RESEARCH PAPER

Effect of Humic Acid and Silicon on Growth, Phenology, and Yield of Tomato (*Solanum lycopersicum* L.)

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Abstract
This study evaluated the individual and combined effects of humic acid and silicon on growth attributes, phenology, and yield of tomato during two consecutive growing seasons (2023-24 and 2024-25). Three levels of humic acid (2, 5, and 10 ml L^{-1}) and silicon (2, 5, and 10 ml L^{-1}), along with a control, were tested under factorial randomized block design. Results revealed that moderate doses (5 ml L^{-1}) of both humic acid and silicon markedly improved plant height, branching, early flowering, cluster formation, fruit set, fruit weight, and final yield. The combined treatment H_2S_2 (humic acid @ 5 ml L^{-1} + silicon @ 5 ml L^{-1}), consistently produced superior performance across both years, indicating strong synergism. These findings suggest that humic acid and silicon, when applied at optimum levels, function as effective biostimulants for enhancing tomato productivity.

Keywords: Humic acid, Silicon, Biostimulants, Tomato yield, Growth and phenology

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Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important and widely cultivated vegetable crops worldwide due to its high economic value and rich nutritional composition. It contributes significantly to farmers' income because of its wide adaptability, high productivity, and consistent demand in both fresh and processing markets. Tomato fruits are a valuable source of essential vitamins such as vitamin C, vitamin A, and vitamin E, minerals, dietary fiber, and bioactive compounds, particularly lycopene, which possesses strong antioxidant properties and is associated with reduced risks of cardiovascular diseases and certain types of cancer (Bhowmik *et al*., 2012; Rai *et al.,* 2013). Owing to its extensive use in culinary preparations and processing industries, including sauces, purees, and ketchups, tomato plays a crucial role in ensuring nutritional security and supporting agro-based industries (FAO, 2021).

Despite its importance, tomato is a nutritionally exhaustive crop and highly sensitive to environmental fluctuations, nutrient imbalances, and abiotic stresses, which often result in poor growth, delayed flowering, reduced fruit set, and yield instability. In this context, the application of biostimulants has emerged as a promising and sustainable approach to enhance crop performance. Humic substances and silicon are increasingly recognized as effective biostimulants because of their ability to improve nutrient availability, physiological efficiency, and stress tolerance in plants. Humic acid enhances nutrient solubility and uptake, stimulates enzymatic and metabolic activities, and regulates hormonal functions, thereby promoting plant growth and reproductive development (Khaled & Fawy, 2011; Nardi *et al.,* 2021). Similarly, silicon, although not considered an essential nutrient, plays a vital role in improving structural integrity, water-use efficiency, photosynthetic performance, and plant defense mechanisms against biotic and abiotic stresses (Epstein, 2009; Ma and Yamaji, 2015). Although several studies have independently documented the beneficial effects of humic acid (Nardi *et al*., 2002; Ampong *et al*., 2022) and silicon (Ma and Yamaji, 2015; Artyszak, 2018), information on their combined application in tomato remains limited. Therefore, the present investigation aimed to assess the interactive influence of humic acid and silicon on the growth, flowering behavior, and yield of tomato.

Materials and Methods

The field experiment was carried out for two consecutive years during 2023-24 and 2024-25 during spring season at Agriculture Research Farm of the IFTM University, Moradabad (U.P.), India. The city, Moradabad is located in a subtropical agro-climatic region characterized by moderate rainfall and congenial temperature conditions for tomato cultivation. The experiment was laid out in a factorial randomized block design (FRBD) with ten treatments and three replications. The treatments consisted of three levels each of humic acid (2, 5, and 10 ml L^{-1}) and silicon (2, 5, and 10 ml L^{-1}), their respective combinations, and an untreated control.

