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Impact of Biostimulants on Yield and Yield Attributing Characteristic of Capsicum (*Capsicum annuum* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In recent years, interest in the cultivation and consumption of capsicum has significantly increased, driving research toward identifying the most favorable conditions for its growth and productivity. Biostimulants are materials or microorganisms used in agriculture to boost a plant's nutrient uptake, enhance its tolerance to abiotic stress, and improve overall crop performance. They are broadly categorized into groups such as humic and fulvic acids, protein hydrolysates, nitrogen-based substances, seaweed extracts, plant-based compounds, chitosan and other biopolymers, inorganic materials, and beneficial microbes like fungi and bacteria. The present study was conducted to evaluate the effect of biostimulants on the yield and yield-attributing traits of capsicum. A total of twelve treatments, including an absolute control, were tested using a Randomized Block Design

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(RBD) with four replications. The research was carried out under polyhouse conditions at the Department of Vegetable Science, CCS Haryana Agricultural University, Hisar, during the Rabi seasons of 2022–23 and 2023–24, utilising the PSM-1 variety as the test material. The results revealed significant differences among treatments for all recorded parameters, including days to first flowering, fruit maturity, number of fruits per plant, fruit size, average fruit weight, and total yield. The treatment T_3 (RDF + Seaweed extract @ 2.5 ml/L) emerged as the most effective, recording the earliest flowering (41.75 days), highest number of fruits per plant (22.50), maximum fruit length (9.55 cm), fruit diameter (7.96 cm), average fruit weight (95.74 g), and highest total yield (399.05 q/ha). Comparatively, treatments involving 87.5% RDF alone or with biostimulants showed moderate improvements but were generally less effective than those with 100% RDF. Thus, the integrated application of biostimulants with full RDF, particularly seaweed extract, is recommended for optimizing capsicum productivity and quality in protected cultivation systems.

Keywords: Capsicum; sustainable cultivation; microorganisms; biostimulants.

1. INTRODUCTION

“Recent years have witnessed an increased interest in the cultivation and consumption of peppers. he selection of high-yielding cultivars that are resistant to pathogens and adverse growing conditions is one of the key factors in integrated vegetable production” (Majkowska-Gadomska et al., 2021; Mezeyová et al., 2024). “Capsicum (*Capsicum annuum* L.), widely known as bell pepper, sweet pepper, or shimla mirch, is a tropical to subtropical vegetable and spice crop belonging to the Solanaceae family, with a chromosome number of 2n = 24. It is well-regarded for its rich taste, appealing aroma, and high nutritional value. Originating in Mexico, bell pepper also has a secondary centre of origin in Guatemala” (Heiser and Smith, 1953). “In India, it was introduced by the British during the 19th century in the Shimla Hills” (Singh *et al.,* 1993). Among the five domesticated species of Capsicum *i.e., C. annuum*, *C. baccatum*, *C. chinense*, *C. frutescens*, and *C. pubescens*. *C. annuum* is the most widely cultivated worldwide. Its popularity stems from high consumer demand, nutritional advantages, and economic importance, benefiting both producers and consumers across developed and developing regions (Singh *et al.,* 2025). Preserving genetic diversity and promoting sustainable cultivation methods are vital for ensuring the long-term viability and global relevance of the crop.

“Biostimulants are materials or microorganisms used in agriculture to boost a plant’s nutrient uptake, enhance its tolerance to abiotic stress, and improve overall crop performance” (Sun *et al.,* 2023). “They are broadly categorised into groups such as humic and fulvic acids, protein hydrolysates, nitrogen-based substances, seaweed extracts, plant-based compounds, chitosan and other biopolymers, inorganic materials, and beneficial microbes like fungi and bacteria” (Du Jardin, 2015). “These inputs support plant growth and productivity by stimulating natural physiological functions. Although mineral nutrition has been extensively explored for enhancing bell pepper quality, studies focusing on the use of biostimulants for the same purpose are still relatively scarce. Biostimulants when applied to plants or soil, enhance plant growth, stress tolerance and crop quality. They provide a complementary approach to conventional fertilizers and pesticides, promoting sustainable and environmentally friendly agricultural practices. Biostimulants work through multiple mechanisms, including promoting root development, improving nutrient availability, enhancing stress tolerance and stimulating beneficial microbial activity in the soil” (Suhaini et al., 2023).

