

Research Article

Impacts of humic acid on soil microbial diversity and productivity in tea cultivation toward sustainable agriculture

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Abstract

Tea is an important perennial plantation crop whose prolonged monoculture practice and continuous usage of inorganic fertilizers often result in soil degradation, depletion of organic matter, and reduced nutrient use efficiency (NUE). In this context, this study evaluated the application of humic acid, a sustainable soil amendment with beneficial effects on soil health across agro-ecosystems, in combination with inorganic fertilizers on soil health, nutrient uptake, and crop productivity under high elevation conditions. A long-term field experiment consisting of eight treatments with three replications in a Randomized Block Design (RBD) was conducted during the year 2021 to 2025. The treatments comprised humic acid at the rate of 20 and 40 kg ha⁻¹, along with reduced inputs of NPK application ranging from 100%, 75%, and 50%. Soil samples were collected annually to assess soil properties and microbial dynamics and green leaf yield during each plucking round was recorded. Results revealed that the humic acid application at 40 kg ha⁻¹ integrated with reduced 75% NPK, helped in achieving relatively higher productivity of 21.1%. This also significantly improved soil nutrients and microbial activity besides the crop yield when compared to untreated control. Thus, the present study confirmed that the integration of humic acid with inorganic NPK fertilizers improves soil health and tea productivity while reducing dependence on synthetic fertilizers up to 25% in high elevation tea growing regions of South India.

Keywords: Humic acid, Soil fertility, Soil health, Synthetic fertilizers, Tea crop

Introduction

Tea, *Camellia sinensis* (L.) O. Kuntze is an economically important perennial plantation crop cultivated in warm and humid climates with temperatures between 15 °C and 30 °C and well-drained, acidic soil (pH 4.5 to 5.5) with an annual rainfall of 1,500 to 2,500 mm. In addition, the tea productivity and quality are strongly influenced by soil fertility, nutrient availability and microbial activity (Han *et al.*, 2018). The tea plantation sector has been severely impaired by several biotic and abiotic stresses, resulting in the reduction of quality and yield (Mendez *et al.*, 2025). In India, tea plantations are predominantly managed under intensive monoculture systems with continuous application of chemical fertilizers to sustain productivity. However, prolonged use of synthetic fertilizers often leads to soil degradation, decline in soil organic carbon, nutrient imbalance, and reduced beneficial microbial activity, particularly in high elevation tea growing regions characterized by acidic soils and heavy rainfall (Rahaman & Aruchamy, 2022). Studies have reported that the long-term usage of NPK fertilizers has made the tea soil more acidic in nature (Venkatesan *et al.*, 2004). These challenges underscore the need for sustainable nutrient management strategies to maintain soil health and long-term productivity in tea plantations, of which humic acid application has emerged as a promising approach.

Humic acid, a major fraction of humic substances that make up nearly 80% of soil organic matter (Hu *et al.*, 2022), is a biochemically active compound that improves both

soil and plant health. At the soil level, it enhances organic matter content, structure, aggregation, moisture retention, and nutrient availability, while promoting the proliferation of beneficial microbial communities (Sun & Zhang, 2024; Bera *et al.*, 2024). The commercial available humic acid contains active ingredient at 1.5% Bioactive Humic Substances (Consists of active Humic acid, Fulvic acid, and Humin fractions). Functional group of Carboxyl (-COOH), Phenolic Hydroxyl (-OH), Carbonyl (C=O), and Methoxy (-OCH₃) groups. Purity derived from 100% Organic Matter via fresh, renewable agricultural biomass. It is highly bioactive with a low molecular weight (<500 Da) Ph at 7.0-9.0 (Alkaline-stabilized granular matrix).

At the plant level, humic acid improves cell membrane permeability and facilitates mineral uptake and transport (Gholami *et al.*, 2013; Duary, 2020), promotes protein synthesis, exhibits plant growth regulator-like activity, enhances photosynthetic efficiency, and modulates enzymatic activity (Canellas & Olivares, 2014; Monda *et al.*, 2021). These effects are attributed to the chelation and mobilization of nutrients and the stimulation of hormonal and enzymatic processes (Kalaichelvi *et al.*, 2006), which together increase the availability of macro- and micronutrients while reducing the toxicity of harmful minerals. Humic acid has also been reported to improve crop tolerance to abiotic stresses such as drought, salinity, and heavy-metal toxicity, positioning it as a potential contributor to climate-resilient agriculture while reducing reliance on synthetic fertilizers (Antu *et al.*, 2025). It can be applied through soil incorporation, foliar spraying, seed treatment, root dipping, fertigation, or drip

irrigation, with soil application generally identified as the most effective method (Bhatt & Singh, 2022). Notably, the combined application of humic substances with inorganic fertilizers has been shown to enhance crop productivity while lowering dependence on synthetic nutrient inputs (Khaled & Fawy, 2011).

Although the beneficial effects of humic acid have been widely reported in several crops, information on its long-term influence in high-elevation tea plantations of South India remains limited. Consequently, an integrated nutrient management schedule incorporating humic acid has not yet been fully developed or recommended for the benefit of tea growers. Therefore, the present study was undertaken to evaluate the synergistic effect of the humic acid along with inorganic NPK fertilizers on tea productivity, soil fertility in terms of enhanced microbial activity, and nutrient content of tea with special reference to the tea growing areas in the high elevation.

