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Characterization of biostimulants and their effects on soil health, enzymatic activity, and disease incidence in tomato (*Solanum lycopersicum* L.)

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Abstract

A field experiment was conducted at the Zonal Agricultural Research Station, GKVK, Bengaluru, Karnataka, to study the characterization of solid and liquid biostimulants and their effect on soil health, enzymatic activity, and disease incidence in tomato cultivation during the experimental period. The experiment consisted of eleven treatments with different combinations of recommended dose of fertilizers (RDF) and solid (BS1) and liquid (BS2) biostimulants. The results revealed that the variation due to different treatments of biostimulants was found significant. Among the treatments, application of 100% RDF + liquid biostimulant (BS2) @ 3.75 L ha⁻¹ (T₉) recorded significantly higher maximum water holding capacity (39.03%), available nitrogen (301.44 kg ha⁻¹), available phosphorus (50.29 kg ha⁻¹), available potassium (286.80 kg ha⁻¹), exchangeable calcium (5.34 c mol (p⁺) kg⁻¹), magnesium (3.79 c mol (p⁺) kg⁻¹), and sulphur content (28.44 mg kg⁻¹). The same treatment also recorded significantly higher dehydrogenase activity (53.68 µg TPF g⁻¹ h⁻¹), acid phosphatase activity (46.90 µg PNP g⁻¹ h⁻¹), and urease activity (41.93 µg NH₄-N g⁻¹ h⁻¹). Further, the lowest incidence of damping-off (2.10%), Fusarium wilt (1.97%), and bacterial wilt (1.54%) was observed in treatment T₉. Therefore, it can be concluded that application of liquid biostimulant along with recommended fertilizer dose significantly improved soil health, nutrient availability, soil enzymatic activity, and reduced disease incidence in tomato cultivation.

Keywords: Bio stimulants, soil health, tomato, enzymatic activity, disease incidence, microbial population, sustainable agriculture

Introduction

Cultivation of high-yielding varieties and hybrids to enhance food production has increased the dependence on synthetic fertilizers. However, their continuous use may adversely affect soil quality and the environment. Therefore, maintaining soil health is essential for key biochemical processes such as organic matter transformation (Miltner *et al.*, 2011) [13], nutrient release (Wicherna *et al.*, 2007) [20] and degradation of xenobiotics. Hence, there is a growing need for sustainable agronomic technologies that improve soil health while enhancing plant growth, nutrient uptake, stress tolerance and crop productivity. Bio stimulants have recently gained considerable attention as an environmentally friendly approach for improving crop performance without imposing additional stress on soil resources. The European Biostimulants Industry Council (EBIC, 2016) defines bio stimulants as substances or microorganisms that stimulate natural processes in plants or the rhizosphere, thereby improving nutrient uptake, nutrient use efficiency, tolerance to abiotic stress and crop quality, irrespective of their nutrient content. Biostimulants, which may be natural or synthetic organic substances containing hormones or their precursors, promote plant growth and development when applied in small quantities and contribute to improved crop productivity and soil properties.

Material and methods

A field experiment was conducted at Zonal Agricultural Research Station, UAS, GKVK, Bengaluru located in the Eastern Dry zone of Karnataka. The experiment consisted of 11 treatments combinations as mentioned below

Table 1: Treatment details

Treatment	Details	Treatment	Details
T ₁	Absolute control	T ₇	75% RDF+ soil drenching with BS ₁ @ 3.75 kg/ha
T ₂	100% RDF	T ₈	100% RDF+ soil drenching with BS ₂ @ 2.5 lt/ha
T ₃	75% RDF	T ₉	100% RDF+ soil drenching with BS ₂ @ 3.75 lt/ha
T ₄	100% RDF+ soil drenching with BS ₁ @ 2.5 kg/ha	T ₁₀	75% RDF+ soil drenching with BS ₂ @ 2.5 lt/ha
T ₅	100% RDF+ soil drenching with BS ₁ @ 3.75 kg/ha	T ₁₁	75% RDF+ soil drenching with BS ₂ @ 3.75 lt/ha
T ₆	75% RDF+ soil drenching with BS ₁ @ 2.5 kg/ha		