Seaweed extracts, known for containing natural growth regulators like cytokinins and auxins, contribute to better plant growth, increased flowering, higher yields, and improved shelf life (Yao *et al.,* 2020). In addition, formulations from seaweed—such as gels and foliar sprays—not only improve soil texture and water-holding capacity but also encourage microbial activity, offering sustainable benefits for plant growth and preservation (Thivy, 1961; Ramani *et al.,* 2020). Salicylic acid (SA) functions as a plant hormone that influences growth regulation, stress resistance, and protection against post-harvest deterioration in crops such as tomatoes and strawberries (Kazemi, 2014; Asghari *et al.,* 2009). At lower concentrations, SA can enhance crop yield and quality (Canakci, 2011). Chitosan, a biodegradable compound derived from chitin found in fungal cell walls and the exoskeletons of crustaceans, plays a vital role in enhancing plant development, resistance to pests, tolerance to environmental stress, and improving post-harvest quality. "It has been reported to boost characteristics such as plant height, leaf area, chlorophyll levels, and photosynthetic efficiency" (Lustriane *et al.,* 2018; Malerba *et al.,* 2016), while also supporting a diverse soil microbial population that aids in nutrient uptake (Rabbi *et al.,* 2016). Humic acid, a naturally occurring organic substance, is known for promoting root development, improving nutrient absorption, and enhancing plant resilience under stress conditions. Similarly, polyamines such as putrescine are involved in regulating plant growth and stress responses. When applied foliarly, putrescine helps extend fruit shelf life and maintain texture (El-Tohamy *et al.,* 2008; Khosroshahi *et al.,* 2007).

The current study was conducted to evaluate the effects of biostimulants on the yield and yield-attributing traits of capsicum.

2. MATERIALS AND METHODS

The present research experiment was conducted at the Polyhouse of the Department of Vegetable Science, CCS Haryana Agricultural University, Hisar during *Rabi* season of 2022-23 & 2023-24 by using capsicum *cv.* PSM-1. The experiment was conducted at polyhouse located near Ram Dhan Seed Farm (RDS), CCS Haryana Agricultural University, Hisar, which is located in semi-arid, subtropical climate zone at 29° 09' to 14.28'' north latitude and 75° 43' to 02.84'' east longitude at an elevation of 215 m above mean sea level on South western border of Haryana state. The field experiment was laid out in a Randomized Block Design (RBD) by using four replications of each twelve biostimulant treatments. Treatment details are:

T_1: RDF (Control)
T_2: 87.5 % RDF
T_3: RDF + Seaweeds extract (2.5 ml/L)
T_4: 87.5 % RDF + Seaweeds extract (2.5 ml/L)
T_5: RDF + Salicylic acid (2 g/L)
T_6: 87.5 % RDF + Salicylic acid (2 g/L)
T_7: RDF + Chitosan 0.5 %
T_8: 87.5 % RDF + Chitosan 0.5 %
T_9: RDF + Putrescine 0.1 g/L
T_{10}: 87.5 % RDF + Putrescine 0.1 g/L
T_{11}: RDF + Humic acid (5 ml/L)
T_{12}: 87.5 % RDF + Humic acid (5 ml/L)

The observation for yield and yield attributes were recorded on randomly selected plant five competetive plant per treatment in each replication. Observations recorded are days taken to first flowering, days taken to first fruit maturity, number of fruits per plant, fruit length (cm), fruit diameter (cm), average fruit weight (g), total yield (q/ha). The experiment was laid out in a Randomized Block Design with four replications. The data obtained from the experiment conducted in RBD were analysed as per standard methods suggested by Panse and Sukhatme (1967). The data observed for various characters during the study were statistically analyzed following the technique of analysis of variance (ANOVA).

