

Marine Macroalgae as Natural Biostimulants for improving growth, yield and functional quality of Capsicum (*Capsicum annuum* L.) under polyhouse condition

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ABSTRACT

The growing emphasis on sustainable agriculture has increased interest in seaweed-based biostimulants as environmentally friendly alternatives to synthetic agrochemicals. A study was conducted under polyhouse conditions at SRM College of Agricultural Sciences, SRMIST, Chengalpattu, Tamil Nadu, India, during the rabi season of 2025–2026 to evaluate the influence of marine macroalgae biostimulants on the growth, yield, and functional quality of capsicum (*Capsicum annuum* L.). The experiment was laid out in a Completely Randomized Design (CRD) with ten treatments and three replications, comprising foliar applications of *Ascophyllum nodosum*, *Kappaphycus alvarezii*, and *Gracilaria edulis* at 2.5, 5.0, and 7.5% concentrations, along with an untreated control. The results indicated significant improvements in vegetative growth, flowering, yield, and fruit quality due to seaweed biostimulant application. Among the treatments, *Ascophyllum nodosum* at 5.0% (T₃) produced the highest plant height (127.0 cm), number of leaves (89.3 plant⁻¹), fruits per plant (31.0), average fruit weight (198.6 g), and fruit yield (19.2 kg m⁻²). It also promoted earlier flowering and enhanced SPAD chlorophyll values. Quality attributes, including ascorbic acid and capsanthin content, were highest under T₃, whereas total phenol content was maximized in T₄ (*Ascophyllum nodosum* at 7.5%). The study demonstrates that foliar application of *Ascophyllum nodosum* at 5.0% is an effective and sustainable strategy for improving capsicum productivity and fruit quality under polyhouse condition.

Keywords: Capsicum, Marine macroalgae, Polyhouse, Biostimulants, Yield, Quality.

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Introduction

Capsicum (*Capsicum annuum* L.), commonly known as sweet pepper or bell pepper, is one of the most economically important vegetable crops belonging to the family Solanaceae. The crop originated in Central and South America and is now cultivated extensively in tropical, subtropical, and temperate regions of the world. Capsicum fruits are highly valued for their nutritional and health-promoting properties, as they are rich sources of vitamins A, C, and E, carotenoids, phenolic compounds, flavonoids, dietary fibre, and essential minerals such as potassium, calcium, and magnesium (Wahyuni *et al.*, 2011; Aminifard *et al.*, 2012). Owing to its high consumer demand, diverse culinary applications, and export potential, capsicum has become a high-value vegetable crop in the global horticultural sector. Globally, major producers of capsicum include China, Mexico, Turkey, Indonesia, Spain, India, and the United States. According to the Food and Agriculture Organization (FAO, 2024), peppers and chillies occupy more than 2 million hectares worldwide,

with an annual production exceeding 38 million tonnes. The increasing demand for fresh vegetables, improved dietary awareness, and expansion of protected cultivation technologies have further accelerated global capsicum production.

India is one of the leading producers of vegetables and ranks among the major capsicum-producing countries in the world. The crop is cultivated across several states including Karnataka, Maharashtra, Himachal Pradesh, Haryana, Punjab, Uttar Pradesh, and Tamil Nadu. In recent years, coloured capsicum production has gained considerable commercial importance due to its high market value in domestic supermarkets, hotels, and export markets. According to the National Horticulture Board (NHB, 2023), the area under protected cultivation of high-value vegetables, particularly capsicum, has expanded significantly in response to increasing urban demand and government support programs. Protected cultivation of capsicum has become an attractive enterprise for farmers because it provides higher productivity, improved fruit quality, and better economic returns compared with open-field cultivation. However, the

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crop remains highly sensitive to environmental stresses, including temperature extremes, water stress, and nutrient imbalances, which can negatively influence flowering, fruit set, yield, and fruit quality.

