

International Journal of Plant & Soil Science

Volume 38, Issue 11, Page 348-355, 2026; Article no.IJPSS.170384
ISSN: 2320-7035

Assessment of Soil and Foliar Potassium Status in Tea (*Camellia sinensis* (L.) Kuntze) Gardens of the Wayanad Central Plateau, Kerala, India

Nila S. Jeevani [a], Kiran Karthik Raj [a*], B. Rani [a], Gowri Priya [a] and Pratheesh P. Gopinath [b]

[a] Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani, Kerala Agricultural University, Thiruvananthapuram, India.
[b] Department of Agricultural Statistics, College of Agriculture, Vellayani, Kerala Agricultural University, Thiruvananthapuram, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i116429

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/170384

Original Research Article

Received: 11/09/2026
Accepted: 13/11/2026
Published: 16/11/2026

Abstract

Aims: To determine ammonium acetate-extractable potassium (K) in surface and subsurface soils and the K concentration in mature tea leaves across the Wayanad Central Plateau, Kerala, India, and to examine their association.
Study Design and Location: A cross-sectional field survey was conducted in November 2025 at 120 georeferenced tea gardens distributed equally across Nenmeni, Ambalavayal, Muttil and Muppainad panchayats in Agro-Ecological Unit 20.
Methods: Soil was sampled at 0–15 and 15–30 cm, with corresponding samples of recently matured third leaves collected at each location. Available soil K was extracted with 1 mol L^{-1} ammonium acetate and determined by flame photometry; leaf K was

**Corresponding Email(s): kiran.kr@kau.in;*

Contact Email(s): nilasjeevani@gmail.com;

Cite as: *Jeevani, N. S., Raj, K. K., Rani, B., Priya, G., & Gopinath, P. P. (2026). Assessment of Soil and Foliar Potassium Status in Tea (Camellia sinensis (L.) Kuntze) Gardens of the Wayanad Central Plateau, Kerala, India. International Journal of Plant & Soil Science, 38(11), 348–355. https://doi.org/10.9734/ijpss/2026/v38i116429*

determined after HNO_3–$HClO_4$ digestion. Descriptive summaries, panchayat-based one-way analysis of variance and Pearson correlation were used to characterise nutrient status.

Results: Surface available K ranged from 67.20 to 179.20 kg ha^{-1} (mean 127.59 kg ha^{-1}), compared with 89.60–224.00 kg ha^{-1} (mean 163.89 kg ha^{-1}) in subsurface samples. Forty per cent of surface samples were below the survey classification boundary of 120 kg ha^{-1}. Mean subsurface K exceeded mean surface K in all four panchayats. Leaf K ranged from 0.70% to 1.10% (mean 0.86%), with the highest panchayat mean in Ambalavayal (0.91%) and the lowest in Muppainad (0.82%). Surface soil K and leaf K were positively correlated ($r = 0.54$, $p < 0.001$, $n = 120$; $r^2 \approx 0.29$).

Conclusion: The results reveal a heterogeneous soil K supply and generally low mature-leaf K concentrations in the surveyed tea gardens. The positive soil–leaf association supports the combined use of soil and foliar analysis to identify gardens requiring closer nutrient management. The contrasting depth pattern provides a basis for targeted investigation of K distribution and the timing of fertiliser applications.

Keywords: Potassium nutrition; tea; Camellia sinensis; lateritic soils; foliar analysis; soil depth; Wayanad.

1. Introduction

Tea (*Camellia sinensis* (L.) Kuntze) is a perennial plantation crop maintained through repeated harvesting of young shoots, a management system that creates sustained demand for mineral nutrients. Potassium contributes to enzyme activation, charge balance, stomatal regulation and assimilate transport and is particularly important in rapidly growing tissues (Marschner, 2012; Wang & Wu, 2013). In tea, nutrient supply is closely linked to vegetative shoot production and the quality of harvested foliage (Hajiboland, 2017; Ranganatha & Natesan, 1985). Reviews of K in tea also connect potassium nutrition with physiological regulation and product quality (Singh & Pathak, 2018).