Note: 1. BS₁ - Bio stimulant solid form BS₂ - Bio stimulant liquid form

2. RDF 250:250:250 kg N, P₂O₅, K₂O ha⁻¹ along with FYM @ 25t ha⁻¹ (T₂-T₁₁)

3. Biostimulants will be applied at the time of transplanting (T₄-T₁₁)

The soil at the experimental site was sandy loam in texture with 62.83, 23.86, and 13.29 per cent sand, silt and clay, respectively and bulk density and maximum water holding capacity of soil was 1.39 Mg m⁻³ and 30.13%. The soil was slightly acidic in reaction (pH 6.26) and low in soluble salts (0.10 dS m⁻¹). The soil was medium in organic carbon (0.52%), medium in available nitrogen (308.6 kg ha⁻¹), medium in available P₂O₅ (34.61 kg ha⁻¹), medium in available K₂O (254.28 kg ha⁻¹) and sufficient in sulphur (18.71 mg kg⁻¹). The exchangeable calcium and magnesium content of soil was 4.85 and 3.46 c mol kg⁻¹, respectively. The content of DTPA extractable iron, manganese, zinc, copper and hot water-soluble boron was 15.44, 7.03, 1.59, 0.87 and 0.38 mg kg⁻¹, respectively.

Characterization of bio stimulants

The analytical results indicated that pH of solid and liquid form of bio stimulant were 6.24 and 6.46, respectively and electrical conductivity of the solid and liquid form of bio stimulant were 0.25 dSm⁻¹ and 0.27 dSm⁻¹, respectively. The nutrient composition of solid form of bio stimulant was composed of N (18.06%), P (16.09%), K (21.45%), Ca (0.18%), Mg (0.26%), S (3.56%), Fe (0.124 ppm), Mn (0.64 ppm), Cu (0.51 ppm), Zn (0.51ppm) and B (0.016 ppm). With respect to nutrient composition of liquid form of bio stimulant composed of N (22.37%), P (20.55%), K (18.6%), Ca (0.34%), Mg (1.50%), S (3.12%), Fe (0.146 ppm), Mn (0.68 ppm), Cu (0.73 ppm), Zn (0.73 ppm) and B (0.029 ppm). From the analysis of the data suggested that liquid form of bio stimulant contained more N and P than solid form of biostimulants, whereas solid form of biostimulants contained more K than liquid form of bio stimulant. The

similar nutrient composition of biostimulants was reported by Keiji *et al.* (2012) ^[11], Colla *et al.* (2017) ^[6] and Roupheal *et al.* (2017) ^[16].

Table 2: Nutrient composition of biostimulants

Parameters	Bio stimulant solid form	Bio stimulant liquid form
pH	6.24	6.46
EC (dS m ⁻¹)	0.25	0.27
Nitrogen (%)	18.06	22.37
Phosphorus (%)	16.09	20.55
Potassium (%)	21.45	18.61
Calcium (%)	0.18	0.34
Magnesium (%)	0.26	1.50
Sulphur (%)	3.56	3.12
Iron (ppm)	0.124	0.146
Manganese (ppm)	0.64	0.68
Zinc (ppm)	0.51	0.73
Copper (ppm)	0.51	0.73
Boron (ppm)	0.016	0.029

Enumeration of microorganisms for biostimulants

Quantitative analysis of solid form of bio stimulant revealed that, it consists of bacterial count (1×10⁷ CFU/g), fungal count (2×10⁵ CFU/g), actinomycetes (1×10⁵ CFU/g), nitrogen fixing bacterial (5×10⁶ CFU/g) and phosphate solubilizing microorganisms (2×10⁵ CFU/g). Quantitative analysis of liquid form of bio stimulant revealed that, it consists of bacterial count (1×10⁸ CFU/ml), fungal count (5×10⁶ CFU/ml), actinomycetes (1×10⁶ CFU/ml), nitrogen fixing bacterial (1×10⁷ CFU/ml) and phosphate solubilizing microorganisms (5×10⁶ CFU/ml) (Table 3).