In Tamil Nadu, capsicum cultivation has emerged as an important component of protected horticulture, particularly in districts such as Krishnagiri, Dharmapuri, Nilgiris, Dindigul, Salem, Erode, Coimbatore, and Tiruppur. The state's diverse agro-climatic conditions, coupled with increasing adoption of precision farming and protected cultivation technologies, have facilitated the expansion of coloured capsicum production. Government initiatives through the Department of Horticulture and Plantation Crops and the Mission for Integrated Development of Horticulture (MIDH) have encouraged farmers to adopt naturally ventilated polyhouses for the cultivation of high-value vegetable crops. Under Tamil Nadu conditions, capsicum grown in protected structures has demonstrated substantially higher yields, improved fruit quality, and greater profitability than open-field cultivation (TNAU, 2023). Nevertheless, intensive cultivation practices often depend heavily on chemical fertilizers and agrochemicals, raising concerns regarding soil health, nutrient-use efficiency, and environmental sustainability.

Protected cultivation has emerged as a key technological intervention for enhancing vegetable productivity under changing climatic conditions. Among the various protected structures, naturally ventilated polyhouses are widely preferred because they provide a favourable microclimate while minimizing operational costs. These structures regulate temperature, relative humidity, solar radiation, and air circulation through natural ventilation mechanisms, thereby creating optimal conditions for crop growth and development. Naturally ventilated polyhouses offer several advantages, including protection from adverse weather conditions, reduced pest and disease incidence, efficient water use, improved nutrient management, and year-round production of quality vegetables. Numerous studies have reported that capsicum cultivated under naturally ventilated polyhouses exhibits superior vegetative growth, enhanced photosynthetic efficiency, improved fruit quality, and significantly higher yields compared with open-field production systems (Singh *et al.*, 2022; Rathore and Bahadur, 2024). Despite these benefits, the sustainability of protected cultivation systems is increasingly challenged by excessive reliance on synthetic fertilizers, which may contribute to soil degradation, nutrient imbalance, and environmental pollution.

In recent years, seaweed-based biostimulants have attracted considerable attention as sustainable alternatives capable of improving crop productivity while reducing dependence on

chemical inputs. Seaweed extracts are rich sources of biologically active compounds, including polysaccharides, amino acids, vitamins, minerals, antioxidants, phenolics, and plant growth regulators such as auxins, cytokinins, and gibberellins (Khan *et al.*, 2024). These bioactive molecules influence several physiological and biochemical processes, including nutrient uptake, photosynthesis, root development, flowering, fruit set, and stress tolerance. Furthermore, seaweed biostimulants enhance antioxidant defence systems and improve plant resilience against abiotic stresses such as drought, salinity, heat stress, and nutrient deficiencies.

Although the beneficial effects of seaweed-based biostimulants have been documented in several horticultural crops, comparative information regarding the influence of *Ascophyllum nodosum*, *Kappaphycus alvarezii*, and *Gracilaria edulis* on capsicum cultivated under naturally ventilated polyhouse conditions remains limited. Therefore, evaluating the effects of these seaweed biostimulants on growth, physiological characteristics, yield, and fruit quality of capsicum under protected cultivation.

Materials and Methods

The present investigation was conducted under polyhouse conditions at the polyhouse facility of SRM College of Agricultural Sciences, SRM Institute of Science and Technology, Baburayanpettai, Chengalpattu District, Tamil Nadu, India, during the Rabi season (2025–2026). The experimental location is situated at an elevation of approximately 36 m above mean sea level (MSL) and is geographically positioned at 12°38' N latitude and 79.74° E longitude. Throughout the crop growth period, recommended agronomic and plant protection practices for capsicum cultivation under polyhouse conditions were uniformly followed to ensure a healthy and vigorous crop stand.

The study was undertaken to evaluate the effectiveness of selected marine macroalgae-based biostimulants on the growth, productivity, and fruit quality of capsicum (*Capsicum annuum* L.). The marine macroalgae were collected from Bay of Bengal of Ramanathapuram district and prepared the extract after drying and powdering. The experiment was laid out in a Completely Randomized Design (CRD) comprising ten treatments with three replications. The treatments included: T₁ – Control (water spray), T₂ – *Ascophyllum nodosum* (2.5%), T₃ – *Ascophyllum nodosum* (5.0%), T₄ – *Ascophyllum nodosum* (7.5%), T₅ – *Kappaphycus alvarezii* (2.5%), T₆ – *Kappaphycus alvarezii* (5.0%), T₇ – *Kappaphycus alvarezii* (7.5%), T₈ – *Gracilaria edulis* (2.5%), T₉ – *Gracilaria edulis* (5.0%), and T₁₀ – *Gracilaria edulis* (7.5%).