Materials and methods

Experimental site and details

The field study was conducted in one of the tea estates in the High Range, Idukki District; Kerala situated at an altitude of 1700 m MSL with the coordinates 10.15° N, 77.06° E. The field consisted of seedling tea plants with 1.2 m × 1.2 m spacing. The experimental plots were laid out in a seedling tea field with three replications and eight treatments. The plots size was around 80 bushes per plot.

The soil application of NPK fertilizers was calculated based on the yield potential of the tea garden. The experiment was conducted in a medium-yielding field, where the recommended annual fertilizer dose consisted of approximately 215 kg N/ha, 161 kg K₂O/ha, and 30 kg P₂O₅/ha. This recommended fertilizer dose was considered as 100% of the standard NPK recommendation and served as the control treatment. To evaluate the possibility of reducing the dependence on synthetic fertilizers, the NPK application was reduced by 25% and 50% from the standard recommendation. As a supplementary organic input, humic acid was applied at 20 and 40 kg/ha/year, respectively, in the reduced-fertilizer treatments. The objective was to assess whether humic acid supplementation could compensate for part of the reduction in synthetic fertilizer inputs while maintaining soil fertility and supporting beneficial soil microbial activity. The experiment comprised combinations of recommended NPK fertilizer levels and humic acid (20 and 40 kg ha⁻¹), along with an untreated control (T8). The treatments are T1) 100% NPK (as per standard recommendation), T2) 100% NPK with 20 kg ha⁻¹ of humic acid, T3) 75% NPK with 20 kg ha⁻¹ of humic acid, T4) 50% NPK with 20 kg ha⁻¹ of humic acid, T5) 100% NPK with 40 kg ha⁻¹ of humic acid, T6) 75% NPK with 40 kg ha⁻¹ of humic acid, T7) 50% NPK with 40 kg ha⁻¹ of humic acid, and T8) untreated control. The humic acid granules were mixed with NPK fertilizers and it was applied yearly four splits through broadcasting method during pre monsoon two splits and post monsoons two splits

Enumeration of micro flora in rhizosphere soil

Soil samples were collected annually from the experimental plots throughout the study period (2021–2025). Samples were collected from a depth of 0–23 cm from the soil surface in each experimental plot. Sampling was carried out at two stages: immediately before the imposition of treatments (pre-treatment) and 90 days after treatment application (post-treatment). The collected soil samples were used for the enumeration of soil microflora. The observations obtained during the four years of experimentation were compiled and used for the overall analysis of the study. The collected soil samples were shade dried at room temperature (25±2 °C) for 48 h, and used for the enumeration of total bacteria, fungi, Actinomycetes, *Azospirillum*, Phosphate solubilising bacteria (PSB), *Pseudomonas* and *Trichoderma*. The media such as Nutrient Agar, Rose Bengal Agar, Starch Casein agar, N₂-free malic acid agar, Pikovskaya's medium, *Trichoderma* selective medium and King's B medium were used to isolate bacteria, fungi, Actinomycetes, *Azospirillum*, Phosphate solubilizing bacteria, *Trichoderma* and *Pseudomonas*, respectively (Pikovskaya, 1948; Martin, 1950; King *et al.*, 1954; Küster & Williams, 1964; Gordon *et al.*, 1973; Day & Döbereiner, 1976). 10 g of soil samples were mixed with 100 mL of sterile distilled water to obtain 1:10 dilution (10⁻¹). From this, 1 mL of the solution was further serially diluted, and aliquots from the appropriate dilutions were plated onto the respective media and incubated. Colonies were counted and expressed as colony-forming units (CFU) per gram of soil.

Crop yield

Regular harvesting was carried out at specific plucking interval after impose the treatment and totally 58 rounds of plucking carried out during the study period. The harvested green leaf was converted to made tea using standard formula and 22.5% out turn from the total green leaf harvested. The crop yield in terms of made tea per hectare was calculated from the harvested green leaf using the following standard following formula:

$$\text{Made tea yield (kg ha}^{-1}\text{)} = \frac{\text{Green leaf yield (kg)} \times 6800 \times 0.225}{\text{Number of bushes in the plot}}$$

Where 6,800 represents the standard bush population per hectare, and 0.225 is the conversion coefficient of green leaf to processed made tea (Ponmurugan & Baby, 2007).

Nutrient analysis of humic acid amended soil samples

The soil samples were shade dried and ground for the nutrient analysis. The nutrients like N, P and K were quantified using the methods described by Murphy and Riley (1962), Bray and Kurtz (1945) and Bremner (1956), respectively.

Statistical analysis

The data generated from the field study were subjected to the analysis of variance (ANOVA) and the significant means were segregated by Critical Difference (CD @ $p=0.05$) followed by Duncan's Multiple Range Test (DMRT) using R Programming with R studio version v.2026.05.1 (Gomez & Gomez, 1984; Schumacker & Tomek, 2013).