The soil K pool accessible to plants varies with parent material, the nature of clay minerals, soil reaction, moisture, weathering and management. Tea-growing soils are often acidic and receive substantial rainfall, conditions under which exchangeable cations may be redistributed within the profile (Chandran *et al*., 2005; Hajiboland, 2017). The mineralogical diversity of Kerala's lateritic soils further influences nutrient retention and release. Greeshma *et al*. (2026) documented marked differences among soluble, exchangeable and non-exchangeable K fractions in northern lateritic soils of Kerala, supporting the need to distinguish an immediately extractable soil pool from the total nutrient reserve. A recent comparison of potassium extractants in Indian soils assessed the consistency of plant-available K estimates under field-moist and air-dried conditions (Singh *et al*., 2025).

Recent work in tea-producing landscapes provides a stronger pedological basis for interpreting potassium status across soil horizons. Li *et al*. (2026) compared paired forest and tea-plantation profiles and documented more advanced chemical weathering, altered nutrient distributions and reduced total soil K in the plantation profiles. These findings illustrate how long-term cultivation and geochemical development can modify the size and vertical organisation of potassium pools. Because ammonium acetate extraction characterises only an operationally defined fraction of the soil K continuum, both current extractability and longer-term replenishment from mineral sources are relevant to plantation nutrition. The regional soil-depth survey in Wayanad contributes an important observational baseline for assessing these complementary processes.

Spatial heterogeneity also has an important landscape component. Chen *et al*. (2025) found that slope position was associated with differences in the concentrations of major nutrients, including K, among tea plant organs. In hilly plantation systems, changes in soil depth, erosion, drainage, root development and management can therefore complicate the interpretation of regional fertility averages. Georeferenced sampling at the garden scale is especially valuable because it allows the observed K distribution to be considered alongside the heterogeneity of the cultivated landscape.

Potassium nutrition has practical consequences for tea production. A synthesis of experimental literature found that K fertilisation can improve tea yield and quality, with the magnitude of the response depending on the soil K supply and production conditions (Xi *et al*., 2023). In South Indian tea systems, Verma and Pund (2014) described the importance of maintaining a balanced potassium supply in highly weathered plantation soils. Recent field and greenhouse studies likewise connect balanced fertilisation with changes in tea growth, nutrient concentrations and the soil biological environment (Tang *et al*., 2023; Wei *et al*., 2025). These findings favour diagnosis-based management over a uniform K dose applied irrespective of initial fertility.

Soil and leaf analyses provide related but different information. An ammonium acetate soil test estimates an operationally defined pool of extractable K; the leaf assay integrates nutrient uptake and internal allocation during plant growth. Tea roots also respond to local K availability, and genotypes can differ in their root-foraging responses to heterogeneous soil K (Ruan *et al*., 2022). In a Taiwanese plantation study, Tseng and Lai (2022) showed that foliar elemental composition is shaped by multiple soil characteristics and does not necessarily mirror an individual soil nutrient measurement. The combined assessment is therefore particularly useful when plantations differ in age, management, plant material and topography. Related regional work in Kerala has combined paired soil and mature-leaf measurements to characterise micronutrient status in coconut (Arun *et al*., 2025), while compositional nutrient diagnosis norms supported by machine-learning algorithms have been used to distinguish multiple co-occurring nutrient deficiencies, including K deficiency, in coconut palms (Neeshma *et al*., 2026). Complementary root-level approaches have also been explored in other crops; radiocarbon labelling of root exudates was used to screen soybean genotypes for iron-deficiency tolerance (Raj *et al*., 2020).

Tea-specific physiological investigations further illuminate the connection between soil supply and plant demand. Yang *et al*. (2025) characterised the root-associated potassium transporter CsHAK4 and showed that its expression was induced by potassium deficiency, while functional assays demonstrated its capacity to mediate K uptake. In a separate controlled experiment, Sun *et al*.