Table 3: Enumeration of microorganisms for biostimulants

Parameters	Bio stimulant solid form (CFU/ g)	Bio stimulant liquid form (CFU/ ml)
Bacterial count	1×10 ⁷	1×10 ⁸
Fungal count	2×10 ⁵	5×10 ⁶
Actinomycetes count	1×10 ⁵	1×10 ⁶
Nitrogen fixing bacteria	5×10 ⁶	1×10 ⁷
Phosphate-Solubilizing microorganism	2×10 ⁵	5×10 ⁶

Results and discussion

Soil physical properties

The data pertaining to bulk density and maximum water holding capacity as influenced by the application of biostimulants and presented in Table 4. Results indicated that bulk density of the post-harvest soil ranged from 1.30 - 1.38 Mg m⁻³. The data revealed that, there was no significant difference in the bulk density between the treatments. Maximum water holding capacity in soil and the influence

of biostimulants on various treatments was found to be statistically significant. However, among the treatments, T₉ treatment with application of 100% RDF along with soil drenching of BS₂ @ 3.75 L ha⁻¹ exhibited the maximum water holding capacity about 39.03% and found on par with 100% RDF+ soil drenching with BS₁ @ 3.75 kg ha⁻¹ (T₅) about 38.11% and had significant difference with 100% RDF (T₂) about 34.60%.

Table 4: Methods followed for the analysis of soil samples

Parameters	Methods	References
Bulk density	Keen rackzowski method	Baruah and Barthakur, 1997) [3]
Maximum water holding capacity	Keen rackzowski method	Baruah and Barthakur, 1997) [3]
pH (1:2.5)	Potentiometric method	Jackson (1973) [9]
EC (1:2.5)	Conductometric method	Jackson (1973) [9]
Available nitrogen (kg N ha ⁻¹)	Alkaline potassium permanganate method	Subbaiah and Asija (1956) [19]
Available phosphorous (kg P ₂ O ₅ ha ⁻¹)	Bray's extractant using spectrophotometer	(Bray and Kurtz, 1945) [5]
Available potassium (kg K ₂ O ha ⁻¹)	Ammonium acetate extract using flame photometry	Jackson (1973) [9]
Exchangeable calcium (c mol (p+) kg ⁻¹)	Complexometric titration	(Jackson, 1973) [9]
Exchangeable magnesium (c mol (p+) kg ⁻¹)	Complexometric titration	(Jackson, 1973) [9]
Available sulphur (mg kg ⁻¹)	Turbidometric method	(Black, 1965) [4]

Soil Chemical properties

Soil pH and Electrical Conductivity

Application of biostimulants, did not show significant differences in soil pH and electrical conductivity. The plots treated continuously with recommended dose of fertilizers alone recorded lower pH and EC values than those treated in combination with biostimulants. However, the higher pH value (6.63) and electrical conductivity (0.17 dS m⁻¹) was observed with the 100% RDF along with soil drenching of liquid form of bio stimulant @ 3.75 L ha⁻¹ (Table 5).

Available Nitrogen

Results revealed that the soil application of 100% RDF along soil drenching with BS₂ @ 3.75 L ha⁻¹ (T₉) showed higher available nitrogen (301.44 kg ha⁻¹) and found on par with treatments T₅: 100% RDF along soil drenching with BS₁ @ 3.75 kg ha⁻¹ (298.77 kg ha⁻¹), T₇ supplied with 75% RDF along with BS₁ @ 3.75 kg ha⁻¹ (294.12 kg ha⁻¹) and treatment T₁₁: 75% RDF along soil drenching with BS₂ @ 3.75 L ha⁻¹ (296.17 kg ha⁻¹) and differ significantly with 100% RDF (286.23 kg ha⁻¹). Arjunmend *et al.* (2015) [1] reported that biostimulants can stimulate the growth and activity of beneficial soil microbes, including nitrogen-fixing bacteria. These bacteria convert atmospheric nitrogen into a form that can be used by plants. Biostimulants would also help to improve the mineralization of organic nitrogen into inorganic form in the soil (Table 6).

