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Status and distribution of available sulphur in tea-growing soils of Bangladesh

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A B S T R A C T

This study assessed the distribution and fertility status of available sulphur in tea-growing soils of Bangladesh using 132 paired soil samples collected from 13 tea estates at depths of 0-23 cm and 23-46 cm. Available sulphur was determined using a 0.15% calcium chloride extraction, followed by turbidimetric measurement of barium sulphate. Surface soils contained 0.12 to 69.13 mg/kg available sulphur and sub-surface soils contained 0.58 to 61.00 mg/kg, with mean values of 15.61 and 15.47 mg/kg, respectively. Based on critical limits, 44.70% of surface samples and 47.73% of sub-surface samples were in the low category, indicating a widespread risk of sulphur deficiency. Marked estate-wise variation was observed. Bilashcherra Experimental Farm, Karnafuli, Kazi and Kazi, and Karotoa showed comparatively high mean values, whereas Allynugger, Malnicherra, BTRI Farm, and Sathgao remained in the low range. Available sulphur was positively associated with soil pH and organic matter at both depths, and the relationship with organic matter was strongest in the sub-surface layer. Mean sulphur concentration did not differ significantly between the two depths, but the wide within-estate and between-estate variation indicated that blanket fertilizer recommendations would be inefficient. The study provides a baseline for site-specific sulphur management in Bangladesh tea soils.

Keywords: Available sulphur, Tea soil, Soil fertility, Bangladesh, Organic matter

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Introduction

Tea [*Camellia sinensis* (L.) O. Kuntze] is an economically important plantation crop in Bangladesh and continues to contribute to employment, rural livelihoods, and the agro-based economy. Tea cultivation in Bangladesh is concentrated mainly in the established tea-growing regions of Sylhet, Chattogram, and the newer northern tea areas, where soil fertility management remains important because nutrient status varies considerably among locations and estates (Boonerjee *et al.*, 2025; Sadi *et al.*, 2025; Zohora and Biswas, 2025).

Sulphur is an essential secondary macronutrient required for normal plant growth and development. It is involved in the synthesis of sulphur-containing amino acids, proteins, vitamins, enzymes, and other important metabolites, and an inadequate sulphur supply can reduce plant growth and yield. In tea plantations, recent work has further emphasized that available sulphur is an important component of nutrient cycling and should receive greater attention in nutrient management (Narayan *et al.*, 2023; Wang *et al.*, 2025a).

The availability of sulphur in soil is influenced by several interacting factors, especially soil pH, organic matter, and fertilization history. Soil pH can strongly affect nutrient transformation and uptake, as well as tea plant performance, while fertilization strategies can alter rhizosphere soil conditions and tea plant quality. Recent broader analyses of tea plantations have also shown that many tea-growing soils are affected by acidification, nutrient deficiencies, and nutrient imbalances, which together can influence nutrient availability and overall soil fertility (Jia *et al.*, 2024; Miao *et al.*, 2024; Wang *et al.*, 2025b).

In Bangladesh, recent studies have reported acidic soil conditions and variable nutrient status in tea-growing areas, and field surveys have documented visible nutrient deficiency symptoms in commercial tea estates. However, detailed information on the distribution and fertility status of available sulphur in tea-growing soils of Bangladesh remains limited, particularly with respect to estate-wise variation, depth-wise comparisons, and its relationship with soil pH and organic matter. Therefore, the present study was undertaken to determine the available sulphur content of tea-growing soils of Bangladesh, classify soil samples into fertility categories, compare sulphur status between surface and sub-surface soils, and examine the relationship of available sulphur with soil pH and organic matter (Sadi *et al.*, 2025; Zohora and Biswas, 2025).

Materials and Methods

Study area

The study was based on 132 sampling locations from 13 tea estates situated in the major tea-growing districts of Bangladesh, namely Moulvibazar, Sylhet, Chattogram, and Panchagarh. At each location, soil samples were collected from two depths: surface soil (0–23 cm) and sub-surface soil (23–46 cm), giving a total of 264 soil samples. The selected estates represented different physiographic settings, plantation ages, and management conditions, allowing comparison of sulphur status across a broad range of tea-growing environments.