3. RESULTS AND DISCUSSION

3.1 Days Taken to First Flowering

Early flowering is one of the most important favourable phenomena in plants since early crop fetches a premium price in the market. The pooled value of days taken to first flowering of both of years ranged from 41.75 days to 47.75 days as indicated in Table 1. Significantly, the minimum days taken to first flowering (41.75 days) was measured in treatment T_3 (**RDF + Seaweed extract 2.5 ml/L)** which was statistically at par with treatment T_5 (RDF + Salicylic acid 2 g/L) and T_7 (RDF + Chitosan 0.5%), while the maximum days taken to first flowering was noticed in (47.75 days) in treatment T_1 (**RDF).** This might be due to early flowering of bell peppr to different sources of nutrients might be due to acceleration of the vegetative phase through the stimulative effect of the absorbed nutrients on photosynthesis process, which certainly reflected positively on vegetative and flowering initiation (Kawthar *et al.* 2010). The present study was in agreement with the findings of Locher *et al*. (2003) in capsicum, Imamsaheb *et al*. (2011) in brinjal and tomato, whereas Godara *et al*. (2024) in capsicum.

The shortening of flowering duration may be due to gibberellins present in seaweed extract that might have reduced the transition between vegetative and reproductive phases and induced early flowering. Yusuf *et al*. (2021) reported that the use of seaweed extract along with NPK had induced early flowering in chilli plants. These results are in conformity with the findings of Venkatesan and Selvakumari (2017); Dookie *et al*. (2021) in tomato.

The foliar application of salicylic acid promotes early flowering in capsicum by modulating key physiological and biochemical processes. Salicylic acid influences hormonal balance by enhancing the levels of flowering-promoting hormones like gibberellins and suppressing those that delay flowering. Similar result was obtained by Munshi *et al.* (2020).

The application of chitosan during the early stages of growth has been linked to earlier flowering in Capsicum plants. This is likely due to enhanced vegetative growth and improved energy allocation towards reproductive structures (Kazimi and Saxena, 2023).

3.2 Days Taken to First Fruit Maturity

Early fruit maturity is one of the most important favourable phenomena in plants since early crop fetches a premium price in the market. The pooled value of days taken to first flowering of both of the years ranged from 105.25 days to 110.75 days as shown in Table 1. Significantly, the minimum days taken to first fruit maturity (105.25 days) was measured in treatment T_3 (**RDF + Seaweed extract 2.5 ml/L**) which was statistically at par with treatment T_5 (RDF + Salicylic acid 2 g/L), while the maximum days taken to first fruit maturity was noticed (110.75 days) in treatment T_1 (**RDF).**

The application of seaweed extract has been shown to significantly influence early fruit maturity in bell peppers. Ertani *et al.* (2015) recorded that capsicum plants treated with seaweed extract produced fruit approximately 10 days earlier than those in the control group. This acceleration in fruit maturity can be particularly beneficial for maximizing the growing season. Similar result was obtained by Ashour *et al.* (2021) in hot pepper.

The application of salicylic acid can accelerate the maturation process of fruits. By influencing metabolic pathways related to ripening, salicylic acid can lead to earlier harvesting times (Ibrahim *et al.,* 2019).

3.3 Number of Fruits Per Plant

The pooled value of number of fruits per plant of both of the years was ranged from 16.25 to 22.50 as shown in Table 1. Significantly, the maximum number of fruits per plant (22.50 fruits) was measured in treatment T_3 (**RDF + Seaweed extract 2.5 ml/L**), which was statistically at par with treatment T_{11} (RDF + Humic acid at 5 ml/L) with 22.25 fruits, whereas the minimum number of fruits per plant (16.25 fruits) was observed in treatment T_2 (**87.5% RDF).** The increase in number of fruits per plant in 100% RDF along with foliar application of biostimulants might be due to supply of nutrients at critical growth stage *i.e.* flowering and fruit set (Narayan *et al.* 2011).

Seaweed extract significantly increases the number of fruits per plant in capsicum by improving nutrient uptake, hormonal balance, stress tolerance, and pollination efficiency. It acts as a natural biostimulant, enhancing both the vegetative and reproductive stages of the plant. Sarhan et al. (2011) reported that cucumber plants treated with seaweed extracts (Alga 600 and sea force2) yielded highest value of number of fruits per plant (21.73). Similar result was obtained by Shanmugam *et al.* (2016) and Arthur *et al.* (2003). Seaweeds have gained importance as foliar sprays for several crops because the extract contains growth promoting hormones (IAA and IBA), cytokinins, trace elements (Fe, Cu, Zn, Co, Mo, Mn and Ni) as well as vitamins and amino acids (Zodape *et al*., 2011; Shabana *et al*., 2020).