Observations were recorded on twelve important growth, yield, physiological, and quality attributes, namely days to first flowering, days to

50% flowering, plant height, number of leaves per plant, average fruit weight, number of fruits per plant, fruit yield (kg m^{-2}), dry matter production (%), SPAD chlorophyll index, ascorbic acid content, total phenol content, and capsanthin concentration. For data collection, five representative plants were randomly selected from each treatment in every replication and tagged for recording observations throughout the experimental period.

The ascorbic acid content of fruits was estimated following the method described by Harris and Ray (1935). Total phenol content was determined using the Folin-Ciocalteu colorimetric method as outlined by Singleton and Rossi (1965) and expressed as mg gallic acid equivalents per 100 g fresh weight. Capsanthin content was quantified according to the procedure described by Ranganna (1986) and expressed as $\text{mg } 100 \text{ g}^{-1}$ fresh weight.

The experimental data generated from various observations were subjected to statistical analysis using the procedures appropriate for a Completely Randomized Design (CRD). Analysis of variance (ANOVA) was performed to assess the significance of treatment effects on growth, yield, physiological, and quality parameters of capsicum. The statistical methodology proposed by Gomez and Gomez (1984) was followed for the analysis.

Result and Discussion

The foliar application of seaweed biostimulants significantly influenced the vegetative growth of capsicum grown under polyhouse conditions. Plant height increased progressively from 30 to 90 days after transplanting (DAT) in all treatments, demonstrating the positive impact of seaweed-based formulations on crop growth. Among the treatments, T₃ recorded the highest plant height of 39.10 cm, 60.70 cm, and 127.00 cm at 30, 60, and 90 DAT, respectively, followed closely by T₆ with values of 38.50 cm, 59.30 cm, and 126.80 cm. In contrast, the untreated control (T₁) exhibited the lowest plant height throughout the experimental period, recording 29.70 cm, 49.80 cm, and 112.40 cm at the respective stages. The mean plant height across all treatments was 34.60 cm, 55.31 cm, and 120.51 cm at 30, 60, and 90 DAT, respectively.

The enhanced plant growth observed in seaweed-treated plants can be attributed to the presence of biologically active compounds such as auxins, cytokinins, gibberellins, amino acids, vitamins, and essential micronutrients. These compounds stimulate cell division, cell elongation, chlorophyll biosynthesis, and nutrient uptake, thereby promoting vigorous vegetative growth. Similar observations were reported by Singh *et al.* (2025), who noted significant improvements in capsicum growth following seaweed biostimulant application under protected cultivation. Likewise, Pramanick *et al.* (2013) demonstrated that extracts of *Kappaphycus* and *Gracilaria* enhanced plant

growth by improving nutrient absorption and metabolic activity.

A similar pattern was evident in the number of leaves per plant. The maximum number of leaf count was recorded in T₃, producing 56.00, 70.60, and 89.30 leaves plant^{-1} at 30, 60, and 90 DAT, respectively. Treatment T₆ ranked next, while the control treatment recorded the fewest leaves at all growth stages. The mean number of leaves across treatments was 49.13, 65.27, and 83.31 leaves plant^{-1} at 30, 60, and 90 DAT, respectively. Increased leaf production may be associated with enhanced photosynthetic efficiency, improved nutrient assimilation, and higher chlorophyll content resulting from seaweed-derived biostimulants. Seaweed extracts contain polysaccharides, betaines, amino acids, and plant growth regulators that stimulate physiological processes and canopy development. Comparable findings were reported by Jayasinghe *et al.* (2016), Deori *et al.* (2023), and Gangam *et al.* (2024), who observed substantial improvements in vegetative growth and leaf development of capsicum following foliar application of biostimulants.