The soil was sandy loam in texture, well-drained, and moderately fertile with near-neutral pH. Healthy and uniform tomato seedlings were transplanted at recommended spacing. Humic acid and silicon were applied twice (at 30 days and 45 days after transplanting) as foliar sprays at the designated

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concentrations using a hand-operated sprayer, ensuring thorough and uniform coverage of the foliage except plots under control. Control plots received foliar spray of water only.

Uniform agronomic practices were maintained across all plots throughout the cropping period. All plots received the recommended dose of fertilizers (RDF) as per regional recommendations to ensure balanced nutrition. Irrigation, intercultural operations, staking, and plant protection measures were carried out uniformly across treatments to minimize variability due to management practices.

Observations were recorded on important growth parameters, including plant height and the number of primary and secondary branches, along with phenological traits such as days to flower initiation. At harvest, yield-attributing characters comprising number of clusters per plant, fruits per cluster, total fruits per plant, average fruit weight, and fruit yield per plant and per plot were documented for analysis. Data were collected from randomly selected plants in each plot and averaged to obtain representative values.

The recorded data for both years were subjected to analysis of variance (ANOVA) appropriate for a factorial randomized block design to test the significance of treatment effects. The significance of differences among treatment means was determined using the critical difference (CD) test at the 5% level of probability, as outlined by standard statistical procedures.

Results and Discussion

Plant Height

Plant height recorded during 2023-24 and 2024-25 was significantly influenced by humic acid and silicon (Table 1). Among humic acid levels, H_2 (5 ml L^{-1}) produced significantly taller plants in 2023-24 (119.81 cm) and 2024-25 (125.98 cm). The superior performance of H_2 (5 ml L^{-1}) in both years may be attributed to enhanced nutrient solubility, improved root growth, and stimulation of plant hormones such as auxins and cytokinins, which promote cell elongation and division. Humic substances are known to activate plasma membrane H^+-ATPase activity, thereby improving nutrient uptake efficiency and vegetative growth (Nardi *et al.*, 2002; Khaled and Fawy, 2011).

Silicon application significantly increased plant height, with S_2 (5 ml L^{-1}) recording the highest values during both years. Silicon improves mechanical strength, leaf erectness, and light interception, which collectively enhance photosynthetic efficiency and biomass accumulation (Epstein, 2009; Ma and Yamaji, 2015).

The interaction effect between humic acid and silicon was significant for plant height. As evident from Table 3, the combined treatment H_2S_2 (T_5) recorded the maximum plant height during 2023-24 (123.55 cm) and 2024-25 (130.55 cm), which was significantly superior to the control (T_{10}). This synergistic response suggests that humic acid improves nutrient availability, while silicon enhances physiological efficiency, leading to cumulative growth benefits (Abdellatif *et al.*, 2017; Ali *et al.*, 2023).

Primary and Secondary Branches

Primary and secondary branches recorded during both years (2023-24 and 2024-25) showed a significant response to humic acid application (Table 1). The maximum number of branches under H_2 can be attributed to humic acid–induced stimulation of lateral bud development and enhanced assimilate availability. Previous studies have reported that humic substances exert auxin-like effects, promoting branching and canopy expansion (Chen *et al.*, 2004; Nardi *et al.*, 2021).

Similarly, silicon application significantly increased branching during 2023-24 and 2024-25, particularly at S_2, suggesting that silicon-mediated branching responses may vary with environmental conditions. Similar responses to silicon have been reported in vegetable crops (More *et al.*, 2019).

Although the interaction effect was statistically non-significant, Table 3 reveals that H_2S_2 (T_5) consistently produced the highest number of primary and secondary branches during 2023-24 (8.00 and 16.39) and 2023-24 (8.25 and 15.00), suggesting complementary physiological effects between humic acid and silicon.

Days to Flower Initiation

Days to flower initiation recorded during 2023-24 and 2024-25 were significantly reduced by humic acid and by silicon in both years (Table 1). Early flowering under H_2 may be attributed to improved physiological maturity and enhanced metabolic activity resulting from better nutrient uptake and hormonal balance (Nardi *et al.*, 2002).