Results and discussion

Impact of humic acid treatments on the beneficial soil micro flora

The results revealed that the different combinations of inorganic fertilizers (NPK) and HA (Humic Acid) significantly influenced soil microbial populations. The results indicated that the application of 100% NPK in combination with 20 kg ha⁻¹ recorded the highest total bacterial population (5.3×10^6 CFU g⁻¹), suggesting that the addition of humic substances along with recommended fertilizer doses creates a favourable environment for bacterial proliferation (Figure 1a). HA is known to improve soil structure, increase nutrient availability, and stimulate microbial activity, which may explain the enhanced bacterial counts observed in this treatment. Marimuthu

et al. (2023) reported the importance of *Methylobacterium*, which regulates plant growth hormones and ACC deaminase enzyme activity, playing a vital role in drought stress adaptation in tea crop. The lower fungal counts recorded under reduced NPK levels may be attributed to limited substrate availability and nutrient constraints (Figure 1b). *Actinomyces* exhibited a different trend, with the highest population observed in the treatment 100% NPK + 20 kg ha⁻¹ HA (12.4×10^6 CFU g⁻¹), followed by the treatment 75% NPK + 40 kg ha⁻¹ HA (11.0×10^6 CFU g⁻¹). This suggests that *Actinomyces* may thrive better under relatively high disturbed or organically balanced soil conditions (Figure 1c). As tea soils are usually acidic in nature and rich in organic matter with low levels of available nutrients, *Actinomyces* help by breaking down organic residues, increasing nutrient availability, especially phosphorus and iron. They also protect tea plants from soil-borne diseases and support better growth and yield (Bhatti *et al.*, 2017). The population of *Trichoderma*, an important bio control fungus was reported as the highest in the 50%NPK along with 20 kg humic acid per ha (1.7×10^6 CFU/g) and followed by 100% NPK + 20 kg ha⁻¹ HA (1.3×10^6 CFU g⁻¹) treatments (Figure 1d). This may be due to reduced competition from other microorganisms or lower chemical inputs, which can occasionally suppress beneficial fungi. Phosphate-solubilizing bacteria (PSB) showed a marked increase under 50% NPK + 20 kg ha⁻¹

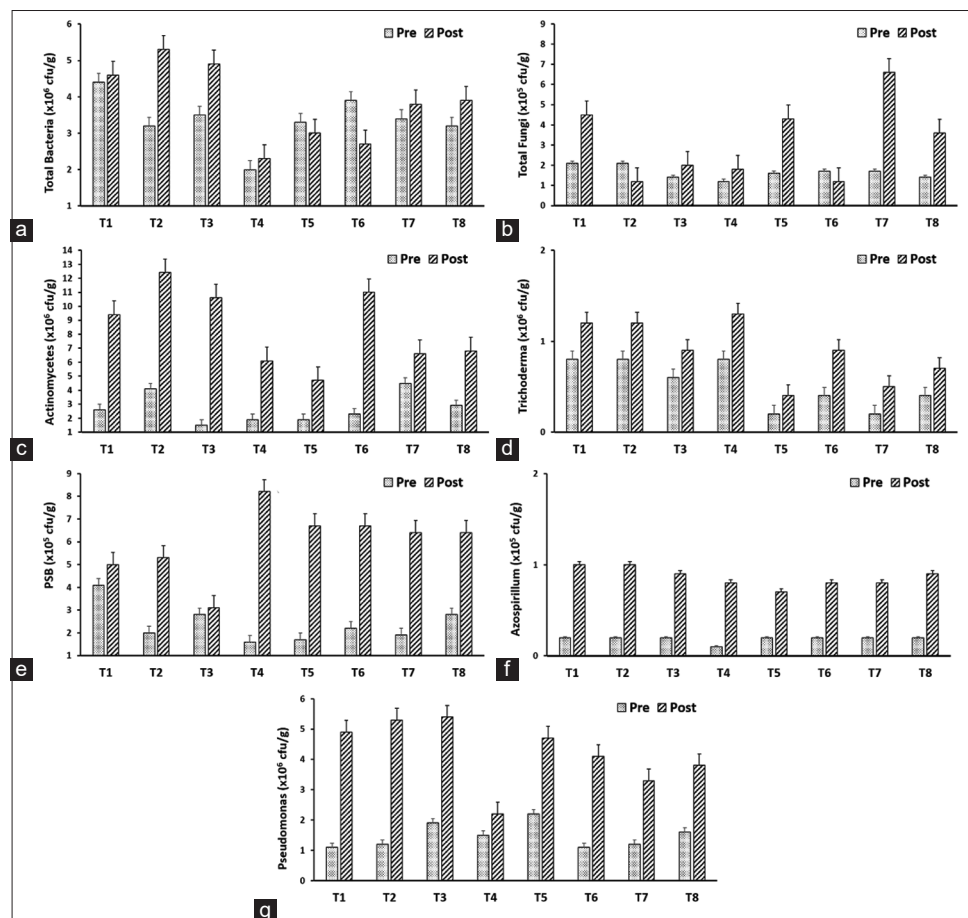


Figure 1: Impact of humic acid treatments on soil microbial population. Treatments: T1-100% NPK (as per standard recommendation); T2-100% NPK with 20 kg ha⁻¹ of humic acid; T3-75% NPK with 20 kg ha⁻¹ of humic acid; T4-50% NPK with 20 kg ha⁻¹ of humic acid; T5-100 % NPK with 40 kg ha⁻¹ of humic acid; T6-75 % NPK with 40 kg ha⁻¹ of humic acid; T7-50 % NPK with 40 kg ha⁻¹ of humic acid and T8-Untreated control