The superior performance of *Ascophyllum nodosum* may be attributed to its higher concentration of natural phytohormones, minerals, and stress-mitigating compounds, which enhance nutrient use efficiency, chlorophyll synthesis, root growth, and photosynthetic activity. Papoui and Koukounaras (2025) reported that *Ascophyllum*-based extracts improved plant vigour through enhanced physiological efficiency and stress tolerance. Similarly, Colla *et al.* (2017) highlighted the role of seaweed biostimulants in improving nutrient status and plant productivity through metabolic regulation and efficient resource utilization. Statistical analysis confirmed significant differences among treatments, indicating that foliar application of seaweed biostimulants, particularly *Ascophyllum nodosum* (T₃), effectively enhanced vegetative growth and plant vigour of capsicum under polyhouse conditions

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Table. 1 Effect of foliar application of seaweed biostimulants on growth and yield of capsicum (*capsicum annuum*) under polyhouse |

Treatments	Plant height			No. of leaves		
	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT
T1 - Control	29.70	49.30	112.40	43.20	38.40	75.30
T2 - <i>Ascophyllum nodosum</i> (2.5%)	36.30	56.50	123.00	50.90	67.80	86.10
T3 - <i>Ascophyllum nodosum</i> (5.0%)	39.10	60.70	127.00	56.00	70.60	89.30
T4 - <i>Ascophyllum nodosum</i> (7.5%)	33.00	54.00	118.70	47.00	63.20	81.00
T5 - <i>Kappaphycus alvarezii</i> (2.5%)	35.20	56.00	121.60	49.80	66.30	84.50
T6 - <i>Kappaphycus alvarezii</i> (5.0%)	38.50	59.30	126.80	53.40	70.60	88.80
T7 - <i>Kappaphycus alvarezii</i> (7.5%)	31.90	52.60	116.20	45.80	61.70	79.40
T8 - <i>Gracilaria edulis</i> (2.5%)	34.10	55.10	120.10	48.60	64.80	82.70
T9 - <i>Gracilaria edulis</i> (5.0%)	37.40	57.90	124.50	52.10	69.20	87.90
T10 - <i>Gracilaria edulis</i> (7.5%)	30.80	51.20	114.80	44.50	60.10	77.60
Mean	34.60	55.31	120.31	49.13	65.27	83.31
SE _d	1.58	2.13	2.23	1.40	2.76	3.57
CD	3.29	4.44	4.66	2.93	5.76	7.45

The influence of foliar-applied seaweed biostimulants on the SPAD chlorophyll index of capsicum grown under polyhouse conditions is illustrated in Figure 1. Significant variations in SPAD readings were observed among the treatments throughout the crop growth period. Plants treated with seaweed-based biostimulants consistently exhibited higher SPAD values than the untreated control, indicating a positive effect on chlorophyll concentration and leaf physiological status. Among all treatments, T₃ recorded the highest SPAD values at every stage of observation, demonstrating its effectiveness in enhancing photosynthetic capacity and maintaining leaf greenness.

The improvement in SPAD readings following seaweed application may be attributed to the diverse range of biologically active constituents present in seaweed extracts, including phytohormones, amino acids, vitamins, betaines, and essential micronutrients. These compounds play a crucial role in stimulating chlorophyll synthesis, improving nitrogen metabolism, and enhancing nutrient absorption, which collectively contribute to greater photosynthetic efficiency. Similar observations were reported by Colla *et al.* (2017), who demonstrated that seaweed-derived biostimulants improved plant nutritional status and physiological performance through enhanced metabolic processes and chlorophyll development.

The superior response observed in T₃ could be linked to its rich composition of natural growth-promoting substances and stress-alleviating

metabolites. Extracts of *Ascophyllum nodosum* have been widely recognized for their ability to enhance photosynthetic activity, nutrient uptake, and plant resilience under varying environmental conditions. Supporting these findings, Papoui and Koukounaras (2025) reported substantial improvements in physiological traits and plant growth following the application of *Ascophyllum*-based formulations.

Treatments T₆ and T₉ also recorded comparatively higher SPAD values, highlighting the beneficial influence of seaweed extracts on chlorophyll retention and leaf quality. The presence of polysaccharides, minerals, and naturally occurring plant growth regulators in these extracts may stimulate chloroplast development and improve cellular metabolic activity. Similar results were documented by Pramanick *et al.* (2013), who reported enhanced nutrient uptake and plant growth following the application of *Kappaphycus*-derived seaweed extracts.