Silicon significantly hastened flowering, particularly at S_2, which may be due to improved photosynthate partitioning and stress mitigation, allowing plants to reach reproductive phase earlier (Ma and Yamaji, 2015; de Souza Junior *et al.*, 2024).

Although the interaction effect was non-significant, Table 3 shows that H_2S_2 (T_5) consistently resulted in the earliest flowering during 2023-24 (45.67 days) and 2024-25 (47.33 days), supporting the hypothesis that combined application of organic biostimulants and silicon accelerates phenological development (Ali *et al.*, 2023).

Clusters per Plant

Clusters per plant recorded during 2023-24 and 2024-25 were significantly influenced by humic acid and silicon (Table 1). The superiority of H_2 may be attributed to enhanced assimilate production and translocation to reproductive organs, leading to improved floral retention (Chen *et al.*, 2004).

Silicon application at S_2 significantly improved cluster formation, likely due to its role in strengthening reproductive tissues and reducing flower drop under fluctuating environmental conditions (Epstein, 2009).

Although the interaction effect was non-significant, Table 3 indicates that H_2S_2 (T_5) recorded the highest number of clusters per plant (21.64 and 23.25) during 2023-24 and 2024-25, thereby, clearly outperforming the control treatment.

Fruits per Cluster

Fruits per cluster recorded during both years were significantly influenced only by humic acid, with H_2 producing the highest values (Table 2). The beneficial effect of humic acid on fruiting may be attributed to humic compounds in regulating plant metabolic and physiological functions i.e. pollen viability, fertilization efficiency, and successful fruit set. Similar enhancements in reproductive performance following humic substance application have been reported by Nardi *et al.* (2021)**.**

Silicon and interaction effects were statistically non-significant; however, Table 4 shows that H_2S_2 (T_5) recorded the highest fruits per cluster during 2023-24 (5.00) and 2024-25 (6.11), reflecting better reproductive efficiency under combined application.

Fruits per Plant

Fruits per plant recorded during 2023-24 and 2024-25 showed a strong response to humic acid and silicon (Table 2). The significant increase under H_2 can be attributed to improved flower retention, reduced abscission, and enhanced sink strength (Chen *et al*., 2004).

Silicon application, particularly at S_2, significantly increased fruit number, likely by improving stress tolerance and photosynthetic efficiency, thereby supporting higher reproductive output (Ma and Yamaji, 2015).

The significant interaction effect, as shown in Table 4, confirms that H_2S_2 (T_5) produced the maximum fruits per plant during 2023-24 (58.11) and 2024-25 (60.30), confirming a strong synergistic response (Ali *et al.*, 2023).

Fruit Weight

Fruit weight recorded during both years increased significantly under humic acid and silicon application (Table 2). The superior fruit weight under H_2 may be due to enhanced assimilate mobilization, improved enzymatic activity, and better hormonal regulation during fruit development (Nardi *et al.*, 2002).

Silicon application at S_2 further improved fruit weight by enhancing water-use efficiency and vascular tissue strength, leading to better fruit filling (Epstein, 2009; Ma and Yamaji, 2015).

The interaction effects were observed statistically non-significant, Table 4 shows that H_2S_2 recorded the maximum fruit weight during 2023-24 (65.12 g) and 2024-25 (68.87 g) which confirms the complementary role of humic acid and silicon.

Fruit Yield

Fruit yield per plot and per hectare recorded during 2023-24 and 2024-25 was significantly influenced by humic acid, silicon, and their interaction (Table 2). The yield superiority under H_2 reflects cumulative improvements in growth, flowering, fruit set, and fruit size.

Silicon application significantly increased yield, particularly at S_2, by enhancing nutrient-use efficiency, stress tolerance, and photosynthetic capacity (Epstein, 2009; Sarma *et al.*, 2024).

