RESEARCH PAPER

Humic Acid–Silicon Synergy Improves Yield, Fruit Quality, and Shelf Life of Tomato (*Solanum lycopersicum* L.) under Field Conditions

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Abstract

The present study investigated the effects of different concentrations of humic acid and silicon on fruit yield and quality attributes during spring season for two consecutive years (2023-24 and 2024-25). Treatments included ten combinations of humic acid (0-10 ml L^{-1}) and silicon (0-10 ml L^{-1}). Results indicated that moderate levels of both inputs (5 ml L^{-1}) significantly enhanced fruit yield, shelf life, specific gravity, dry matter content, total soluble solids (TSS), and acidity. The interaction treatment H_2S_2 (5 ml L^{-1} humic acid + 5 ml L^{-1} silicon) consistently recorded the highest values across most parameters in both years. These findings demonstrate a strong synergistic effect between humic acid and silicon in improving productivity and fruit quality.

Keywords: Tomato (*Solanum lycopersicum* L.), Humic Acid, Silicon Nutrition, Fruit Quality Attributes**,** Biostimulant Interaction

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Introduction

Among vegetable crops, tomato (*Solanum lycopersicum* L.) occupies a prominent position due to its high economic value, widespread adaptability, and year-round cultivation. Tomato is one of the most widely grown and consumed vegetable crops globally and is valued both as a fresh market vegetable and as a raw material for processing industries. It serves as a rich source of vitamins (particularly vitamin C and provitamin A), minerals, organic acids, and antioxidants such as lycopene and β-carotene, which are associated with reduced risks of chronic diseases and improved human health.

The importance of tomato extends beyond yield, as fruit quality attributes largely determine consumer preference, processing efficiency, nutritional value, and market price. Key quality parameters in tomato include total soluble solids (TSS), titratable acidity, TSS–acid ratio, dry matter content, specific gravity, firmness, shelf life, and pigment concentration (especially lycopene). Higher TSS and balanced acidity contribute to better taste and flavor, while elevated dry matter and specific gravity enhance processing recovery for products such as paste, puree, ketchup, and juice. Lycopene content is particularly important due to its strong antioxidant properties and health-promoting effects. Fruit firmness and extended shelf life are critical for reducing post-harvest losses and improving transportability and storage stability. Therefore, agronomic practices that enhance both yield and quality attributes are of considerable importance in tomato production systems.

Enhancing fruit yield along with superior quality attributes remains a major objective in sustainable crop production systems, particularly under conditions of soil degradation, nutrient imbalance, and increasing abiotic stress. Modern nutrient management strategies increasingly focus on eco-friendly biostimulants and beneficial elements that enhance nutrient use efficiency, physiological performance, and post-harvest quality without imposing environmental risks. Among these, humic acid and silicon have emerged as promising inputs with documented positive effects on plant growth, productivity, and fruit quality.

Humic substances are heterogeneous organic compounds formed during the decomposition and humification of plant and microbial residues. Humic acid, the most active fraction, plays a significant role in improving soil physical, chemical, and biological properties. It enhances soil aggregation, increases cation exchange capacity, buffers soil pH, and stimulates beneficial microbial populations (Stevenson, 1994; Tan, 2003). At the plant level, humic acid promotes root elongation, increases membrane permeability, and enhances nutrient uptake and translocation (Chen *et al*., 2004; Nardi *et al*., 2002). It has been reported to exhibit hormone-like activity, particularly auxin- and cytokinin-like effects, thereby influencing cell division, elongation, and differentiation (Canellas and Olivares, 2014; Trevisan *et al.,* 2010).

Several studies have demonstrated that humic acid application improves photosynthetic activity, chlorophyll synthesis, enzyme activation, and carbohydrate metabolism (Pettit, 2004; Atiyeh *et al*.,

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2002). These physiological enhancements result in improved vegetative growth, flowering, fruit set, and ultimately yield. In tomato, humic acid has been reported to increase fruit weight, yield per plant, TSS, dry matter content, and nutrient concentration, thereby improving both quantitative and qualitative traits (Delfine *et al*., 2005; Calvo *et al.,* 2014). Furthermore, humic acid enhances nutrient use efficiency, particularly of nitrogen, phosphorus, potassium, and micronutrients, which are directly linked to fruit development, sugar accumulation, and pigment synthesis (Rose *et al.,* 2014).