Humic acid increases the number of fruits per capsicum plant by improving soil fertility, nutrient availability, root growth, photosynthetic efficiency, and stress tolerance. Its role in stimulating natural plant hormones further supports flower retention and fruit set. A similar result was observed by Karakurt *et al.* (2009). According Jan *et al.* (2020), the maximum number of fruits per plant (57.50) was recorded at 50 g/L humic acid foliar application.

3.4 Fruit Length (cm)

Fruit length is one of the most important quality components that are attributed to the size and appearance. The pooled value of fruit length of both of the years ranged from 7.32 cm to 9.55 cm as shown in Table 2. Significantly, the maximum fruit length (9.55 cm) was measured in treatment T_3 **(RDF + Seaweed extract 2.5 ml/L**), followed by treatment T_7 (RDF + Chitosan 0.5%) with 9.23 cm and T_9 (RDF + Putrescine at 0.1 g/L) with 8.96 cm, whereas the minimum fruit length (7.32 cm) was observed in treatment T_2 (**87.5% RDF). This might be due to** higher vegetative growth helped in the synthesis of greater amount of fruit material, which was later translocated into developing fruits resulting in increased fruit length (Lal and Kanaujia, 2013).

As liquid seaweed fertilizer is a very good source of K, it helps to regulate the water status of the plants, controls the opening and closing of stomata and thereby, to a large extent, controls photosynthesis. Improving the physiological activities such as photosynthesis and plant nutrition and this could be reflected in fruit growth, with increased fruit length, weight, girth and flesh thickness which may be due to more assimilates reaching the fruits or an increase in the sink strength of the fruits, allowing them to attract more water and assimilates as a result of the use of biostimulants. These results are also in accordance with Ashour *et al.* (2021) and Segmen and Ozdamar (2023) in capsicum.

Chitosan enhances fruit length in capsicum by improving nutrient uptake, regulating growth hormones, mitigating stress, and stimulating enzymatic activity. Its multifunctional benefits make it an effective and eco-friendly biostimulant for promoting capsicum growth and achieving higher yields (Dzung *et al.,* 2017; El-Tantawy, 2009). Kramchote and Suwor (2022) found that all concentrations of chitosan increased fruit length, which was statistically significant compared to the control group.

Cell division and flower bud initiation and development are enhanced by putrescine, which results in earlier and more abundant flowering, as well as larger fruits and diameter (Yang *et al.,* 2007). Alizadeh *et al.* (2017) suggested that foliar application of 1.5 mM putrescine recorded the highest fruit length (16.56 cm) in sweet pepper.

3.5 Fruit Diameter (cm)

The pooled value of fruit diameter of both of the years was ranged from 7.96 cm to 6.41 cm as indicated in Table 2. Significantly, the maximum fruit diameter (7.96 cm) was measured in treatment T_3 (**RDF + Seaweed extract 2.5 ml/L**), followed by treatment T_7 (RDF + Chitosan 0.5%) and T_9 (RDF + Putrescine at 0.1 g/L), whereas the minimum fruit diameter (6.41 cm) was observed in treatment T_2 (**87.5% RDF).** Higher vegetative growth helped in the synthesis of a greater amount of fruit material, which was later translocated into developing fruits, resulting in increased the fruit diameter (Lal and Kanaujia, 2013).

Seaweed extract affects fruit growth, as it contains growth regulators that stimulate cell division and elongation during the initial phase of fruit development (Rana *et al.,* 2023). These results are also in accordance with Ashour *et al.* (2021) and Segmen and Ozdamar (2023) in capsicum.

Chitosan enhances fruit diameter in capsicum by improving nutrient uptake, regulating growth hormones, mitigating stress, and stimulating enzymatic activity (Dzung *et al.,* 2017). Kramchote and Suwor (2022) found that all concentrations of chitosan increased fruit diameter, which was statistically significant compared to the control group.

Cell division and flower bud initiation and development are enhanced by putrescine, which results in earlier and more abundant flowering, as well as larger fruits and diameter (Yang *et al.,* 2007). Mahmood *et al.* (2017) also reported that the plants sprayed with 3 mM putrescine had the highest diameter (54.51 mm) compared to the control (46.1 mm). These findings are also in agreement with the study of Zodape *et al.* (2011) and Saravanan *et al.* (2003) in tomato.