The interaction effect was significant for yield, and Table 4 clearly demonstrates that H_2S_2 (T_5) produced the maximum yield during 2023-24 (397.07 q ha^{-1}) and 2024-25 (408.84 q ha^{-1}), registering a substantial improvement over the control. Earlier findings showed that integrated application of humic substances and silicon leads to substantial yield enhancement through improved physiological stability and nutrient efficiency (Abdellatif *et al.*, 2017; Ali *et al.*, 2023).

Conclusion

The study demonstrated that moderate doses of humic acid (5 ml L^{-1}) and silicon (5 ml L^{-1}), either individually or in combination, significantly enhance tomato growth, reproductive traits, and yield. Among all treatments, H_2S_2 consistently outperformed others, indicating strong synergism. The findings recommend the combined application of humic acid and silicon as an effective, eco-friendly strategy for improving tomato productivity under field conditions.

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Table 1: Main effects of Humic Acid and Silicon on growth and phonological characters.

Factors	*detail*	*Plant height (cm)*		*Primary Branches*		*Secondary Branches*		*Days to Flower Initiation*		*Clusters/Plant*	
		2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
H1	Humic Acid-2 ml/l	106.19	115.30	5.14	5.04	12.47	10.56	48.92	49.00	17.96	18.11
H2	Humic Acid-5 ml/l	119.81	125.98	6.50	7.45	15.51	13.15	47.61	48.83	20.56	21.31
H3	Humic Acid-10 ml/l	112.39	121.77	5.99	5.83	13.90	12.11	50.69	50.24	18.69	20.82
S.E.(m)		0.58	0.67	0.31	0.36	0.47	0.39	0.44	0.38	0.27	0.70
C.D.		1.71	1.99	0.92	1.07	1.39	1.16	1.30	1.14	0.82	2.07
S1	Silicon- 2 ml/l	110.17	118.01	5.62	5.49	12.84	10.71	49.26	49.70	18.59	18.44
S2	Silicon- 5 ml/l	115.23	123.27	6.83	6.92	15.02	13.36	47.64	48.15	20.02	20.83
S3	Silicon- 10 ml/l	112.98	121.78	5.17	5.91	14.01	11.75	50.33	50.22	18.60	20.97
S.E.(m)		0.58	0.67	0.31	0.36	0.47	0.39	0.44	0.38	0.27	0.70
C.D.		1.71	1.99	0.92	1.07	1.39	1.16	1.30	1.14	0.82	2.07
Interaction (H×S)		Significant	Significant	Non-Significant	Non-Significant	Non-Significant	Non-Significant	Non-Significant	Non-Significant	Non-Significant	Non-Significant

Table 2: Main effects of Humic Acid and Silicon on yield parameters.

Factors	*detail*	*Fruits/Cluster*		*Fruits/Plant*		*Fruit Weight (g)*		*Yield/Plot (kg)*		*Yield/ha (q)*	
		2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
H1	Humic Acid- 2 ml/l	3.67	3.76	28.22	31.48	53.49	56.16	15.39	16.27	205.12	216.81
H2	Humic Acid- 5 ml/l	4.67	5.57	56.26	57.08	63.69	66.63	28.27	27.95	372.89	386.38

H3	Humic Acid- 10 ml/l	3.83	5.33	44.14	46.36	62.18	64.33	23.68	25.17	315.58	328.40
S.E.(m)		0.24	0.38	0.49	0.55	0.45	0.55	0.37	0.32	0.93	0.57
C.D.		0.72	1.14	1.45	1.63	1.35	1.63	1.11	0.96	2.75	1.69
S1	Silicon- 2 ml/l	3.78	4.67	40.44	43.41	58.81	61.61	21.18	21.88	282.28	297.21
S2	Silicon- 5 ml/l	4.33	5.13	43.81	45.46	61.07	63.59	23.95	24.54	315.24	322.51
S3	Silicon- 10 ml/l	4.06	4.86	44.36	46.04	59.49	61.92	22.21	22.96	296.07	311.87
S.E.(m)		0.24	0.38	0.49	0.55	0.45	0.55	0.37	0.32	0.93	0.57
C.D.		Non-Significant	Non-Significant	1.45	1.63	1.35	1.63	1.11	0.96	2.75	1.69
Interaction (H×S)		Non-Significant	Non-Significant	Significant	Significant	Non-Significant	Non-Significant	Significant	Significant	Significant	Significant