Silicon (Si), though not universally recognized as an essential element, is widely acknowledged as a beneficial element for many crop species. Its positive role in plant growth and stress tolerance has been extensively documented (Epstein, 1999; Ma and Takahashi, 2002). Silicon is absorbed as monosilicic acid and deposited in plant tissues as amorphous silica, strengthening cell walls and improving structural rigidity (Savant *et al.,* 1999; Ma and Yamaji, 2015). This structural reinforcement enhances resistance to lodging, pests, and diseases, while also reducing transpiration and improving water use efficiency (Guntzer *et al.,* 2012).

Silicon application has been reported to enhance photosynthetic efficiency, chlorophyll stability, and antioxidant defense mechanisms under both biotic and abiotic stresses (Liang *et al.,* 2007; Zhu and Gong, 2014). In tomato, silicon has been associated with improved fruit firmness, higher TSS, enhanced lycopene content, balanced acidity, and extended shelf life due to improved cell wall strength and reduced physiological disorders (Kaya *et al*., 2006; Soundararajan *et al.,* 2014). These improvements are particularly valuable in reducing post-harvest losses and enhancing marketability.

Recent research indicates that the combined application of humic acid and silicon may produce synergistic effects. Humic acid improves soil nutrient availability and root uptake efficiency, whereas silicon enhances stress tolerance and structural stability. Together, these inputs may optimize physiological processes such as photosynthesis, nutrient assimilation, and assimilate translocation toward fruits, leading to enhanced yield and superior quality attributes. Ali et al. (2019) reported significant improvements in fruit yield and quality with integrated humic acid and silicon application. Similarly, Yadav *et al.* (2022) observed enhanced growth performance, higher TSS, improved dry matter accumulation, and better post-harvest attributes under combined treatments. Comparable synergistic responses have also been documented by Ekinci *et al*. (2014) and Artyszak (2018), indicating improved nutrient efficiency and stress resilience when silicon and organic biostimulants are applied together.

Although numerous studies have examined the individual effects of humic acid and silicon, comprehensive investigations evaluating their interactive influence across multiple growing seasons remain limited. Seasonal variations in climatic factors can significantly affect nutrient dynamics, plant physiological responses, and fruit quality parameters. Therefore, multi-year experimentation is essential to validate consistency and reproducibility of treatment effects.

In view of the nutritional, economic, and processing importance of tomato and the growing interest in sustainable nutrient management, the present study was undertaken to evaluate the main and interactive effects of varying concentrations of humic acid and silicon on fruit yield and quality parameters. The research aims to elucidate their synergistic potential and to develop scientifically sound strategies for enhancing productivity and quality in tomato cultivation.

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 randomized block design (RBD) with three replications. Ten treatment combinations were evaluated, consisting of three levels of humic acid ($H_1 = 2$ ml L^{-1}, $H_2 = 5$ ml L^{-1}, $H_3 = 10$ ml L^{-1}) and three levels of silicon ($S_1 = 2$ ml L^{-1}, $S_2 = 5$ ml L^{-1}, $S_3 = 10$ ml L^{-1}), along with an untreated control (H_0S_0).

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 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.

Observations on yield and quality parameters were recorded using standard procedures. Fruits were harvested at physiological maturity, and yield was calculated as quintals per hectare based on total fruit weight per plot. Shelf life was assessed under ambient conditions by recording the number of days taken for fruits to become unmarketable. Specific gravity was determined using the water displacement method, while dry matter percentage was estimated after oven-drying samples to constant weight. Total soluble solids (TSS) were measured with a hand refractometer and expressed as °Brix, and titratable acidity was determined by titration with 0.1 N NaOH and expressed as percent citric acid equivalent.

Data recorded during cropping seasons in both years were subjected to analysis of variance (ANOVA) appropriate for randomized block design. The significance of treatment effects was tested at the 5% probability level ($p \leq 0.05$). Treatment means were compared using the least significant difference (LSD) test at the same significance level. Statistical analyses were performed using standard statistical software packages.