HA (8.2×10^5 CFU g^{-1}), indicating that reduced chemical fertilizer levels coupled with organic amendments stimulate native PSB activity. This could be attributed to increased root exudation and improved beneficial soil microbial population, enhancing phosphorus solubilization processes. Similarly, treatment with 40 kg of HA also maintained relatively higher PSB populations compared to the control plots (Figure 1e).

On the other hand, the population of *Azospirillum* remained relatively consistent across treatments, with only minor variations between treatments, suggesting that this group may be less sensitive to changes in nutrient levels and humic acid application (Figure 1f). *Azospirillum* species are plant growth-promoting rhizobacteria extensively studied due to their association with nitrogen fixation and the biosynthesis of phytohormones (Cassán & Diaz-Zorita, 2016). However, *Pseudomonas* populations were recorded as the highest in the treatment with 75% NPK + 20 kg ha^{-1} HA (5.4×10^6 CFU g^{-1}) and 100% NPK + 20 kg ha^{-1} HA (5.3×10^6 CFU g^{-1}), indicating the fact that, integrated nutrient management practices support the growth of these beneficial rhizobacteria (Figure 1g). Overall, the findings of this study suggested that an integrated applications of NPK fertilizers with HA, particularly at 40 kg ha^{-1} , enhanced soil microbial activity more effectively than either higher HA levels or reduced fertilizer doses alone. Moderate application (20 kg ha^{-1}) in combination with recommended or slightly reduced NPK levels proved beneficial. These results highlight the importance of balanced nutrient management in sustaining soil microbial diversity and activity, which is essential for retaining soil health and sustaining crop productivity. Among the treatment 75% NPK with 40 kg humic acid per hectare gives significant improve in term of yield and holding adequate beneficial microbial population. This trend is encouraging the tea production in high elevation tea gardens.

Impact of humic acid treatments on physiochemical properties of the tea soil

Nutrient management plays an important role in sustaining tea productivity and soil health. The combined application of inorganic fertilizers such as NPK with organic amendments like humic acid is often explored to improve the nutrient use efficiency and crop yield. The

post treatment soil samples were analyzed and the levels of nutrients were represented in Table 1. The nutrients among all the treatments were at adequate levels suitable for tea cultivation practices and addition of 75% NPK with 20 kg to 40 kg humic acid is often enhance the phosphorus. Moreover the sustainability of soil nutrients. In a three-year peanut experiment, HA increased total and available nutrients and organic matter, with the largest effects in year three (Li *et al.*, 2019). It also improved soil pH and cation exchange in an embankment study (Ali & Mindari, 2016). However, electrical conductivity generally increased, and saturated hydraulic conductivity decreased in some sandy and clayey soils (Gümüş & Şeker, 2015).

Effect on the integration of humic acid with NPK fertilizers on crop yield

The present study demonstrated that, application of reduced level of NPK to 75% along with the inclusion of humic acid showed a relatively positive effect. The treatment with 75% NPK + 40 kg ha^{-1} HA yielded 9489 kg ha^{-1} (21.1% increase from untreated control), which is comparatively closer to the 100% recommended dose of NPK treatment. This indicated the role of HA in improving the nutrient use efficiency and particularly compensated for reduced fertilizer input. In contrast, 75% NPK + 20 kg ha^{-1} HA resulted in a lower yield of 8458 kg ha^{-1} , suggesting that a higher dose of HA is more effective at this nutrient level. Moreover, the reduction of NPK to 50% resulted in a significantly reduced crop yield, regardless of HA application. The treatments 50% NPK + 20 kg ha^{-1} HA and 50% NPK + 40 kg ha^{-1} HA recorded a maximum total yield of 8810 kg ha^{-1} and 8596 kg ha^{-1} , respectively (Table 2). This is a long term experiments the results reveals that the addition of humic acid stabilize the population of soil micro organism and the yield also gradually increase second year onwards and end of the experiments the 75% NPK along with 40 kg humic acid per hectare gives significant yield increase even it was marginal decrease of 1.26 per cent crop when compared to 100% NPK. It can be compensate with reduction of synthetic fertilizers and soil sustainability. These combined treatments have led to increased biomass accumulation, better vegetative growth, and ultimately higher crop yield. Enhanced root development and nutrient assimilation

Table 1: Effect of application of humic acid on physico-chemical properties in high elevation tea soil