3.6 Average Fruit Weight (g)

Fruit weight is one of the main yield components because of its direct impact on yield. The data regarding fruit weight of capsicum is influenced by foliar application of various biostimulant treatments. The pooled value of fruit diameter of both of the years was ranged from 83.15 g to 95.74 g as presented in Table 2. Significantly, the maximum average fruit weight (95.74 g) was measured in treatment T_3 (**RDF + Seaweed extract 2.5 ml/L**), followed by treatment T_{11} (RDF + Humic acid 5 ml/L) at 94.13 g and T_5 (RDF + Salicylic acid 2 g/L) at 92.96 g, whereas the minimum average fruit weight (83.15 g) was observed in treatment T_2 (**87.5% RDF).**

Liquid seaweed fertilizer significantly improves capsicum fruit characteristics such as length, weight, girth, and flesh thickness by optimising plant water status, boosting photosynthesis, and enhancing sink strength. Its potassium content and biostimulatory effects work synergistically to channel more nutrients and assimilates to the fruits, leading to superior growth and yield. Regular and timely application during key growth stages maximises these benefits. These results are in conformity with the findings of Sridhar and Rengasamy (2012); Ozbay and Demirkiran (2019); Vijayakumar *et al.* (2019); Ashour *et al.* (2021) and Azzam *et al.* (2022) in capsicum.

Table 1. Effect of fertilizer levels along with foliar application of biostimulants on days taken to first flowering, days taken to first fruit maturity and no. of fruit per plant of capsicum *cv.* PSM-1 under polyhouse

Treatments	Days taken to first flowering			Days taken to first fruit maturity			No. of fruit per plant		
	2022-23	2023-24	Pooled mean	2022-23	2023-24	Pooled mean	2022-23	2023-24	Pooled mean
T_1: RDF (control)	48.50	47.00	47.75	113.50	108.00	110.75	16.90	18.60	17.75
T_2: 87.5 % RDF	47.75	45.75	46.75	113.00	107.50	110.25	15.30	17.20	16.25
T_3: RDF + Seaweeds extract (2.5 ml/L)	42.50	41.00	41.75	107.00	103.50	105.25	21.50	23.50	22.50
T_4: 87.5 % RDF + Seaweeds extract (2.5 ml/L)	44.75	43.25	44.00	110.25	105.00	107.63	19.20	20.80	20.00
T_5: RDF + Salicylic acid (2 g/L)	42.75	41.25	42.00	108.50	103.75	106.13	20.60	22.90	21.75
T_6: 87.5 % RDF + Salicylic acid (2 g/L)	45.00	43.50	44.25	110.50	105.50	108.00	18.20	20.30	19.25
T_7: RDF + Chitosan 0.5 %	43.00	41.50	42.25	108.75	104.50	106.63	20.30	21.70	21.00
T_8: 87.5 % RDF + Chitosan 0.5 %	45.75	44.25	45.00	110.50	106.50	108.50	17.60	19.40	18.50
T_9: RDF + Putrescine 0.1 g/L	44.25	42.75	43.50	110.00	104.00	107.00	19.70	21.80	20.75
T_{10}: 87.5 % RDF + Putrescine 0.1 g/L	46.75	45.25	46.00	113.00	106.50	109.75	17.30	19.20	18.25
T_{11}: RDF + Humic acid (5 ml/L)	43.75	42.25	43.00	108.75	104.25	106.50	21.20	23.30	22.25
T_{12}: 87.5 % RDF + Humic acid (5 ml/L)	46.00	44.50	45.25	112.00	106.00	109.00	18.40	20.00	19.20
C.D. at 5% level of significance	1.29	1.08	0.84	2.11	1.21	1.00	0.54	0.49	0.39

Table 2. Effect of fertilizer levels along with foliar application of biostimulants on fruit length (cm), fruit diameter (cm) and average fruit weight (g) of capsicum *cv.* PSM-1 under polyhouse