Results and Discussion

Fruit Yield per Hectare

The main effects of humic acid and silicon on fruit yield were highly significant during both years, 2023-24 and 2024-25 (Table 1). In 2023-24, H_2 (5 ml L^{-1}) recorded the highest yield (372.89 q ha^{-1}), followed by H_3 (315.58 q ha^{-1}) and H_1 (205.12 q ha^{-1}). A similar trend was observed in 2024-25, where H_2 again produced the maximum yield (386.38 q ha^{-1}). Silicon at S_2 (5 ml L^{-1}) also recorded superior yields in both years.

The interaction effect was significant in both years (Table 1). Treatment H_2S_2 produced the highest yield in 2023-24 (397.07 q ha^{-1}) and 2024-25 (408.84 q ha^{-1}), as shown in Table 2, representing an increase of 120-160 q ha^{-1} over the control. The improvement may be attributed to enhanced nutrient uptake and metabolic activity under humic acid (Nardi *et al.*, 2002; Chen *et al.*, 2004) and improved structural and physiological efficiency under silicon (Savant *et al.*, 1999; Ma and Yamaji, 2015). Similar synergistic responses were reported by Ali *et al.* (2019) and Yadav *et al.* (2022).

Shelf Life

Shelf life was significantly influenced by humic acid and silicon during both years of experimentation, 2023-24 and 2024-25 (Table 1). In 2023-24, H_2 recorded 6.46 days, while in 2024-25 it recorded 9.56 days. Silicon at S_2 showed the highest shelf life in both years. Although the interaction effect was non-significant (Table 1), treatment means (Table 2) revealed that H_2S_2 produced the longest shelf life in 2023-24 (7.45 days) and 2024-25 (10.21 days). Improved shelf life may result from enhanced antioxidant systems and membrane stability under humic acid (Nardi *et al.*, 2002), while silicon strengthens cell walls and reduces post-harvest deterioration (Ma and Yamaji, 2015).

Specific Gravity

Specific gravity was significantly affected during 2023-24 and showed similar trends in 2024-25 (Table 1). In 2023-24, H_2 recorded the highest value (1.055), while in 2024-25 it recorded 1.045. Silicon at S_2 produced higher values in both years. Although the interaction was non-significant (Table 1), H_2S_2 recorded the highest specific gravity in 2023-24 (1.077) and 2024-25 (1.065) as shown in Table 2. The increase indicates improved dry matter and solute accumulation under integrated application (Chen *et al.*, 2004; Savant *et al.*, 1999).

Dry Matter Content

Dry matter content was significantly influenced by treatments during both years, 2023-24 and 2024-25 (Table 1). In 2023-24, H_2 recorded 6.74%, and in 2024-25 it increased to 8.05%. Silicon at S_2 also recorded maximum values in both years. The interaction was significant (Table 1), and H_2S_2 produced the highest dry matter in 2023-24 (7.56%) and 2024-25 (9.27%) as presented in Table 2. This enhancement may be due to improved photosynthesis and carbohydrate accumulation under humic acid (Nardi *et al.*, 2002) and structural carbohydrate retention under silicon (Ma and Yamaji, 2015). Similar findings were reported by Yadav *et al.* (2022).

Total Soluble Solids (TSS)

TSS was significantly affected during 2023-24 and 2024-25 (Table 1). In 2023-24, H_2 recorded 6.09°Brix, while in 2024-25 it recorded 5.58°Brix. Silicon at S_2 also recorded higher values in both years. The interaction effect was significant (Table 1), and H_2S_2 recorded the highest TSS in 2023-24 (6.54°Brix) and 2024-25 (6.11°Brix), as shown in Table 2. Improved TSS may be due to enhanced carbohydrate metabolism under humic acid (Chen *et al.*, 2004) and improved photosynthetic efficiency under silicon (Savant *et al.*, 1999).

Titratable Acidity

Acidity was significantly influenced during both years, 2023-24 and 2024-25 (Table 1). In 2023-24, the highest acidity was observed under H_3 (0.52%), while in 2024-25 it reached 0.50%. Silicon at S_2 recorded the highest acidity in both years. Although the interaction was non-significant (Table 1), treatment means (Table 2) show H_2S_2 consistently recorded the highest acidity in 2023-24 (0.55%) and 2024-25 (0.53%). The increase in acidity may be associated with enhanced organic acid synthesis and balanced metabolic activity under humic acid and silicon application (Nardi *et al.,* 2002; Ma and Yamaji, 2015). Similar integrated effects were reported by Yadav *et al.* (2022).