T. No.	pH	EC (dSm ⁻¹)	OM (g/100 g)	Nitrogen (g/10 g)	Phosphorus (mg kg ⁻¹)	Potassium (mg kg ⁻¹)	Calcium (mg kg ⁻¹)	Magnesium (mg kg ⁻¹)	Sulphur (mg kg ⁻¹)	Zinc (mg kg ⁻¹)	Manganese (mg kg ⁻¹)	CEC (cmol kg ⁻¹)
T1	5.10	0.12	8.07	0.45	10.33	248.33	780.00	118.33	3.67	0.63	3.33	9.60
T2	4.80	0.11	7.27	0.49	5.67	109.33	288.00	86.00	2.33	0.47	3.00	6.17
T3	5.00	0.17	7.87	0.44	35.77	148.33	304.33	86.00	1.00	0.70	7.00	6.83
T4	4.37	0.17	7.00	0.49	21.33	170.00	274.67	162.00	2.00	0.63	2.67	8.43
T5	4.83	0.16	7.80	0.58	12.00	243.33	483.00	128.33	1.67	0.63	2.67	9.77
T6	4.57	0.24	6.70	0.40	25.00	200.00	221.67	88.00	4.67	0.57	8.33	6.73
T7	4.57	0.19	7.87	0.52	7.00	168.33	383.67	106.33	1.67	0.60	5.33	8.30
T8	4.47	0.15	6.70	0.46	5.33	76.67	195.33	48.00	1.00	0.57	3.67	4.83
CD @ p=0.05	1.0	0.2	1.8	0.1	37.3	217.1	389.6	112.0	2.7	0.4	9.1	3.0

Values represent the mean of three replications recorded post-treatment application

Table 2: Effect of integration of humic acid with reduction of NPK fertilizers on crop productivity in high elevation tea plantation of South India

T. No.	Treatment	Yield (Made tea kg ha ⁻¹)**					
		First Year (2021-2022)	Second Year (2022-2023)	Third Year (2023-2024)	Fourth Year (2024-2025)	Mean*	Total
T1	100% NPK	2282	2296	2462	2878	2479.5 ^a	9918
T2	100% NPK+20 kg Humic acid	2061	2111	2300	2605	2269.3 ^{bc}	9077
T3	75% NPK+20 kg Humic acid	1902	2098	2042	2416	2114.5 ^d	8458
T4	50% NPK+20 kg Humic acid	2088	1889	2149	2684	2202.5 ^{cd}	8810
T5	100% NPK+40 kg Humic acid	2171	2022	2160	2576	2232.3 ^{cd}	8929
T6	75% NPK+40 kg Humic acid	2139	2112	2396	2842	2372.3 ^{ab}	9489
T7	50% NPK+40 kg Humic acid	1931	1975	2186	2504	2149 ^{cd}	8596
T8	Control	1871	1893	1798	2271	1958.3 ^e	7833
	CD @ $p=0.05$	691.3	584.9	547.4	243.5	129.3	

** Yield (kg made tea/ha) was recorded during the study period from June 2021 to March 2025. *Values are the mean of three replications. Treatments with same letters are not significantly different at $p<0.05$ according to Duncan's Multiple Range Test (DMRT)

under HA treatment have contributed directly to improved yield components such as shoot development, leaf production, and overall crop productivity.

Humic acid has been reported to improve crop performance across several crops, although the magnitude and consistency of the response depend on the crop, application method, fertilizer regime, and soil conditions. Humic substance application increased tea shoot yield, improved soil chemical properties, and enhanced P availability. Diluted Humic fertilizer further increased P availability; possibly through greater soil phosphatase activity and phosphate-solubilising bacteria (PSB) activity (Pramanik *et al.*, 2017). Humic acid based organic–inorganic fertilizers enhanced the growth of 2-year-old tea plants and improved soil fertility (Sui *et al.*, 2022). The combined application of chemical fertilizer and humic acid was more effective in increasing soil organic matter, total N, P, K, and available P and K than the other treatments (Huang *et al.*, 2016). In maize, its integration with phosphorus fertilizer increased plant growth, yield components, grain yield, and economic returns relative to the corresponding treatments without HA (Ahmad *et al.*, 2020). Potato also responded positively: humic-acid-based multinutrient fertilizer increased yield by 9.3% compared with chemical fertilizer alone and by 88.2% compared with the untreated control. In tomato, the same type of humic-acid multinutrient fertilizer increased yield by 7.7% over chemical fertilizer alone and improved quality attributes including lycopene, ascorbic acid, acidity, pH, and total soluble solids (Rajendiran & Purakayastha, 2014). Peanut showed improvements in shoot dry weight, nodulation, tissue nutrient content, and yield, particularly when HA was applied as a coating treatment in combination with plant-growth-promoting rhizobacteria (El-Syed *et al.*, 2016). Evidence for rice is also generally positive, with reviews associating humic-acid application with enhanced growth, yield, nutrient uptake, root development, and soil properties; however, the rice evidence cited here is review-based rather than a single quantified field comparison (Bera *et al.*, 2024).

Therefore, HA could be considered as an effective input for boosting both yield and soil fertility while maintaining sustainable agricultural practices (El-Ghamry *et al.*, 2009). The addition of HA does not significantly enhanced yield

when nutrient supply was maintained at optimum. However, under reduced fertilizer conditions, particularly at a reduced level of 75% NPK, the application of 40 kg of HA could help to sustain the relatively high tea productivity. HA has been reported to enhance soil quality and significantly improves crop yield when applied to different crops at appropriate rates and dosages (Mankotia, 2024).