Available Phosphorous

Plots treated with 100% RDF along with soil drenching with liquid form of bio stimulant @ 3.75L ha⁻¹ (T₉) showed higher available phosphorous (50.29 kg ha⁻¹) and found on par with 100% RDF along with soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ (48.51 kg ha⁻¹), T₇ which receives 75% RDF+ soil drenching with BS₁ @ 3.75 kg ha⁻¹ (46.55 kg ha⁻¹) and treatment T₁₁: 75% RDF+ soil drenching with BS₂ @ 3.75 L ha⁻¹ (47.92 kg ha⁻¹) and found significantly difference with 100% RDF (37.14 kg ha⁻¹). The increase in available phosphorus levels may be attributed to enhanced phosphate solubilization by application of biostimulants, a process facilitated by certain microorganisms that possess the capacity to solubilize inorganic phosphorus through mechanisms such as chelation, exchange reactions, phosphate production and the release of organic acids, thereby transforming insoluble phosphates into soluble forms. Similar results were also reported by Bade *et al.*, (2017) [2] in Chilli and Kumari *et al.*, (2013) [12] in tomato (Table 6).

Available Potassium: The available potassium content of soil was recorded significantly higher with the 100% RDF

along with soil drenching with BS₂ @ 3.75 L ha⁻¹ (286.80 kg ha⁻¹) and found on par with with treatments T₅: 100% RDF along with soil drenching with BS₁ @ 3.75 kg ha⁻¹ (284.15 kg ha⁻¹), T₇ which received 75% RDF+ soil drenching with BS₁ @ 3.75 kg ha⁻¹ (274.40 kg ha⁻¹) and T₁₁: 75% RDF+ soil drenching with BS₂ @ 3.75 L ha⁻¹ (280.92 kg ha⁻¹) over 100% RDF (267.07 kg ha⁻¹). The increase in potassium content could potentially be attributed to enhanced mineral dissolution rates, leading to the release of potassium, as well as the enzymatic activities of chitinase and cellulases, which contribute to the breakdown of minerals. These results align with previous studies conducted by Bade *et al.*, (2017) [2] in chilli and Kumari *et al.*, (2013) [12] in tomato (Table 6).

Table 5: pH, Electrical Conductivity, Available N, P₂O₅ and K₂O present in soil after harvest of tomato as influenced by biostimulants application

Treatment details	Bulk density (Mg m ⁻³)	Maximum water holding capacity (%)	pH	EC (dS m ⁻¹)
T ₁	1.38	31.04	6.28	0.10
T ₂	1.36	34.60	6.32	0.12
T ₃	1.35	33.65	6.31	0.12
T ₄	1.34	36.43	6.48	0.14
T ₅	1.31	38.11	6.49	0.16
T ₆	1.33	36.21	6.32	0.13
T ₇	1.32	37.94	6.27	0.15
T ₈	1.34	37.12	6.47	0.16
T ₉	1.30	39.03	6.63	0.17
T ₁₀	1.33	36.08	6.37	0.14
T ₁₁	1.32	38.67	6.31	0.15
S. Em±	0.04	1.06	0.09	0.07
CD @ (5%)	NS	3.14	NS	NS

Table 6: Primary and Secondary nutrients content of soil after harvest of tomato as influenced by biostimulants application

Treatment details	Avail. N	Avail. P ₂ O ₅	Avail. K ₂ O	Calcium	Magnesium	Sulphur (mg kg ⁻¹)
	(kg ha ⁻¹)			(c mol (p+) kg ⁻¹)		
T ₁	269.07	33.35	248.72	4.62	3.14	17.44
T ₂	286.23	37.14	267.07	4.80	3.47	20.52
T ₃	281.23	34.67	263.79	4.66	3.35	18.79
T ₄	292.36	40.22	275.78	5.24	3.67	21.33
T ₅	298.77	48.51	284.15	5.28	3.78	27.13
T ₆	286.14	40.64	265.55	5.14	3.67	20.69
T ₇	294.12	46.85	274.40	5.18	3.71	25.47
T ₈	288.32	42.22	257.11	5.10	3.67	20.10
T ₉	301.44	50.29	286.80	5.34	3.79	28.44
T ₁₀	281.89	43.51	268.79	5.26	3.70	21.69
T ₁₁	296.17	47.92	280.92	5.28	3.76	23.90
S. Em±	8.13	1.82	6.85	0.15	0.13	0.96
CD @ (5%)	23.98	5.38	18.27	0.44	0.37	2.84