Treatments	Fruit length (cm)			Fruit diameter (cm)			Average fruit weight (g)		
	2022-23	2023-24	Pooled mean	2022-23	2023-24	Pooled mean	2022-23	2023-24	Pooled mean
T_1: RDF (control)	7.4	7.62	7.51	6.43	6.67	6.55	84.83	85.59	85.21
T_2: 87.5 % RDF	7.19	7.45	7.32	6.28	6.54	6.41	81.80	84.50	83.15
T_3: RDF + Seaweeds extract (2.5 ml/L)	9.4	9.7	9.55	7.83	8.09	7.96	95.04	96.44	95.74
T_4: 87.5 % RDF + Seaweeds extract (2.5 ml/L)	8.17	8.45	8.31	7.05	7.33	7.19	89.67	90.27	89.97
T_5: RDF + Salicylic acid (2 g/L)	8.37	8.55	8.46	7.18	7.36	7.27	91.93	93.99	92.96
T_6: 87.5 % RDF + Salicylic acid (2 g/L)	7.54	7.76	7.65	6.58	6.76	6.67	86.8	88.86	87.83
T_7: RDF + Chitosan 0.5 %	9.1	9.36	9.23	7.60	7.82	7.71	90.86	93.52	92.19
T_8: 87.5 % RDF + Chitosan 0.5 %	8.12	8.28	8.20	7.02	7.20	7.11	85.97	88.17	87.07
T_9: RDF + Putrescine 0.1 g/L	8.9	9.02	8.96	7.44	7.68	7.56	90.76	91.36	91.06
T_{10}: 87.5 % RDF + Putrescine 0.1 g/L	7.8	8.04	7.92	6.84	7.02	6.93	85.73	86.97	86.35
T_{11}: RDF + Humic acid (5 ml/L)	8.55	8.81	8.68	7.28	7.52	7.4	92.69	95.57	94.13
T_{12}: 87.5 % RDF + Humic acid (5 ml/L)	7.73	7.87	7.80	6.69	6.93	6.81	87.03	89.85	88.44
C.D. at 5% level of significance	0.26	0.19	0.15	0.21	0.16	0.14	2.96	3.23	2.01

Turkmen *et al.* (2004) suggested that the plant cell metabolism was increased with the application of humic acid and as a result the yield of the plant increased. Kasperbauer (1987) concluded that humic acid can enhanced plant growth, plant canopy due to which plant can intercept light in a good way and as a result fruit weight of plant increased and thus increased yield of the plant. In another experiment Albayrak and Camas (2005) reported that the application of humic acid significantly affect the reproductive growth and yield of the plant. The same results were observed by Karakurat *et al.* (2009) and Jan *et al.* (2020).

The application of salicylic acid in capsicum cultivation enhances physiological processes, nutrient uptake, stress tolerance, and sugar translocation, all of which collectively increase the average fruit weight. Similar result was observed by Hanieh *et al.* (2013) and Munshi *et al* (2020).

3.7 Total Yield (kg/ha)

In capsicum crop, total fruit yield is the cumulative effect of fruit yield per plant which in turn depends on yield components *viz.,* number of fruits per plant, length of the fruits and fruit weight. The pooled value of total yield of both of the years was ranged from 250.46 q/ha to 399.05 q/ha as indicated in Table 3. Significantly, the maximum total yield (399.05 q/ha) was measured in treatment T_3 (RDF + Seaweed extract 2.5 ml/L), followed by treatment T_{11} (RDF + Humic acid 5 ml/L) with 388.13 q/ha and T_5 (RDF + Salicylic acid 2 g/L) with 374.64 q/ha, whereas the minimum total yield (250.46 q/ha) was observed in treatment T_2 (87.5% RDF). This increase in yield in which 100% RDF was applied might be due to greater availability of nutrients, increased uptake of nutrients and water, resulting in more photosynthesis and enhanced food accumulation in the edible part of the fruits (Chetri *et al*. 2012). According to Godara *et al*. (2013) this might be due to better water utilization and uptake of nutrients and excellent soil-water and air relationship with higher oxygen concentration in the root zone. It may be due to the optimum moisture conditions in the entire root zone of the crop, which reflected in better physiological activities of plants resulting in increased dry matter accumulation and enhanced overall tield. The maximum fruits per plant and the highest individual average fruit weight of capsicum are positively correlated with the highest yield per plant and marketable yield of capsicum Brahma *et al.* (2014).