The present findings are consistent with the reports of Jayasinghe *et al.* (2016) and Singh *et al.* (2025), who observed improved physiological performance and growth of capsicum following seaweed biostimulant application. The gradual increase in SPAD values from 30 to 90 DAT across all treatments suggests sustained enhancement of chlorophyll content and photosynthetic activity during crop development. Increased chlorophyll concentration promotes efficient light harvesting, carbon fixation, and biomass accumulation, ultimately contributing to improved plant growth and productivity. Therefore, the superior SPAD values recorded under T₃ confirm its potential as an effective foliar biostimulant for enhancing photosynthetic efficiency and maintaining crop vigour in capsicum cultivated under protected conditions.

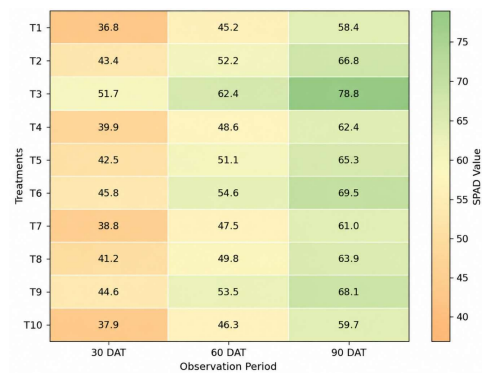


Figure 1. Effect of foliar application of seaweed biostimulants on spad value of capsicum (*capsicum annuum* l.) under polyhouse conditions

Source: Author's Computation

The effect of foliar application of seaweed biostimulants on days to first flowering and 50 per cent flowering of capsicum under polyhouse conditions is presented in Figure 2. The results

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indicated that seaweed biostimulant treatments significantly reduced the time required for flowering compared to the untreated control. Among the treatments, T₃ recorded the earliest flowering, requiring only 20.80 days for first flowering and 33.50 days for 50 per cent flowering, demonstrating its effectiveness in promoting reproductive development under protected cultivation.

The reduction in flowering duration may be attributed to the presence of bioactive compounds such as auxins, cytokinins, gibberellins, amino acids, vitamins, and micronutrients in seaweed extracts. These compounds enhance physiological activities, nutrient translocation, and hormonal balance, thereby accelerating the transition from vegetative to reproductive growth. Similar findings were reported by Sharma *et al.* (2024), who observed that seaweed biostimulants improved crop development through enhanced nutrient-use efficiency and hormonal regulation.

The superior performance of *Ascophyllum nodosum* may be associated with its high concentration of natural growth regulators and stress-mitigating compounds. Faize *et al.* (2021) reported that *Ascophyllum*-based extracts stimulate plant development by improving metabolic activity and hormonal signalling. Treatments T₆ and T₉ also promoted earlier flowering, supporting the findings of Singh *et al.* (2017) on the positive effects of red seaweed extracts on crop growth and productivity.

The present results are in agreement with Ichwan *et al.* (2021) and Arokia Rajan *et al.* (2020), who reported enhanced growth and flowering in capsicum following seaweed biostimulant application. Early flowering under T₃ is advantageous in protected cultivation as it facilitates earlier fruit set, extends the harvesting period, and contributes to higher yield potential and economic returns.

highest values for all yield and quality parameters, indicating its superior effectiveness in enhancing fruit production and quality.

The improved performance of T₃ may be attributed to the presence of phytohormones, amino acids, vitamins, polysaccharides, and micronutrients that stimulate photosynthesis, nutrient uptake, and assimilate translocation towards developing fruits. Similar findings were reported by Hidangmayum and Sharma (2017), who observed significant improvements in crop growth and yield following the application of *Ascophyllum nodosum* extracts. The higher fruit yield obtained in the present study is also supported by Bahar *et al.* (2025), who attributed enhanced productivity in capsicum to improved physiological efficiency and nutrient acquisition.