(2024) found that potassium supplementation modified photosynthetic performance and ion-related stress responses in tea exposed to excess fluoride. Together, these studies show that potassium nutrition involves dynamic transporter activity and physiological adjustment, beyond the concentration of exchangeable K determined in a routine soil test. The relevance of these processes to plantation nutrition strengthens the value of measurements from both soil and plant tissue.

The Wayanad Central Plateau is an important tea-growing landscape within the humid Western Ghats. The available regional evidence has not comprehensively described K distribution between shallow soil layers in conjunction with mature-leaf K status at the garden scale in Agro-Ecological Unit 20. This study examined 120 tea gardens across four panchayats to (i) quantify the distribution of extractable K at 0–15 and 15–30 cm, (ii) characterise mature-leaf K concentrations and (iii) assess the association between surface soil K and foliar K. The resulting dataset provides a regional diagnostic baseline for more closely targeted nutrient management and agronomic field research. Studies of tea in northeast India have shown that plantation age, fertiliser application and environmental management jointly affect yield, further emphasising the value of recording management history in nutrient surveys (Dutta *et al*., 2010).

2. Materials and Methods

2.1 Study Area and Sampling Design

The field survey was carried out in November 2025 in Agro-Ecological Unit 20 (Wayanad Central Plateau), Kerala, India. Four tea-growing grama panchayats—Nenmeni, Ambalavayal, Muttil and Muppainad—were included. Thirty tea-garden locations were sampled in each panchayat, yielding 120 georeferenced garden-level observations. Surface and subsurface soil samples and mature-leaf samples were associated with the same garden locations. The panchayat was used as the principal geographical grouping factor.

2.2 Soil and Leaf Sampling

At each garden location, soil was collected from two depth intervals: 0–15 cm (surface) and 15–30 cm (subsurface). Samples were air-dried, crushed, passed through a 2-mm sieve and stored in labelled polyethylene bags until chemical analysis. Recently matured third leaves, counted from the shoot apex, were collected at the corresponding locations. The sampling design comprised 120 soil samples at each depth and 120 corresponding leaf samples.

2.3 Potassium Determination

Soil-extractable K was determined using the neutral normal ammonium acetate method: 5 g of air-dried soil was shaken with 25 mL of 1 mol L^{-1} ammonium acetate for 5 min, filtered through Whatman No. 42 filter paper and analysed by flame photometry (Jackson, 1973). Soil K values were expressed in kg ha^{-1}. For the descriptive fertility classification applied in the survey, K values below 120 kg ha^{-1} were assigned to the low category, values from 120 to 240 kg ha^{-1} to the medium category and values above 240 kg ha^{-1} to the high category. These operational boundaries were used consistently for the reported frequency comparisons.

Leaf material was dried and ground, and the samples were digested with an HNO_3–$HClO_4$ di-acid mixture (9:4, v/v). Potassium in the digest was measured by flame photometry and expressed as a percentage of leaf dry matter (Jackson, 1973). Nitric acid and perchloric acid are denoted by HNO_3 and $HClO_4$, respectively; potassium measured by flame photometry is reported as elemental K.

2.4 Statistical Analysis

The dataset was summarised using panchayat means and standard deviations (n = 30 per panchayat), overall means, observed ranges and coefficients of variation. One-way analysis of variance treated panchayat as the grouping factor for each of the three measured variables, using the RAISINS platform (Hisham *et al*., 2025). Table 1 presents the pooled residual coefficient of variation and the standard error of a panchayat mean (SEm). The linear association between surface available K and mature-leaf K was described using Pearson's correlation coefficient across the 120 paired garden-level observations, with a two-sided significance level of 0.05.

3. Results and Discussion

3.1 Distribution of Available Potassium between Soil Depths

Extractable K varied appreciably across sampled gardens. In the 0–15 cm layer, values ranged from 67.20 to 179.20 kg ha^{-1}, with an overall mean of 127.59 kg ha^{-1}. The highest surface mean occurred in Ambalavayal (135.15 kg ha^{-1}), followed by Muttil (131.41 kg ha^{-1}), Muppainad (123.57 kg ha^{-1}) and Nenmeni (120.21 kg ha^{-1}). On the survey's predefined scale, 40% of surface observations were below 120 kg ha^{-1}, corresponding to 48 of 120 gardens. None of the measured surface values exceeded 240 kg ha^{-1}.