Table 3: Treatment Means for Both Years (Growth and Phenological Characters)

Treatment	*Plant height (cm)*		*Primary Branches*		*Secondary Branches*		*Days to Flower Initiation*		*Clusters/Plant*	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
T1 (H1S1)	104.00	111.48	4.91	4.27	10.78	9.36	49.43	49.00	17.48	16.33
T2 (H1S2)	106.91	115.03	5.50	6.00	13.00	11.08	47.33	48.00	18.70	18.00
T3 (H1S3)	107.65	119.38	5.00	4.85	13.62	11.25	50.00	50.00	17.69	20.00
T4 (H2S1)	114.57	122.12	6.17	7.10	15.91	12.77	47.34	48.83	19.43	19.67
T5 (H2S2)	123.55	130.55	8.00	8.25	16.39	15.00	45.67	47.33	21.64	23.25
T6 (H2S3)	121.30	125.26	5.33	7.00	14.22	11.67	49.83	50.33	20.60	21.00
T7 (H3S1)	111.94	120.42	5.78	5.11	11.84	10.00	51.00	51.26	18.85	19.33
T8 (H3S2)	115.22	124.21	7.00	6.50	15.66	14.00	49.92	49.13	19.71	21.22
T9 (H3S3)	110.00	120.69	5.17	5.88	14.19	12.33	51.17	50.31	17.50	21.91
T10 (Control)	101.65	108.57	4.50	3.87	8.32	8.00	52.00	52.00	16.47	15.67
S.E. (m)	1.01	1.18	0.55	0.63	0.83	0.69	0.77	0.67	0.48	1.23
C.D.(p=0.05)	2.21	2.57	1.19	1.38	1.80	1.50	1.68	1.47	1.05	2.68

Table 4: Treatment Means for Both Years (Yield Parameters)

Treatment	*Fruits/Cluster*		*Fruits/Plant*		*Fruit Weight (g)*		*Yield/Plot (kg)*		*Yield/ha (q)*	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
T1 (H1S1)	3.33	3.67	23.33	28.81	52.08	55.35	14.19	15.30	189.14	203.91
T2 (H1S2)	3.67	3.60	28.33	31.45	54.48	57.64	16.53	17.04	220.39	227.11
T3 (H1S3)	4.00	4.00	33.00	34.18	53.90	55.49	15.44	16.46	205.84	219.40
T4 (H2S1)	4.33	5.00	55.00	55.32	63.57	65.49	25.52	25.56	340.11	357.27
T5 (H2S2)	5.00	6.11	58.11	60.30	65.12	68.87	30.67	29.79	397.07	408.84
T6 (H2S3)	4.67	5.59	55.67	55.61	62.40	65.52	28.62	28.50	381.49	393.04
T7 (H3S1)	3.67	5.33	43.00	46.11	60.77	63.98	23.83	24.79	317.59	330.46
T8 (H3S2)	4.33	5.67	45.00	44.63	63.61	64.26	24.63	26.80	328.26	331.57
T9 (H3S3)	3.50	5.00	44.43	48.34	62.17	64.74	22.57	23.91	300.89	323.18
T10 (Control)	3.10	3.00	24.00	25.63	50.41	54.56	11.26	12.35	150.08	164.58
S.E. (m)	0.43	0.68	0.86	0.97	0.80	0.97	0.66	0.57	1.63	1.00
C.D.(p=0.05)	0.93	1.47	1.87	2.10	1.74	2.11	1.43	1.24	3.56	2.18