Treatments T₆ and T₉ also showed notable improvements in yield and fruit quality, confirming the beneficial role of seaweed extracts in reproductive growth and fruit development. Similar results were reported by Jayasinghe *et al.* (2016) and Pramanick *et al.* (2013). Increased dry matter content under seaweed treatments suggests enhanced accumulation of carbohydrates and metabolites, which agrees with the findings of Colla *et al.* (2017). The present results are further supported by Singh and Singh (2023), who reported improved yield and quality of capsicum under protected cultivation. Overall, *Ascophyllum nodosum* (T₃) proved to be the most effective treatment for maximizing yield and fruit quality in capsicum grown under polyhouse conditions.

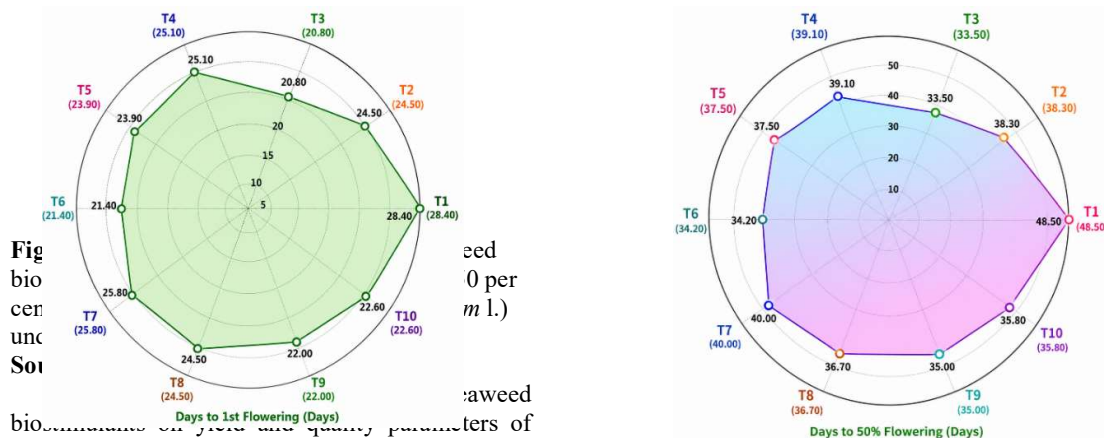


Fig 1. Comparison of yield and quality parameters of capsicum under polyhouse conditions is presented in Table 2. The results revealed that seaweed biostimulant treatments significantly improved the number of fruits per plant, average fruit weight, fruit yield, and dry matter content compared with the control. Among the treatments, T₃ recorded the

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Table 2. Effect of foliar application of seaweed biostimulants on yield and quality parameters of capsicum (*capsicum annum l.*) under polyhouse conditions

Treatments	No. of fruits per plant	Average fruit weight	Yield kg m ⁻²	Dry matter (%)
T1 - Control	17.20	136.40	7.40	6.80
T2 - <i>Ascophyllum nodosum</i> (2.5%)	21.90	171.80	11.80	9.30
T3 - <i>Ascophyllum nodosum</i> (5.0%)	31.00	198.60	19.20	10.70
T4 - <i>Ascophyllum nodosum</i> (7.5%)	19.50	183.40	15.60	8.10
T5 - <i>Kappaphycus alvarezii</i> (2.5%)	21.10	160.70	10.40	9.10
T6 - <i>Kappaphycus alvarezii</i> (5.0%)	23.50	188.90	18.10	10.40
T7 - <i>Kappaphycus alvarezii</i> (7.5%)	18.70	176.20	13.90	7.60
T8 - <i>Gracilaria edulis</i> (2.5%)	20.30	156.30	9.60	8.60
T9 - <i>Gracilaria edulis</i> (5.0%)	22.70	186.10	16.80	10.00
T10 - <i>Gracilaria edulis</i> (7.5%)	18.00	179.40	14.70	7.20
Mean	21.39	173.98	13.35	8.80
SEd	0.92	5.36	0.33	0.39
CD	1.92	11.19	1.11	0.82

he effect of foliar application of seaweed biostimulants on the ascorbic acid content of capsicum fruits under polyhouse conditions is presented in Figure 3. The results demonstrated that seaweed biostimulant treatments significantly increased the ascorbic acid content compared to the control. Among all treatments, T₃ (*Ascophyllum nodosum*) recorded the highest ascorbic acid content, indicating its effectiveness in improving the nutritional quality of capsicum fruits.