Exchangeable Calcium and Magnesium

Exchangeable calcium and magnesium in soil (5.34 and 3.79 c mol (p+) kg⁻¹) was significantly recorded higher in treatment T₉ with application of 100% RDF along with soil drenching of liquid form of bio stimulant @ 3.75 L ha⁻¹ and found on par with treatments T₅ (5.28 and 3.78 c mol (p+) kg⁻¹) with application of 100% RDF along with soil drenching of solid form of bio stimulant @ 3.75 kg ha⁻¹, T₇ (5.18 and 3.71 c mol (p+) kg⁻¹) which receives 75% RDF along with soil drenching of solid form of bio stimulant @ 3.75 kg ha⁻¹ and treatment T₁₁ (5.28 and 3.76 c mol (p+) kg⁻¹) which receives 75% along with soil drenching of liquid form of bio stimulant @ 3.75 L ha⁻¹ and having significantly difference with treatment T₂ (4.80 and 3.47 c mol (p+) kg⁻¹) receiving 100% RDF (Table 6).

Available Sulphur

Plots treated with 100% RDF along with soil drenching of BS₂ @ 3.75 L ha⁻¹ (T₉) recorded significantly higher available sulphur in soil (28.44 mg kg⁻¹) and found on par with the treatment T₅ (27.13 mg kg⁻¹) receiving 100% RDF along with soil drenching of BS₁ @ 3.75 kg ha⁻¹ and having significantly difference with treatment T₂ (20.52 mg kg⁻¹) receiving 100% RDF (Table 6).

The increase of secondary nutrients (Ca, Mg and S) availability might be due to stimulatory effect of biostimulants and FYM on release of Ca, Mg and S from its mineral sources by releasing acidifying compounds from biostimulants and FYM decomposition. Mindari *et al.* (2014) [14] stated that in *khari* rice, the acidic compounds by organic substances dissolve the elements from the mineral source. Application of biostimulants and FYM increasing the availability of nutrients by improving soil structure and beneficial microbial activity because of presence of polysaccharides which leads to breakdown of organic matter and release of nutrients to the soil.

Biological properties of soil

Dehydrogenase activity

Dehydrogenase activity (DHA) is an index of microbial activity in the soil. Significantly, higher soil dehydrogenase activity was recorded in treatment T₉ with application of 100% RDF along soil drenching with liquid form of bio stimulant @ 3.75 L ha⁻¹ (53.68 g TPF g⁻¹ h⁻¹) and found on par with treatment T₅: 100% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ (51.58 g TPF g⁻¹ h⁻¹), T₇: 75% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ (49.58 g TPF g⁻¹ h⁻¹) and T₁₁: 75% RDF along soil drenching with liquid form of bio stimulant @ 3.75 L ha⁻¹ (50.67 g TPF g⁻¹ h⁻¹) and found significantly difference with treatment T₂: 100% RDF (46.55 g TPF g⁻¹ h⁻¹) (Table 7).

The increased dehydrogenase activity in soil following seaweed extract and humic acid and FYM application is

likely due to the combined effects of increased nutrient availability, stimulation of microbial activity and improved soil structure (Zhang *et al.*, 2017) [21].

Acid phosphatase activity

Significantly, higher soil acid phosphatase activity was recorded in treatment T₉ with application of 100% RDF along soil drenching with liquid form of bio stimulant @ 3.75 L ha⁻¹ (46.90 µg PNP g⁻¹ h⁻¹) and found on par with treatments T₅: 100% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ (44.21 µg PNP g⁻¹ h⁻¹), T₇ treatment receiving 75% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ (42.84 µg PNP g⁻¹ h⁻¹) and T₁₁ treatment receiving 75% RDF along soil drenching with liquid form of bio stimulant @ 3.75 L ha⁻¹ (42.94 µg PNP g⁻¹ h⁻¹) and found significantly difference with treatment T₂ which receives 100% RDF (38.43 µg PNP g⁻¹ h⁻¹) (Table 7).

The increased enzymatic activity observed due to the application of bio stimulants and FYM along with full dose of NPK had a positive effect on soil health and microbial communities. This application of bio stimulants in conjunction with FYM likely increased the biomass production and the generation of abundant root exudates in the rhizosphere. The application of biostimulants induces a more robust proliferation of roots, which in turn contributes to the augmented activity of soil enzymes. Similar findings were documented by Sabeetha *et al.* (2011) [17].