Soil analysis

Soil pH was determined in a 1:2.5 soil: water suspension using the method described by Jackson (1973). Soil organic carbon was determined by the Walkley and Black wet oxidation method, and soil organic matter was estimated from the organic carbon content following the conventional conversion procedure (Walkley and Black, 1934). Available sulphur was extracted with 0.15% calcium chloride and determined turbidimetrically as barium sulphate, following Williams and Steinbergs (1959); turbidity was measured spectrophotometrically at 420 nm.

Statistical analysis

Data were entered and organized in Microsoft Excel (Microsoft 365, Microsoft Corporation, Redmond, WA, USA), and statistical analyses were performed using Minitab 21. Descriptive statistics were computed for each tea estate and for the complete dataset, including sample size, mean, minimum, maximum, median, and standard deviation. Based on available sulphur concentration, soil samples were classified as low (<10 mg/kg), medium (10–20 mg/kg), and high (>20 mg/kg). Pearson's correlation coefficient was used to examine the relationships of available sulphur with soil pH and organic matter content. A paired t-test was used to compare the mean sulphur concentration between surface and sub-surface soils. Statistical significance was assessed at the 5% probability level.

Results and Discussion

Overall sulphur status

Available sulphur in surface soils ranged from 0.12 to 69.13 mg/kg, with a mean of 15.61 mg/kg and a median of 15.00 mg/kg. In sub-surface soils, available sulphur ranged from 0.58 to 61.00 mg/kg, with a mean of 15.47 mg/kg and a median of 11.61 mg/kg. The paired comparison showed no significant difference in overall mean sulphur concentration between the two depths ($p = 0.861$). The wide range of values at both depths indicated marked spatial heterogeneity in sulphur availability across tea-growing soils. This variation likely reflects differences among estates in soil condition, organic matter status, topographic position, drainage, leaching intensity, and fertilizer management. Therefore, the results support estate-specific rather than blanket sulphur management. A recent study in tea soils of Lalmonirhat, Bangladesh, also reported available sulphur in the low-to-moderate range, although with a narrower range than observed in the present multi-estate dataset (Sadi *et al.*, 2025). Broader recent tea-soil analyses likewise show strong spatial variation in nutrient status and pH across tea plantations, driven by the combined influence of climate, location, soil type, elevation, and management (Sadi *et al.*, 2025; Wang *et al.*, 2025b).

Table 1. Estate-wise statistics of available sulphur in surface soils (0-23 cm) of tea estates in Bangladesh.

Tea Estate	No. of samples	Mean (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	SD
Bilashcherra Experimental Farm	21	30.19	25.00	44.00	4.76
Karnafuli	8	25.64	10.74	41.04	10.49
Kazi & Kazi	14	23.14	12.00	31.00	6.00
Karotoa	9	21.33	15.00	29.00	4.87
Neptune	10	15.67	2.44	33.66	10.89
Oodaleah	9	13.77	2.78	69.13	21.12
Patrakhola	5	10.05	3.87	18.46	5.69
Rajghat	9	9.68	1.52	24.44	8.88
Sathgao	10	8.75	1.18	24.85	9.28
Jagcherra	11	7.99	0.80	36.85	11.02
BTRI Farm	5	5.52	0.29	15.84	6.16
Malnicherra	10	4.55	0.74	7.84	2.21
Allynugger	11	3.53	0.12	11.08	3.33

Surface soil sulphur distribution

Surface soil sulphur status varied markedly among estates (Table 1). Bilashcherra Experimental Farm recorded the highest mean surface sulphur concentration (30.19 mg/kg), followed by Karnafuli (25.64 mg/kg), Kazi and Kazi (23.14 mg/kg), and Karotoa (21.33 mg/kg). In contrast, Allynugger (3.53 mg/kg), Malnicherra (4.55 mg/kg), and BTRI Farm (5.52 mg/kg) recorded the lowest mean values, while Jagcherra (7.99 mg/kg), Sathgao (8.75 mg/kg), and Rajghat (9.68 mg/kg) also remained within the low fertility range. Oodaleah showed the widest spread of surface values, including the highest individual observation in the surface dataset (69.13 mg/kg), which indicated marked within-estate heterogeneity.