The enhancement in ascorbic acid content may be attributed to the presence of bioactive compounds such as amino acids, vitamins, minerals, polysaccharides, and natural plant growth regulators in seaweed extracts. These compounds stimulate nutrient uptake, metabolic activity, and antioxidant biosynthesis, leading to increased accumulation of vitamin C in fruits. Similar observations were reported by Wahyuni *et al.* (2013), who highlighted the importance of nutritional and physiological factors in regulating ascorbic acid content in Capsicum fruits.

The superior performance of T₃ may be due to the rich composition of *Ascophyllum nodosum*, which enhances nutrient utilization and metabolic efficiency. Papoui and Koukounaras (2025) reported that *Ascophyllum*-based biostimulants improve physiological processes and promote the accumulation of beneficial compounds in plant tissues. Higher ascorbic acid levels observed in T₄, T₆, and T₉ further support the positive role of seaweed extracts in enhancing fruit quality. Similar findings were reported by Deori *et al.* (2023), Gangam *et al.* (2024), and Sharma *et al.* (2024). Overall, the results indicate that foliar application of

seaweed biostimulants, particularly *Ascophyllum nodosum* (T₃), significantly improved the antioxidant quality and nutritional value of capsicum fruits under polyhouse conditions.

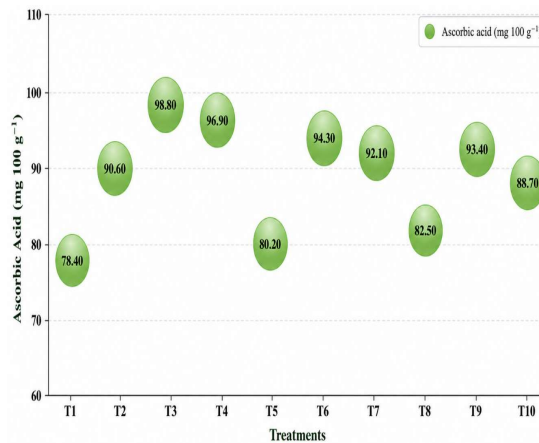


Figure 3. Effect of foliar application of seaweed biostimulants on ascorbic acid content of capsicum (*capsicum annum l.*) under polyhouse conditions.

Source: Author's Computation

The effect of foliar application of seaweed biostimulants on capsanthin content of capsicum fruits under polyhouse conditions is presented in Figure 4. The results revealed that seaweed biostimulant treatments significantly increased capsanthin accumulation compared to the control. Among the treatments, T₃ recorded the highest capsanthin content (2.28 mg g⁻¹ DW), indicating its superior ability to enhance fruit colour, antioxidant properties, and overall fruit quality. T₄, T₆ (*Kappaphycus alvarezii*), and T₉ also showed higher pigment accumulation than the untreated control. Capsanthin is the principal carotenoid responsible for the characteristic red colour of ripe capsicum fruits and contributes significantly to their nutritional and commercial value (Wahyuni *et al.*, 2013).

The enhanced capsanthin content under seaweed treatments may be attributed to the presence of phytohormones, amino acids, vitamins, minerals, and other bioactive compounds that stimulate carotenoid biosynthesis and improve nutrient utilization. Similar findings were reported by Colla *et al.* (2017), who observed improved fruit quality and antioxidant accumulation following seaweed biostimulant application. Increased photosynthetic efficiency, nutrient uptake, and assimilate translocation may have further supported pigment synthesis (Sharma *et al.*, 2024). Comparable improvements in fruit quality and antioxidant composition were reported by Bahar *et al.* (2025), Sanon *et al.* (2025), Papoui and Koukounaras (2025), and Faize *et al.* (2021). The positive effects of *Kappaphycus* extracts reported by Pramanick *et al.* (2013) and Singh *et al.* (2017) also

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support the present findings. Overall, *Ascophyllum nodosum* (T₃) proved to be the most effective treatment for enhancing capsanthin accumulation and improving fruit quality under polyhouse conditions.

