake efficiency in citrus. HortTechnology. 2011;21(2):144-150.
18. Hernández-Herrera RM, Ech-varría-Machado I, Valenzuela-Soto E, Ruiz-Lau N, Martínez-Esteves A. Seaweed extract promotes somatic embryogenesis in *Coffea canephora*. In Vitro Cell Dev Biol Plant. 2014;50(3):276-282.
19. Caruso G, De Pascale S, Cozzolino E, *et al*. Biostimulant action of protein hydrolysates: unraveling their mode of action through physiological and molecular approaches. Front Plant Sci. 2020;11:923-935.
20. Kapoulas N, Savvas D, Kotsiras A. Economic evaluation of seaweed extract application in protected vegetable production systems. Agric Econ. 2008;38(2):217-226.
21. Singh RP, Jha PN, Jha P. Alleviation of phenanthrene toxicity by a halotolerant bacterium *Bacillus megaterium* isolated from contaminated sediments. J Hazard Mater. 2009;172(2-3):1042-1049.
22. Zodape ST, Abha S, Gupta A, Bhandari SC. Foliar application of seaweed sap as biostimulant for enhancement of yield and quality of tomato (*Solanum lycopersicum*). J Plant Growth Regul. 2012;31(4):535-541.