The estate-wise mean values are shown in Figure 1. The chart confirms that Bilashcherra Experimental Farm maintained the strongest surface and sub-surface sulphur status, whereas Allynugger, Malnicherra, BTRI Farm, Jagcherra, Sathgao, and Rajghat remained in the low range. Similar heterogeneity in available sulphur between estates has been reported in tea-growing areas of India, where local differences in soil acidity, organic carbon status, and garden-level management produced contrasting sulphur classes among gardens and sub-districts (Ghosh *et al.*, 2006; Malakar *et al.*, 2022).

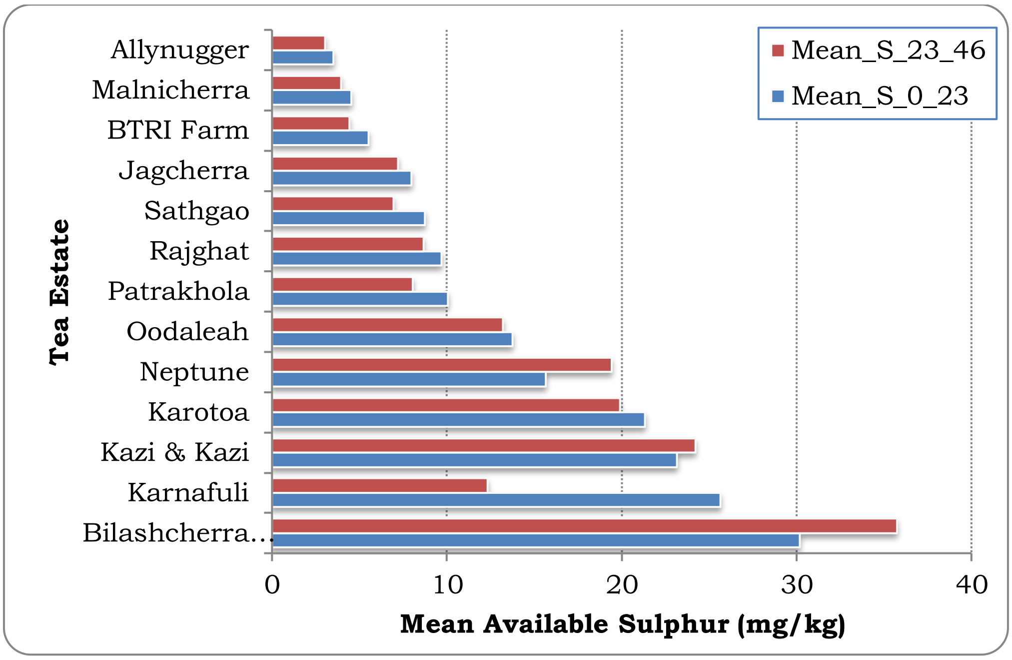

Fig. 1. Mean available sulphur by tea estate at 0-23 cm and 23-46 cm depths.

Sulphur fertility classes by depth

Based on the critical limits used in this study, 59 surface samples (44.70%) were low in available sulphur, 23 were medium (17.42%), and 50 were high (37.88%). In the sub-surface layer, 63 samples (47.73%) were low, 27 (20.45%) were medium, and 42 (31.82%) were high (Figure 2). The predominance of low-class samples at both depths indicates that sulphur deficiency is a widespread concern in tea soils. This pattern is agronomically important because plant-available sulphur occurs mainly as sulphate, which is mobile in soil and susceptible to loss, while a large proportion of soil sulphur is associated with organic matter and becomes available only through mineralization. Under acidic, high-rainfall tea-growing environments, inadequate replenishment can therefore lead to sulphur deficiency (Narayan *et al.*, 2023; Wang *et al.*, 2025a).