Urease enzymatic activity

Plots treated with 100% RDF along with soil drenching of liquid form of bio stimulant @ 3.75 L ha⁻¹ (T₉) recorded significantly higher soil urease activity T₉ (41.93 µg NH₄-N g⁻¹ h⁻¹) and found on par with treatments T₅ (40.71 µg NH₄-N g⁻¹ h⁻¹) with application of 100% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ which was statistically on par with T₇ treatment (39.88 µg NH₄-N g⁻¹ h⁻¹) receiving 75% RDF along soil drenching with solid form of bio stimulant @ 3.75 kg ha⁻¹ and T₁₁ treatment (40.29 µg NH₄-N g⁻¹ h⁻¹) supplied with 75% RDF along soil drenching with liquid form of bio stimulant @ 3.75 L ha⁻¹ and found significantly difference with treatment T₂ which receives 100% RDF (35.97 µg NH₄-N g⁻¹ h⁻¹) (Table 8).

The increase in urease activity can be attributed to the ability of biostimulants to improve soil structure and moisture retention, creating a more favourable environment for microbial growth and enzyme function. Biostimulants also stimulate microbial activity directly, providing substrates that boost enzyme production. As a result, the addition of HA enhances the overall metabolic processes in the soil, leading to increased urease activity (Kaur and Reddy, 2015) [10].

Table 7: Soil dehydrogenase, acid phosphatase and urease enzyme activities in soil after the harvest of tomato as influenced by biostimulants application

Treatment details	Dehydrogenase activity ($\mu\text{g TPF g}^{-1}\text{ soil h}^{-1}$)	Acid phosphatase activity ($\mu\text{g PNP g}^{-1}\text{ h}^{-1}$)	Urease activity ($\mu\text{g NH}_4\text{-N g}^{-1}\text{ h}^{-1}$)
T ₁	37.75	35.16	24.17
T ₂	46.55	38.43	35.97
T ₃	42.49	36.80	29.77
T ₄	45.58	37.77	33.94
T ₅	51.58	44.21	40.71
T ₆	46.54	39.19	37.12
T ₇	49.58	42.84	39.88
T ₈	46.67	41.67	33.94
T ₉	53.68	46.90	41.93
T ₁₀	47.05	40.39	37.22
T ₁₁	50.67	42.94	40.29
S. Em±	1.46	1.62	1.40
CD @ (5%)	4.31	4.77	4.13

Percent incidence disease

Damping off

The data revealed that highest incidence of damping off is observed in the control treatment T₁ (7.90%). The application of 100% RDF reduces the incidence to 6.57%, and suggesting that fertilizers alone have some effect in reducing the disease and slightly higher in treatment T₃ (6.18%) due to reducing fertilizer application might lead to a slight increase in susceptibility to damping off. The lowest incidence of damping off is observed in T₉ (100% RDF + BS2 @ 3.75 L ha⁻¹) with 2.10%, indicating that this treatment is most effective in controlling the disease. The trend shows that higher application rates of BS1 and BS2 (T₅ - 100% RDF+ soil drenching with BS1 @ 3.75 kg ha⁻¹ and T₉ - 100% RDF+ soil drenching with BS2 @ 3.75 L ha⁻¹ are more effective than lower rates (T₄ - 100% RDF+ soil drenching with BS1 @ 2.5 kg ha⁻¹ and T₈ -100% RDF+ soil drenching with BS2 @ 2.5 L ha⁻¹) (Table 8).

Fusarium Wilt

The data revealed that highest incidence of Fusarium wilt is observed in the control treatment T₁ (7.50%). The application of 100% RDF reduces the incidence to 5.91%, suggesting that fertilizers alone have some effect in reducing the disease and slightly higher in treatment T₃ (7.12%) due to reducing fertilizer application might lead to a slight increase in susceptibility to damping off. The lowest incidence of damping off is observed in T₉ (100% RDF + BS2 @ 3.75 L ha⁻¹) with 1.97%, indicating that this treatment is most effective in controlling the disease. The trend shows that higher application rates of BS1 and BS2 (T₅: 100% RDF+ soil drenching with BS1 @ 3.75 kg ha⁻¹ and 100% RDF+ soil drenching with BS2 @ 3.75 L ha⁻¹ (T₉) are more effective than lower rates (T₄: 100% RDF+ soil drenching with BS1 @ 2.5 kg ha⁻¹ and T₈: 100% RDF+ soil drenching with BS2 @ 2.5 L ha⁻¹) (Table 8).