The reduction or fruit yield of capsicum at lower levels of fertilizers indicated its early competition of 50 per cent flowering and fruiting as compared to that of optimum fertilizer levels. These results further supported that the plants fertilized with lower fertilizer doses suffered badly due to nutrient deficiency and hence reduced fruit yields. Contrary to these results, Neginahal *et al.* (2009) observed that the fruit yield of chilli increased significantly up to the highest levels of NPK (300:150:150 kg ha^{-1}) compared to lowest levels of fertilization. Continuous supply of the required quantity of nutrients in the root zone of the crop, which creates favorable conditions for growth and development by way of increasing metabolic activities in the plant system, might be the cause for higher marketable fruit yield in capsicum with 100% fertigation level. Increased marketable yield with 100 percent recommended dose of N & K (75:60 kg/ha), applied through fertigation was also reported by Brahma *et al.* (2010) in tomato and Brahma *et al.* (2014) in capsicum.

The hormonal components present in the seaweed extracts, particularly cytokinins, are believed to be linked with the higher yield in seaweed-treated plants. Cytokinins are linked to nutrient partitioning in vegetative plant organs, whereas large levels of cytokinins in reproductive organs may be linked to nutrient mobilization. Jayasinghe *et al*. (2016) found seaweed liquid fertilizer was more successful as effective fertilizer for enhancing shoot length, dry weight of root, number of leaves, number of flowers, number of pods, and yield of *Capsicum annum* and indicated that seaweed liquid fertilizer was more effective to enhance plant growth combined with chemical fertilizer than applied individually. These results are also in accordance with Sridhar and Rengasamy (2012) and Ashour *et al.* (2021) and in capsicum.

Humic acid increases the physiological processes of the plant. The application of humic acid also increases the micro and macro nutrients availability to plants and thus improves proteins, vitamins and plant growth regulators such as auxin, cytokinin and abscisic acid contents of the plant (Yildirim, 2007). In another study, Rahman *et al.* (2007) reported that the application of humic acid significantly increased the tomato yield.

Table 3. Effect fertilizer level along with foliar application of biostimulants on total yield of capsicum *cv.* PSM-1 under polyhouse

Treatments	Total yield (q/ha)		
	2022-23	2023-24	Pooled mean
T_1: RDF (control)	265.49	294.81	280.15
T_2: 87.5 % RDF	231.77	269.15	250.46
T_3: RDF + Seaweeds extract (2.5 ml/L)	378.40	419.69	399.05
T_4: 87.5 % RDF + Seaweeds extract (2.5 ml/L)	318.83	347.71	333.27
T_5: RDF + Salicylic acid (2 g/L)	350.70	398.59	374.64
T_6: 87.5 % RDF + Salicylic acid (2 g/L)	292.55	334.05	313.30
T_7: RDF + Chitosan 0.5 %	341.57	375.81	358.69
T_8: 87.5 % RDF + Chitosan 0.5 %	280.20	316.76	298.48
T_9: RDF + Putrescine 0.1 g/L	331.11	368.82	349.96
T_{10}: 87.5 % RDF + Putrescine 0.1 g/L	274.65	309.23	291.94
T_{11}: RDF + Humic acid (5 ml/L)	363.89	412.37	388.13
T_{12}: 87.5 % RDF + Humic acid (5 ml/L)	296.55	332.78	314.66
C.D. at 5% level of significance	9.51	13.76	8.39

The application of salicylic acid in capsicum cultivation enhances total yield by promoting growth, improving stress tolerance, boosting photosynthetic efficiency, and reducing losses from biotic and abiotic factors. Similar result was obtained by Ibrahim *et al.* (2019); Munshi *et al.* (2020) and Dobon-Suarez *et al.* (2021).

4. CONCLUSION

The present study clearly demonstrates that the application of biostimulants in combination with recommended doses of fertilizers significantly enhances the growth, yield, and quality parameters of capsicum cv. PSM-1 under polyhouse conditions. Among the various treatments, the combination of RDF + Seaweed extract (T3) resulted in the earliest flowering (41.75 days), earliest fruit maturity (105.25 days), highest number of fruits per plant (22.50), maximum fruit size (9.55 cm length, 7.96 cm diameter), heaviest average fruit weight (95.74 g), and highest total yield (399.05 q/ha). Treatments with RDF + Salicylic acid (T5) and RDF + Humic acid (T11) also performed significantly better than the control in most parameters, closely following T3. Comparatively, treatments involving 87.5% RDF alone or with biostimulants showed moderate improvements but were generally less effective than those with 100% RDF. Thus, the integrated application of biostimulants with full RDF, particularly seaweed extract, is recommended for optimizing capsicum productivity and quality in protected cultivation systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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