Subsurface K ranged from 89.60 to 224.00 kg ha^{-1} and had an overall mean of 163.89 kg ha^{-1}. Panchayat means were 173.97 kg ha^{-1} in Ambalavayal, 167.63 kg ha^{-1} in Muttil, 160.53 kg ha^{-1} in Muppainad and 153.44 kg ha^{-1} in Nenmeni. In every panchayat, the subsurface mean exceeded the corresponding surface mean, with an overall difference of 36.30 kg ha^{-1}. The two layers nevertheless showed overlapping ranges, indicating that the depth pattern was not uniform at every garden.

The individual panchayat means and their standard deviations, together with the overall summaries and pooled within-panchayat variation statistics, are given in Table 1. The table establishes the regional range against which subsequent leaf K observations and soil–leaf associations can be interpreted.

Table 1. Available potassium in surface and subsurface soils and potassium concentration in mature tea leaves in four panchayats of Agro-Ecological Unit 20, Wayanad

Panchayat	Surface K, 0–15 cm (kg ha^{-1})	Subsurface K, 15–30 cm (kg ha^{-1})	Leaf K (%)
Nenmeni	120.21 ± 35.16	153.44 ± 35.07	0.85 ± 0.13
Ambalavayal	135.15 ± 33.53	173.97 ± 32.18	0.91 ± 0.13
Muttil	131.41 ± 31.67	167.63 ± 28.74	0.87 ± 0.13
Muppainad	123.57 ± 35.11	160.53 ± 33.96	0.82 ± 0.11
Overall mean	127.59	163.89	0.86
Range	67.20-179.20	89.60-224.00	0.70 - 1.10
Pooled CV (%)	26.57	19.88	14.31
SEm	6.19	5.95	0.02

Values for each panchayat are mean ± SD (n = 30 gardens). CV, pooled residual coefficient of variation from the panchayat-based ANOVA; SEm, standard error of a panchayat mean. Ranges represent observed individual values across all sampled gardens

The higher mean extractable K at 15–30 cm is a notable feature of the surveyed tea soils. Potential contributors include downward redistribution with percolating water, differences in fertiliser placement and uptake, and inherent variation in soil mineralogy and exchange capacity. In highly weathered soils of Kerala, the mineral assemblage and degree of pedogenic development influence K retention and release (Chandran *et al*., 2005). The fractionation study by Greeshma *et al*. (2026) similarly illustrates that extractable K forms represent only part of a larger soil K system. Thus, the depth contrast provides a useful basis for studying nutrient supply in the root environment rather than a direct estimate of K leaching losses.

A comparison with recent soil-profile research underscores the distinction between extractable K and total reserves. Li *et al*. (2026) documented weathering-linked nutrient redistribution in forest-to-tea land-use transitions, including reductions in soil total K. The availability of K to a tea bush is controlled not only by the concentration in one horizon but also by exchange reactions, mineral replenishment and access to a moist root zone. Consequently, the higher extractable K measured in the Wayanad subsurface could reflect several interacting soil processes. It identifies a vertical distribution that deserves consideration in nutrient diagnosis, particularly when surface tests are interpreted as indicators of the broader rooting environment.

Interpretation of depth differences also depends on the perennial root system. Tea plants can respond to patchy potassium distribution by altering root proliferation and nutrient acquisition processes (Ruan *et al*., 2022). Root development, litter distribution, nutrient return through pruning and the placement of fertilisers may generate marked soil heterogeneity, even among neighbouring plantations. Accordingly, the observed surface deficiency class identifies sites where further soil and foliar monitoring is especially relevant, while the subsurface K pool may have different accessibility depending on rooting depth and soil moisture.