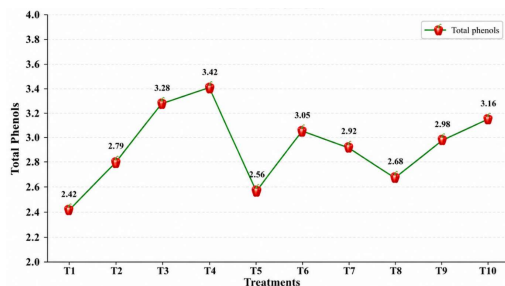


Figure 4. Effect of foliar application of seaweed biostimulants on capsanthin pigment content of capsicum (*Capsicum annuum* L.) under polyhouse conditions.

Source: Author's Computation

The effect of foliar application of seaweed biostimulants on the total phenol content of capsicum fruits under polyhouse conditions is presented in Figure 5. The results indicated that seaweed biostimulant treatments significantly increased phenolic compound accumulation compared to the control. Among the treatments, T₄ recorded the highest total phenol content, followed by T₃, demonstrating the effectiveness of *Ascophyllum*-based biostimulants in enhancing the antioxidant and nutritional quality of capsicum fruits.

The increased phenol content may be attributed to the presence of bioactive compounds such as amino acids, polysaccharides, vitamins, minerals, and natural plant growth regulators that stimulate secondary metabolism and phenolic biosynthesis. Similar findings were reported by Colla *et al.* (2017), who observed enhanced accumulation of phenolics and antioxidants following seaweed biostimulant application. The superior performance of *Ascophyllum* treatments is supported by Papoui and Koukounaras (2025) and Faize *et al.* (2021), who reported improved metabolic activity and synthesis of beneficial compounds through *Ascophyllum*-based extracts.

Higher phenolic content in T₆ and T₉ further confirms the positive role of seaweed extracts in improving fruit quality. Similar observations were reported by Pramanick *et al.* (2013), Jayasinghe *et al.* (2016), Hidangmayum and Sharma (2017), and Arokia Rajan *et al.* (2020). Furthermore, Wahyuni *et al.* (2013) and Sharma *et al.* (2024) emphasized the importance of phenolic compounds in enhancing antioxidant capacity and nutritional quality. Overall, T₄ proved to be the most effective treatment for increasing total phenol content and improving the functional quality of capsicum fruits under protected cultivation.

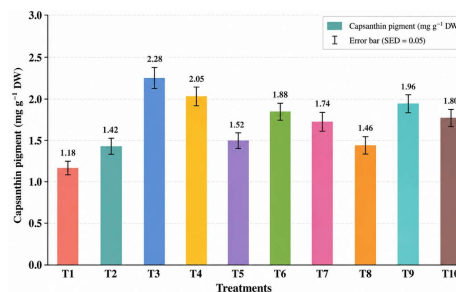


Figure 5. Effect of foliar application of seaweed biostimulants on total phenol content of capsicum (*Capsicum annuum* L.) under polyhouse conditions.

Source: Author's Computation

Conclusion

The present study revealed that foliar application of seaweed biostimulants significantly improved the growth, flowering, yield, and quality of capsicum under polyhouse conditions. Among the treatments, T₃ (*Ascophyllum nodosum*) consistently recorded superior performance in most parameters. It produced the highest plant height, number of leaves, SPAD value, fruit number, average fruit weight, and fruit yield. The treatment also promoted early flowering, resulting in improved crop earliness. Enhanced chlorophyll content and physiological activity contributed to greater photosynthetic efficiency and biomass accumulation. Quality parameters such as ascorbic acid and capsanthin pigment content were also highest under T₃. However, the maximum total phenol content was recorded in T₄ (*Ascophyllum nodosum*). The beneficial effects were attributed to the presence of phytohormones, amino acids, vitamins, and micronutrients in seaweed extracts. Overall, seaweed biostimulants proved effective in enhancing productivity and fruit quality of capsicum. Therefore, foliar application of *Ascophyllum nodosum* (T₃) is recommended for sustainable and profitable capsicum cultivation under polyhouse conditions.

Reference

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