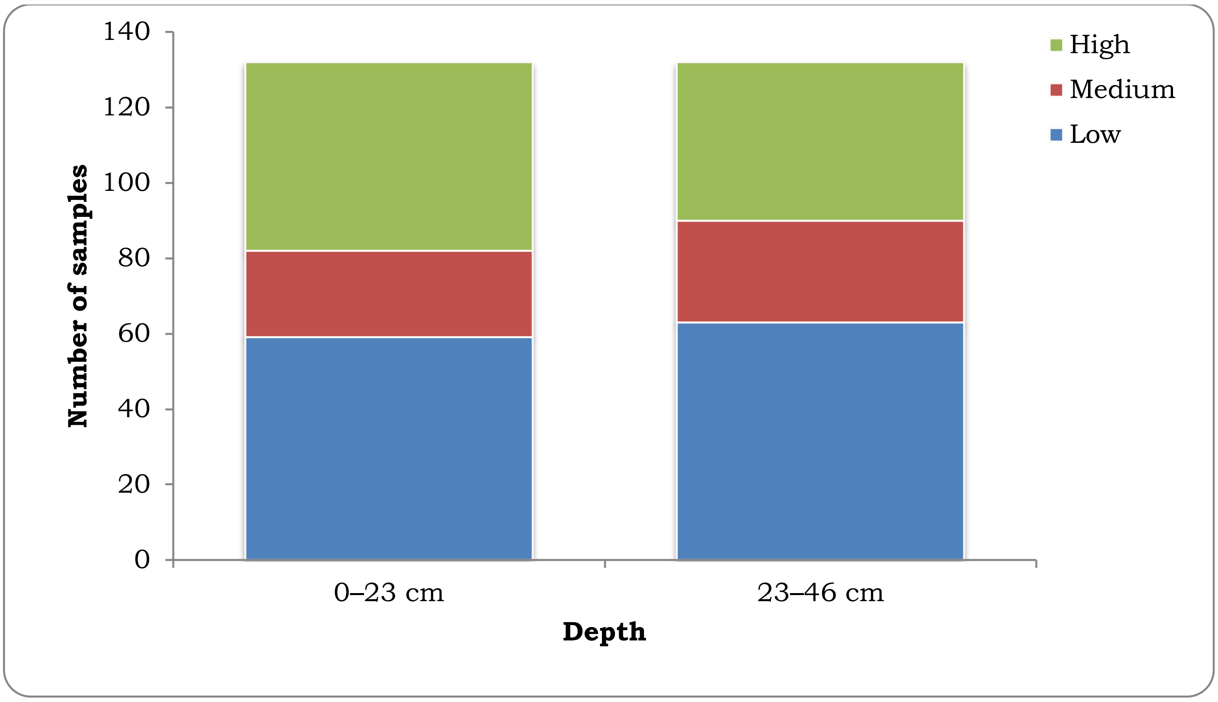

Fig. 2. Sulphur fertility classes by depth for tea-soil samples collected at 0-23 cm and 23-46 cm.

Sub-surface sulphur distribution

Sub-surface sulphur status also varied markedly among tea estates (Table 2). Bilashcherra Experimental Farm recorded the highest mean subsurface sulphur concentration (35.76 mg/kg), and comparatively high values were also observed at Kazi (24.21 mg/kg), Karotoa (19.89 mg/kg), and Neptune (19.42 mg/kg). In contrast, Allynugger (3.03 mg/kg), Malnicherra (3.94 mg/kg), and BTRI Farm (4.43 mg/kg) recorded the lowest mean values, while Jagcherra (7.20 mg/kg), Sathgao (6.97 mg/kg), and Rajghat (8.66 mg/kg) also remained in the low range. Mean sulphur increased with depth in Bilashcherra Experimental Farm, Neptune, and Kazi and Kazi, but declined sharply in Karnafuli, indicating that vertical sulphur distribution in tea soils is estate-specific rather than uniform. Recent work in tea plantations has similarly shown that sulphur availability can vary across sites and environmental gradients rather than following a single, uniform pattern, suggesting that local soil and landscape controls are important in shaping the availability of sulphur (Wang *et al.*, 2025a).

Table 2. Estate-wise statistics of available sulphur in sub-surface soils (23-46 cm) of tea estates in Bangladesh.