The same regional pattern may also contain smaller-scale topographic contrasts. In the field investigation by Chen *et al*. (2025), potassium allocation to tea tissues differed significantly among upper, middle and lower slope positions, demonstrating that landscape position can be relevant to plant nutrient status. The observed differences among Wayanad panchayat means should thus be understood as averages of potentially diverse garden conditions rather than homogeneous fertility signatures of the administrative units. Linking georeferenced soil and leaf results with slope position, soil profile characteristics and plantation management would make future nutrient maps more informative for locally targeted intervention.

3.2 Potassium Concentration in Mature Leaves

Leaf K concentrations ranged from 0.70% to 1.10% across the 120 samples, with an overall mean of 0.86%. Mean concentrations were 0.91% in Ambalavayal, 0.87% in Muttil, 0.85% in Nenmeni and 0.82% in Muppainad. The within-panchayat SD ranged from 0.11 to 0.13 percentage points, while the pooled residual CV was 14.31%. This narrower proportional variability in leaf K than in surface soil K suggests a partially buffered relationship between soil nutrient extraction and plant nutrient concentrations.

The mean foliar concentration of 0.86% lies slightly above the 0.8% adult-leaf threshold discussed in the tea potassium review of Huang *et al*. (2022), although several values fell below this boundary. Other tea nutrition literature reports considerably higher sufficiency ranges, including approximately 1.5–2.0% for the tissue standard discussed by Tseng and Lai (2022). Differences in leaf position, tissue age, cultivar, growth stage and production system affect the transferability of numerical thresholds. The observed low mature-leaf K values are therefore most appropriately interpreted as a strong diagnostic signal for further nutrition assessment, rather than as a direct measure of yield loss or a uniform fertiliser requirement.

Plantation age is another important context for leaf-based diagnosis. Zhang *et al*. (2026) examined tea stands of different ages and found that mature-leaf mineral concentrations, including K, varied with stand age alongside changes in rhizosphere soil properties. This finding is particularly pertinent when survey samples are collected from working plantations that may differ in bush maturity and pruning history. In the Wayanad survey, the between-panchayat range in mean leaf K was comparatively narrow (0.82–0.91%), whereas individual measurements spanned 0.70–1.10%. A standard leaf position and consistent sampling season therefore improve comparability, and combined interpretation of leaf K with garden-level soil supply offers a more meaningful basis for identifying nutritional priorities than a single regional mean.

Potassium is important for osmotic regulation, carbohydrate transport and water relations, functions that are central to the continuous production of harvestable tea shoots (Wang & Wu, 2013). Earlier South Indian tea research summarised benefits of balanced K nutrition for crop growth and stress responses under lateritic-soil conditions (Verma & Pund, 2014), while a broader

synthesis of tea fertiliser trials documented a positive response of tea production and quality to appropriate K application (Xi *et al*., 2023). The mature-leaf results from Wayanad identify where such responses may merit direct local testing.

The physiological importance of K extends to responses under environmental stress. Sun *et al*. (2024) observed that K supply improved selected photosynthetic and antioxidant responses of tea plants experimentally exposed to fluoride stress, while Yang *et al*. (2025) linked a tea-root K transporter with ion homeostasis under potassium deficiency and salinity treatments. These studies provide complementary mechanistic evidence for the importance of sufficient potassium uptake. The Wayanad leaf measurements are valuable because they define the nutritional status encountered in cultivated gardens, while controlled physiological studies explain why persistent shortages of accessible K may matter for shoot production and plant resilience.

Fig. 1 compares soil K means at the two depths with mature-leaf K means for the same four panchayats. Both panels follow the panchayat ordering in Table 1, illustrating the relatively consistent depth contrast and the smaller spread of leaf K means.