This is a long term experiments the results reveals that the addition of humic acid stabilize the population of soil micro organism and the yield also gradually increase second year onwards and end of the experiments at 75% NPK along with 40 kg humic acid per hectare gives significant yield increase even it was marginal decrease of 1.26 per cent crop when compared to 100% NPK. It can be compensate with reduction of synthetic fertilizers and soil sustainability. Consequently, integrated nutrient management involving partial substitution of chemical fertilizers with organic amendments and conserve the native beneficial microorganisms may be considered for soil health improvement, though it may result in as light compromise in yield in an economically viable manner. Additionally, HA enhances nutrient use efficiency, reducing reliance on chemical fertilizers and contributing to sustainable tea cultivation. The previous research by Chen and Aviad (1990) highlighted the role of humic substances in improving plant growth and nutrient uptake. Similarly, Nardi *et al.* (2002) reported that the HA stimulates plant metabolism and root development. In teaspecific contexts, Ruan *et al.* (2007) demonstrated improved nutrient efficiency and growth responses in tea plants treated with organic amendments, including humic substances.

Input cost and economic benefit

The input cost of applying 100% of the recommended NPK fertilizers, including subsidized urea, was estimated at approximately ₹24,574 ha⁻¹. In comparison, the application of 75% of the recommended NPK dose along with 40 kg ha⁻¹ of humic acid incurred an input cost of approximately ₹21,884 ha⁻¹. Thus, the integrated application of humic acid with a reduced NPK dose resulted in a saving of approximately ₹2,690 ha⁻¹, corresponding to a 12.3% reduction in input cost compared with the conventional 100% NPK application. These findings indicate that the

application of the recommended dose of humic acid in combination with 75% NPK can reduce fertilizer input costs while maintaining a more efficient nutrient-management strategy. Such an approach has potential to improve the economic viability and long-term sustainability of tea cultivation, particularly through reduced dependence on inorganic fertilizers and more efficient utilization of applied nutrients.

Conclusion

This four-year field study (2021–2025) on integrated soil health management in high-elevation tea gardens demonstrated that humic acid, applied in combination with inorganic NPK fertilizers, is an effective strategy for restoring soil fertility and enhancing tea productivity. Application of reduced NPK fertilizer dose at 75% combined with HA at 40 kg ha⁻¹ resulted in significantly higher yield compared to the untreated control. This treatment also improved soil microbial activity, including increased populations of beneficial bacteria, Actinomycetes, and phosphate-solubilising bacteria. Soil nutrient levels, particularly potassium, calcium, and magnesium were also higher in humic acid-treated plots relative to the control. These findings support the use of humic acid integrated with 75% NPK as a viable strategy for improving soil health, sustaining microbial diversity, and enhancing crop productivity in high-elevation tea gardens, while reducing dependence on synthetic fertilizers.

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Author contributions

RK: Investigation, data collection, writing- original draft; NP: conceptualization, Supervision, Validation; AB: Writing- review and editing; KM: field trials and data collection; MS: Writing and editing.

References

Ahmad, Z., Khan, Q. U., Qadoos, A., Khan, M. J., Saleem, A., & Bibi, Z. (2020). Humic acid, an effective amendment used for amelioration of Phosphatic fertilizer and enhancing maize yield. *Pure and Applied Biology*, 9(1), 750-759. <https://doi.org/10.19045/bspab.2020.90081>

Ali, M., & Mindari, W. (2016). Effect of humic acid on soil chemical and physical characteristics of embankment. *MATEC Web of conferences*, 58, 01028. <https://doi.org/10.1051/mateconf/20165801028>

Antu, U. B., Roy, T. K., Kulsum, T. I., Mitu, P. R., Ismail, Z., Arifin, M., Datta, M., Hossain, S. A., Islam, M. S., Mahiddin, N. A., Al Bakky, A., Hossin, S., Islam, S., & Idris, A. M. (2025). Role of humic acid for climate change adaptation measures to boost up sustainable agriculture and soil health: A potential review. *International Journal of Biological Macromolecules*, 313, 144043. <https://doi.org/10.1016/j.ijbiomac.2025.144043>

Bera, B., Bokado, K., Barkha, & Arambam, S. (2024). Effect

of humic acid on growth, yield and soil properties in rice: A review. *International Journal of Plant & Soil Science*, 36(6), 26-35. <https://doi.org/10.9734/ijpss/2024/v36i64603>

Bhatt, P., & Singh, V. K. (2022). Effect of humic acid on soil properties and crop production—A review. *The Indian Journal of Agricultural Sciences*, 92(12), 1423-1430. <https://doi.org/10.56093/ijas.v92i12.124948>

Bhatti, A. A., Haq, S., & Bhat, R. A. (2017). Actinomycetes benefaction role in soil and plant health. *Microbial Pathogenesis*, 111, 458-467. <https://doi.org/10.1016/j.micpath.2017.09.036>

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59(1), 39-46. <https://doi.org/10.1097/00010694-194501000-00006>