Bacterial Wilt

The highest incidence of bacterial wilt was recorded in the control treatment (T₁, 7.43%). Application of the recommended dose of fertilizers (T₂) reduced the disease incidence to 4.98%, whereas a slightly higher incidence was observed under 75% RDF (T₃, 5.11%). Among the treatments, the lowest bacterial wilt incidence (1.54%) was recorded in T₉ (100% RDF + soil drenching with BS2 @ 3.75 L ha⁻¹), which was significantly lower than the control. Treatments receiving the liquid biostimulant (BS2)

generally recorded lower bacterial wilt incidence than those receiving the solid biostimulant (BS1). The reduction in disease incidence may be attributed to the beneficial effects of biostimulants on plant vigour, nutrient uptake, microbial activity and induced plant defence mechanisms, which collectively enhance resistance against pathogen infection (Table 8).

Table 8: Percent incidence disease of damping off, *fusarium* wilt and bacterial wilt as influenced by bio stimulant application in tomato

Treatment details	Damping off (%)	Fusarium wilt (%)	Bacterial wilt (%)
T ₁	7.90	7.50	7.43
T ₂	6.57	5.91	4.98
T ₃	6.89	7.12	5.11
T ₄	4.57	5.98	6.50
T ₅	5.21	6.10	6.12
T ₆	5.49	6.25	6.89
T ₇	6.10	6.74	6.11
T ₈	3.87	2.91	3.01
T ₉	2.10	1.97	1.54
T ₁₀	2.46	2.31	1.99
T ₁₁	2.24	1.89	1.76
S. Em±	1.43	1.54	1.31
CD @ (5%)	4.39	4.76	4.98

Biostimulants had significant effect in controlling in pathogen in crops. The bioactive compounds found in biostimulants, such as complex polysaccharides, fatty acids, proteins (amino acids), carotenoids, polyphenols, and carbohydrates, exhibit bactericidal, antiviral, and fungicidal effects against various plant pathogens. These compounds contribute to the plant's defence mechanisms, improving tolerance to abiotic stresses and enhancing soil properties (Raj *et al.*, 2018) [15]. Biostimulants improve nutrient uptake, nutrient use efficiency, and tolerance to abiotic stresses, thereby indirectly reducing the impact of pathogens (Hamid *et al.*, 2021) [7]. Biostimulants enhance seedling vigour and root development, leading to stronger and more resilient plants that can better resist pathogen attacks. It also stimulates the plant's immune system, improving its ability to fend off diseases like damping-off and root rot. Additionally, biostimulants improve soil structure and microbial activity, which can suppress the growth and spread of harmful pathogens like *Fusarium solani* (Hussein and Aljarah., 2023) [8]. Biostimulants enhance the

production of key defence-related enzymes like phenylalanine ammonia lyase, chitinase, peroxidase, and polyphenol oxidase, which play crucial roles in pathogen resistance. Additionally, the biostimulants increase phenolic content and alter the expression of defence genes, leading to a stronger and more effective immune response against fungal blast disease. The combined application methods further optimize the plants' resistance to pathogens (Sahana *et al.*, 2022) ^[18].

Conclusion

The characterization of both solid and liquid biostimulants revealed the presence of appreciable quantities of nutrients and beneficial microorganisms. The results of the field experiment demonstrated that the application of FYM @ 25 t ha⁻¹ and the recommended dose of fertilizers (250:250:250 kg N:P₂O₅: K₂O ha⁻¹) in combination with biostimulants, particularly the liquid biostimulant (BS2) @ 3.75 L ha⁻¹, improved soil nutrient availability, water-holding capacity and soil enzymatic activities. The integrated application of biostimulants also reduced the incidence of damping-off, Fusarium wilt and bacterial wilt in tomato. Therefore, the use of biostimulants along with recommended nutrient management practices can be considered an effective strategy for improving soil health and promoting sustainable tomato production.

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