Conclusion

The study concludes that moderate doses of humic acid (5 ml L^{-1}) and silicon (5 ml L^{-1}) significantly enhance fruit yield and improve quality characteristics. The interaction treatment H_2S_2 consistently outperformed all other treatments across all measured parameters. These findings support integrated use of humic acid and silicon as an effective strategy for improving productivity and post-harvest fruit quality.

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

Factors	*detail*	*Yield (q/ha)*		*Shelf life (days)*		*Specific Gravity*		*Dry Matter (%)*		*T.S.S. (°Brix)*		*Acidity (%)*	
		2023-24	2024-25	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	205.12	216.81	4.97	6.46	1.027	1.014	5.39	6.48	4.53	4.44	0.45	0.41
H2	Humic Acid- 5 ml/l	372.89	386.38	6.46	9.56	1.055	1.045	6.74	8.05	6.09	5.58	0.50	0.49
H3	Humic Acid- 10 ml/l	315.58	328.40	5.73	9.02	1.040	1.027	6.38	7.65	6.05	4.69	0.52	0.50
S.E.(		0.93	0.57	0.20	0.23	0.01	0.01	0.11	0.19	0.07	0.08	0.01	0.01

m)													
C.D.		2.75	1.69	0.58	0.70	0.02	0.02	0.34	0.57	0.20	0.25	0.03	0.04
S1	Silicon-2 ml/l	282.28	297.21	5.21	7.73	1.031	1.018	5.83	6.94	5.23	4.56	0.46	0.43
S2	Silicon-5 ml/l	315.24	322.51	6.18	8.83	1.053	1.041	6.72	7.86	5.80	5.25	0.52	0.49
S3	Silicon-10 ml/l	296.07	311.87	5.78	8.48	1.038	1.026	5.96	7.36	5.63	4.90	0.48	0.48
S.E.(m)		0.93	0.57	0.20	0.23	0.01	0.01	0.11	0.19	0.07	0.08	0.01	0.01
C.D.		2.75	1.69	0.58	0.70	0.02	0.02	0.34	0.57	0.20	0.25	0.03	0.04
Interaction (H×S)		Sign.	Sign.	N.S.	N.S.	N.S.	N.S.	Sign.	Sign.	Sign.	Sign.	N.S.	N.S.

Table 2: Treatment Means of All Parameters (2023–24 and 2024–25)

Treatment	*Yield (q/ha)*		*Shelf life (days)*		*Specific Gravity*		*Dry Matter (%)*		*T.S.S. (°Brix)*		*Acidity (%)*	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
H1S1	189.14	203.91	4.67	5.80	1.013	0.994	5.25	6.07	4.27	3.82	0.42	0.39
H1S2	220.39	227.11	5.04	6.64	1.027	1.016	5.48	6.15	4.61	4.18	0.47	0.42
H1S3	205.84	219.40	5.20	6.95	1.042	1.031	5.45	7.21	4.70	5.31	0.45	0.43
H2S1	340.11	357.27	5.78	8.81	1.051	1.035	6.20	7.35	5.54	5.39	0.47	0.44
H2S2	397.07	408.84	7.45	10.21	1.077	1.065	7.56	9.27	6.54	6.11	0.55	0.53
H2S3	381.49	393.04	6.17	9.67	1.037	1.036	6.45	7.52	6.18	5.24	0.49	0.51
H3S1	317.59	330.46	5.19	8.58	1.030	1.026	6.04	7.41	5.89	4.47	0.50	0.47
H3S2	328.26	331.57	6.04	9.64	1.055	1.042	7.11	8.18	6.25	5.45	0.54	0.52
H3S3	300.89	323.18	5.98	8.83	1.034	1.012	5.98	7.35	6.00	4.14	0.51	0.50
H0S0	150.08	164.58	4.23	5.68	0.936	0.905	3.75	6.03	3.70	3.54	0.36	0.35
S.E. (m)	1.63	1.00	0.35	0.41	0.01	0.01	0.20	0.34	0.12	0.15	0.02	0.03
C.D.(p=0.05)	3.56	2.18	0.75	0.90	0.02	0.02	0.43	0.73	0.26	0.34	0.04	0.06