Tea Estate	No. of samples	Mean (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	SD
Bilashcherra Experimental Farm	21	35.76	22.00	61.00	9.08
Kazi & Kazi	14	24.21	9.00	35.00	8.25
Karotoa	9	19.89	15.00	26.00	3.79
Neptune	10	19.42	8.46	59.06	16.74
Oodaleah	9	13.20	1.89	30.94	10.76
Karnafuli	8	12.33	3.88	20.97	5.96
Rajghat	9	8.66	1.39	22.45	8.34
Patrakhola	5	8.06	2.57	15.32	4.90
Jagcherra	11	7.20	0.58	33.20	9.83
Sathgao	10	6.97	0.89	20.26	7.56
BTRI Farm	5	4.43	1.35	11.71	4.27
Malnicherra	10	3.94	0.95	6.92	1.93
Allynugger	11	3.03	0.59	9.25	2.54

Relationship of available sulphur with Soil pH and organic matter

Available sulphur showed significant positive relationships with both soil pH and organic matter at the two sampled depths (Table 3). In surface soil, available sulphur was positively related to soil pH ($r = 0.298$, $p < 0.001$; $n = 132$) and organic matter ($r = 0.406$, $p < 0.001$; $n = 132$). In sub-surface soil, the corresponding relationships were $r = 0.354$ ($p < 0.001$; $n = 132$) for soil pH and $r = 0.502$ ($p < 0.001$; $n = 132$) for organic matter. The stronger association with organic matter is agronomically plausible because it serves as a major reservoir of soil sulphur and contributes to sulphate release through mineralization (Scherer, 2009; Islam *et al.*, 2021).

The soil pH trend is illustrated in Figure 3. The relationship was positive at both depths, but the scatter indicates that soil pH influenced sulphur availability without fully determining it. Some estates already maintained adequate or high sulphur status, whereas others remained low at similar soil pH levels. This suggests that soil pH affected sulphur availability, alongside other site-specific controls such as organic matter supply, drainage conditions, and fertilizer history. Recent tea research has shown that soil pH significantly affects nutrient enrichment, plant growth, photosynthetic capacity, and leaf quality, while broader tea-soil analyses have also emphasized the central role of pH in nutrient balance and acidification processes (Jia *et al.*, 2024; Wang *et al.*, 2025b).

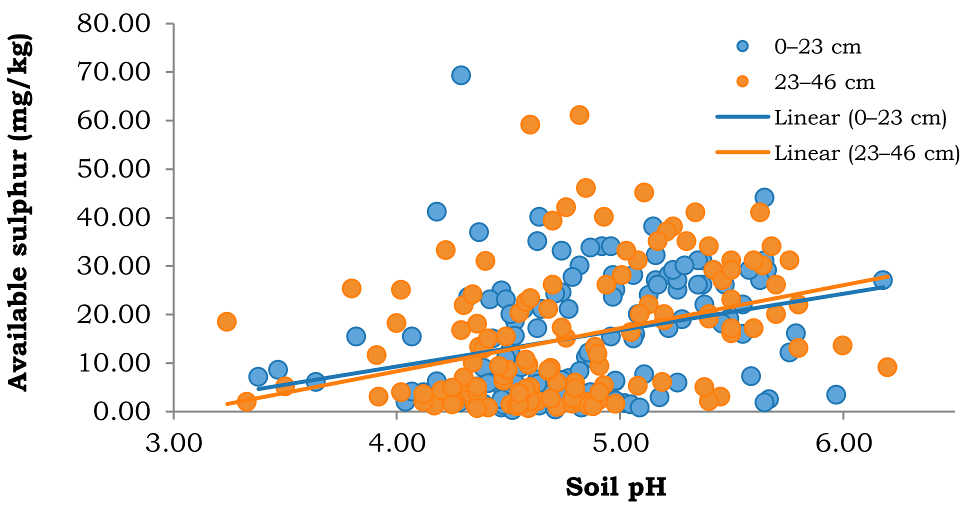

Fig. 3. Relationship between soil pH and available sulphur in tea soils at 0-23 cm and 23-46 cm depths.

The organic-matter trend is shown in Figure 4 and is more clearly positive, especially in the sub-surface layer. This pattern supports the central role of organic matter in storing and gradually releasing sulphur through mineralization. Maintenance of soil organic matter through litter return, management of pruning residues, and the use of organic amendments should therefore improve the resilience of sulphur supply over time (Scherer, 2009; Islam *et al.*, 2021). Recent research on tea fertilization has also shown that combined organic and chemical fertilization significantly increased soil organic matter and soil pH, thereby improving overall soil nutrient quality in tea plantations (Miao *et al.*, 2024; Narayan *et al.*, 2023).