Bremner, J. M. (1965). Total Nitrogen. In A. G. Norman (Eds.), *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties* (pp. 1149-1178). American Society of Agronomy Inc. <https://doi.org/10.2134/agronmonogr9.2.c32>

Canellas, L. P., & Olivares, F. L. (2014). Physiological responses to humic substances as plant growth promoter. *Chemical and Biological Technologies in Agriculture*, 1, 3. <https://doi.org/10.1186/2196-5641-1-3>

Cassán, F., & Diaz-Zorita, M. (2016). *Azospirillum* sp. in current agriculture: From the laboratory to the field. *Soil Biology and Biochemistry*, 103, 117-130. <https://doi.org/10.1016/j.soilbio.2016.08.020>

Chen, Y., & Aviad, T. (1990). Effects of humic substances on plant growth. In P. MacCarthy, C. E. Clapp, R. L. Malcolm, & P. R. Bloom (Eds.), *Humic Substances in Soil and Crop Sciences: Selected Readings* (pp. 161-186). John Wiley & Sons, Inc. <https://doi.org/10.2136/1990.humicsubstances.c7>

Day, J. M., & Döbereiner, J. (1976). Physiological aspects of N₂-fixation by a *Spirillum* from *Digitaria* roots. *Soil Biology and Biochemistry*, 8(1), 45-50. [https://doi.org/10.1016/0038-0717\(76\)90020-1](https://doi.org/10.1016/0038-0717(76)90020-1)

Duary, S. (2020). Humic acid - A critical review. *International Journal of Current Microbiology and Applied Sciences*, 9(10), 2236-2241. <https://doi.org/10.20546/ijcmas.2020.910.270>

El-Ghamry, A. M., Abd El-Hai, K. M., & Ghoneem, K. M. (2009). Amino and humic acids promote growth, yield, and disease resistance of faba bean cultivated in clayey soil. *Australian Journal of Basic and Applied Sciences*, 3(2), 731-739.

El-Syed, F. R., Hoda, A. G., & Yassen, M. Y. (2016). Growth, nodulation, yield and mineral tissue content of peanut in response to foliar and coating application of humic acid and plant growth –promoting rhizobacteria. *Journal of Environmental Studies and Researches*, 6(E2), 195-202. <https://doi.org/10.21608/jesr.2017.57341>

Gholami, H., Samavat, S., & Ardebili, Z. O. (2013). The alleviating effects of humic substances on photosynthesis and yield of *Plantago ovata* in salinity conditions. *International Research Journal of Applied and Basic Sciences*, 4(7), 1683-1686.

Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. (2nd ed). John Wiley and Sons, Inc.

Gordon, R. E., Haynes, W. C., & Pang, C. H. (1973). *The genus Bacillus. Agriculture Handbook No. 427*. ScienceOpen, Inc.

Gümüş, İ., & Şeker, C. (2015). Influence of humic acid applications on soil physicochemical properties. *Solid Earth Discuss*, 7, 2481-2500.

Han, W., Li, X., Yan, P., Zhang, L., & Ahammed, G. J. (2018). Tea cultivation under changing climatic conditions. In V. S. Sharma & M. T. Kumudini Gunasekare (Eds.), *Achieving Sustainable Cultivation of Tea* (pp. 455-472). Burleigh Dodds Science Publishing. <https://doi.org/10.19103/>