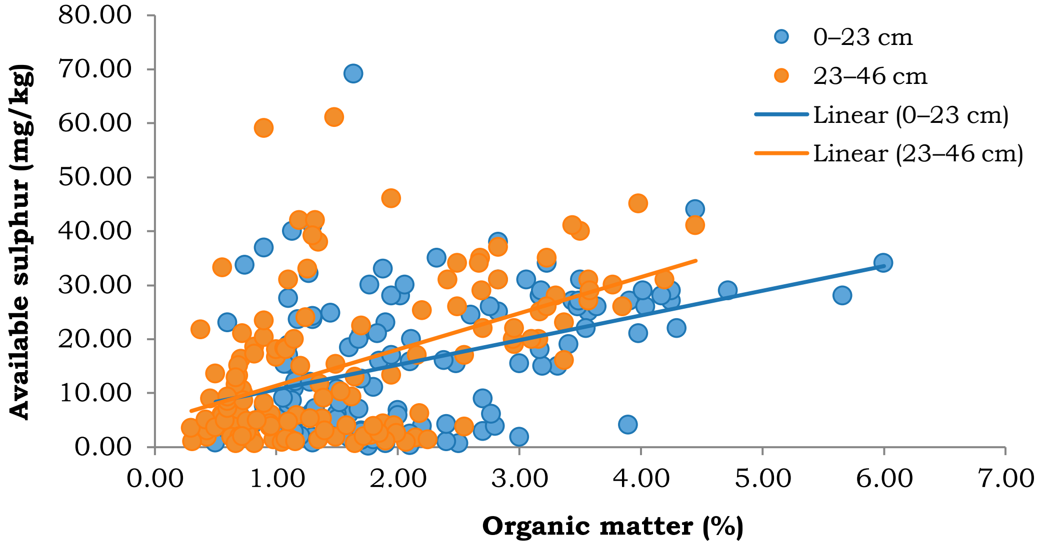

Fig. 4. Relationship between soil organic matter and available sulphur in tea soils at 0-23 cm and 23-46 cm depths.

Table 3. Pearson correlation coefficients of available sulphur with Soil pH and organic matter.

Depth	Variable	n	Pearson r	p-value
0-23 cm	Soil pH	132	0.298	<0.001
0-23 cm	Organic matter	132	0.406	<0.001
23-46 cm	Soil pH	132	0.354	<0.001
23-46 cm	Organic matter	132	0.502	<0.001

Overall, the results showed that sulphur deficiency remained common in tea-growing soils of Bangladesh, but the problem was not uniform. Some estates already maintained adequate or high sulphur status, whereas others fell well below the critical limit at both depths. Regular soil testing, balanced fertilization, and maintenance of soil organic matter should therefore be emphasized in nutrient management programs for tea. The dataset provides a useful baseline for site-specific sulphur fertilization and for improving nutrient stewardship in Bangladesh tea plantations. This interpretation is consistent with recent evidence showing that nutrient management in tea systems should account for local variation in soil condition, acidification, and organic matter status rather than relying on uniform recommendations (Wang *et al.*, 2025b; Miao *et al.*, 2024).

Conclusion

The present study revealed considerable variation in available sulphur among tea estates in Bangladesh, although the overall mean sulphur concentration was very similar between the two sampling depths. Mean available sulphur was 15.61 mg/kg in the 0–23 cm layer and 15.47 mg/kg in the 23–46 cm layer, and the paired t-test indicated that the difference was not statistically significant. A large proportion of samples fell within the low to medium sulphur range, with 44.7% of surface soils and 47.7% of sub-surface soils classified as low in available sulphur, suggesting that sulphur deficiency remains an important concern in many tea soils of Bangladesh. Marked estate-wise variation was observed, with Bilashcherra Experimental Farm, Karnafuli, Kazi & Kazi, and Karotoa showing relatively higher sulphur status, whereas Allynugger, Malnicherra, BTRI Farm, Jagcherra, and Sathgao had comparatively lower values. Available sulphur was positively and significantly related to both soil pH and organic matter at both depths, with the strongest relationship observed between sub-surface sulphur and organic matter. These findings indicate that sulphur availability in tea soils is influenced by both estate-specific conditions and general soil properties. Therefore, regular soil testing and estate-specific sulphur management should be emphasized to maintain balanced soil fertility and support sustainable tea production.

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