- AS.2017.0036.19
- Hu, Z.-T., Huo, W., Chen, Y., Zhang, Q., Hu, M., Zheng, W., Shao, Y., Pan, Z., Li, X., & Zhao, J. (2022). Humic substances derived from biomass waste during aerobic composting and hydrothermal treatment: a review. *Frontiers in Bioengineering and Biotechnology*, 10, 878686. <https://doi.org/10.3389/fbioe.2022.878686>
- Huang, D., Wang, L., & Luo, T. (2016). Effects of applying humic fertilizers on tea's yield, nutritional quality and soil fertility in a tea garden. 3rd International Conference on Materials Engineering, Manufacturing Technology and Control (pp. 1046-1051). Springer. <https://doi.org/10.2991/icmemtc-16.2016.207>
- Kalaichelvi, K., Chinnusamy, C., & Swaminathan, A. A. (2006). Exploiting the natural resource-lignite humic acid in agriculture-a review. *Agricultural Reviews*, 27(4), 276-283.
- Khaled, H., & Fawy, H. A. (2011). Effect of different levels of humic acids on the nutrient content, plant growth, and soil properties under conditions of salinity. *Soil and Water Research*, 6(1), 21-29. <https://doi.org/10.17221/4/2010-SWR>
- King, E. O., Ward, M. K., & Raney, D. E. (1954). Two simple media for the demonstration of pyocyanin and fluorescin. *The Journal of Laboratory and Clinical Medicine*, 44(2), 301-307.
- Küster, E., & Williams, S. T. (1964). Selection of media for isolation of *Streptomyces*. *Nature*, 202, 928-929. <https://doi.org/10.1038/202928a0>
- Li, Y., Fang, F., Wei, J., Wu, X., Cui, R., Li, G., Zheng, F., & Tan, D. (2019). Humic acid fertilizer improved soil properties and soil microbial diversity of continuous cropping peanut: A three-year experiment. *Scientific Reports*, 9, 12014. <https://doi.org/10.1038/s41598-019-48620-4>
- Mankotia, S. (2024). Impact of humic acid on various properties of soil and crop productivity: A review. *Journal of Agriculture and Ecology*, 18, 1-6. <https://doi.org/10.58628/JAE-2418-101>
- Marimuthu, S., Anitha, S., Ragupathi, G., Nepolean, P., Mendez, L., Thangaraj, P., & Suganthi, S. (2023). Isolation and in vitro screening of Pink Pigmented Facultative Methylobacterium (PPFMs) isolates for the production of phytohormones and ACC deaminase activity from the tea plantations of South India. *Journal of Plantation Crops*, 51(1), 9-15. <https://doi.org/10.25081/jpc.2023.v51.i1.8467>
- Martin, J. P. (1950). Use of acid, rose bengal, and streptomycin in the plate method for estimating soil fungi. *Soil Science*, 69(3), 215-232. <https://doi.org/10.1097/00010694-195003000-00006>
- Mendez, F. L., Paneerselvam, N., Joseph, B., & Selladurai, R. (2025). Green synthesis of silver nano particles from cymbopogon citratus and their efficacy against grey blight disease of tea. *Journal of Plantation Crops*, 52(2), 26-42. <https://doi.org/10.25081/jpc.2024.v52.i2.9620>
- Monda, H., McKenna, A. M., Fountain, R., & Lamar, R. T. (2021). Bioactivity of humic acids extracted from shale ore: Molecular characterization and structure-activity relationship with tomato plant yield under nutritional stress. *Frontiers in Plant Science*, 12, 660224. <https://doi.org/10.3389/fpls.2021.660224>
- Murphy, J., & Riley, J. P. (1962) A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, 27, 31-36. [https://doi.org/10.1016/S0003-2670\(00\)88444-5](https://doi.org/10.1016/S0003-2670(00)88444-5)
- Nardi, S., Pizzeghello, D., Muscolo, A., & Vianello, A. (2002). Physiological effects of humic substances on higher plants. *Soil Biology and Biochemistry*, 34(11), 1527-1536. [https://doi.org/10.1016/S0038-0717\(02\)00174-8](https://doi.org/10.1016/S0038-0717(02)00174-8)
- Pikovskaya, R. I. (1948). Mobilization of phosphorus in soil in connection with the vital activity of some microbial species. *Microbiology*, 17, 362-370.
- Ponmurugan, P., & Baby, U. I. (2007). Morphological, physiological and biochemical changes in resistant and susceptible cultivars of tea in relation to *Phomopsis* disease. *Plant Pathology Journal*, 6, 91-94. <https://doi.org/10.3923/ppj.2007.91.94>
- Pramanik, P., Safique, S., Jahan, A., & Bhagat, R. M. (2017). Humic substrates application in diluted form enhanced availability of phosphorus (P) and its uptake by tea bushes in the tea-growing soil of Northeast India. *Journal of Plant Nutrition*, 40(20), 2841-2849. <https://doi.org/10.1080/01904167.2017.1383420>
- Rahaman, S. A., & Aruchamy, S. (2022). Land suitability evaluation of tea (*Camellia sinensis* L.) plantation in Kallar watershed of Nilgiri Biosphere Reserve, India. *Geographies*, 2(4), 701-723. <https://doi.org/10.3390/geographies2040043>
- Rajendiran, S., & Purakayastha, T. J. (2014). Effect of humic acid multinutrient complex fertilizers on yield and quality of tomato and potato. *Vegetable Science*, 41(2), 155-159.
- Ruan, J., Gerendás, J., Härdter, R., & Sattelmacher, B. (2007). Effect of nitrogen form and root-zone pH on growth and nitrogen uptake of tea (*Camellia sinensis*) plants. *Annals of Botany*, 99(2), 301-310. <https://doi.org/10.1093/aob/mcl258>
- Schumacker, R., & Tomek, S. (2013). *Understanding Statistics Using R*. Springer. <https://doi.org/10.1007/978-1-4614-6227-9>
- Sui, C., Guan, X., Zhang, W., Zeng, B., Zhang, Q., Luo, L., Hu, L., & Liu, L. (2022). Tea plant growth and soil nutrients in response to the application of fertilizer in Guizhou province, China. *Agronomy Journal*, 114(4), 2011-2020. <https://doi.org/10.1002/agj2.20982>
- Sun, Y., & Zhang, J. (2024). Advances in the application of humic acid in agriculture: impacts on soil fertility, crop growth, and carbon emissions. *International Journal of Public Health and Medical Research*, 2(3), 27-30. <https://doi.org/10.62051/ijphmr.v2n3.05>
- Venkatesan, S., Murugesan, S., Ganapathy, M. N. K., & Verma, D. P. (2004). Long-term impact of nitrogen and potassium fertilizers on yield, soil nutrients and biochemical parameters of tea. *Journal of the Science of Food and Agriculture*, 84(14), 1939-1944. <https://doi.org/10.1002/jsfa.1897>