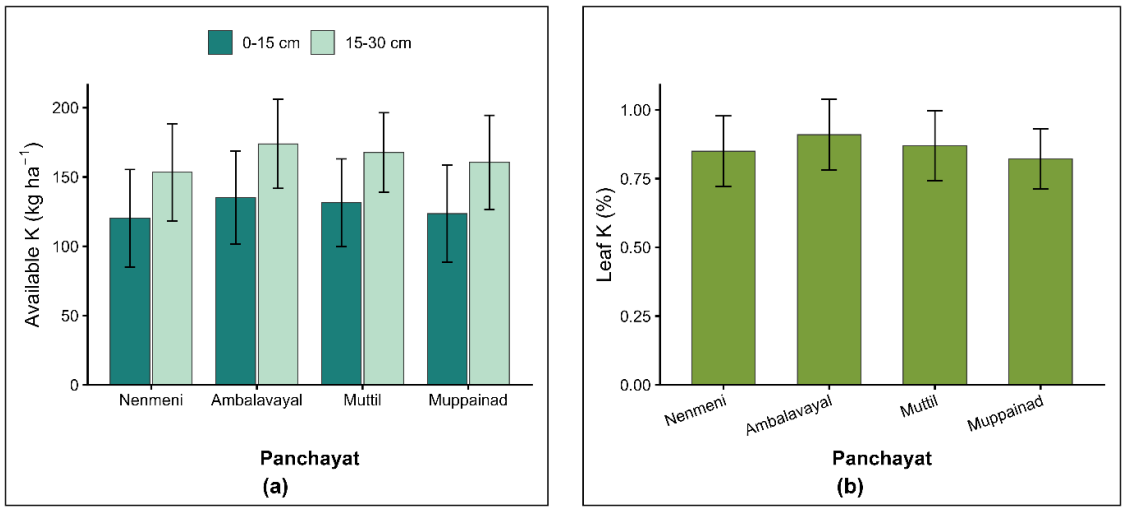


Fig. 1. Mean (a) extractable soil K at 0–15 and 15–30 cm (kg ha^{-1}) and (b) mature-leaf K concentration (%) across four panchayats of Agro-Ecological Unit 20, Wayanad. Error bars show variation around the displayed group means

3.3 Relationship between Surface Soil K and Foliar K

The correlation between garden-level surface extractable K and mature-leaf K was positive and moderate ($r = 0.54$, $p < 0.001$; $n = 120$). Squaring the reported coefficient gives $r^2 \approx 0.29$, indicating that the fitted bivariate linear association accounted for approximately 29% of the observed variation in leaf K. Soil K and leaf K thus moved in the same general direction across the sampled gardens, while a substantial proportion of the variation in foliar K was associated with other sources of heterogeneity.

The strength of this relationship is agronomically plausible. The soil test characterises the K readily extracted under standard laboratory conditions, whereas plant K status integrates root access to water and nutrients, uptake dynamics, allocation among tissues and management effects. Experiments in tea demonstrate root-foraging responses to spatially variable K supply (Ruan *et al*., 2022), and studies of tea plantation nutrient stocks identify plant age and genotype among the factors that influence the distribution of nutrients within the perennial crop (Kamau *et al*., 2008). Soil–leaf concordance is consequently useful for screening nutritional status without assuming a direct one-to-one conversion between a soil test result and leaf K concentration.

Biological regulation of uptake contributes to the imperfect correspondence between the soil and leaf tests. The root-foraging responses described by Ruan *et al*. (2022) indicate that tea plants can explore non-uniform K sources, and Yang *et al*. (2025) demonstrated that the expression of a root K transporter responds to nutrient stress. Zhang *et al*. (2026) additionally identified variation in mature-leaf mineral accumulation across stand ages. These independent findings identify plausible sources of variation in plant K beyond the concentration extracted from surface soil. They also help explain why a moderate positive association can provide a useful screening relationship without making leaf K predictable from one soil measurement alone.

The relationship is shown in Fig. 2, in which the individual garden observations, fitted linear trend and uncertainty band display the positive association and the dispersion around it. The scatterplot reinforces the practical value of interpreting soil and foliar tests together for individual gardens.

3.4 Implications for Potassium Management

The combination of a sizeable low-K surface-soil group and generally low mature-leaf K concentrations suggests that garden-specific monitoring can improve the prioritisation of nutrient management. Surface extractable K alone is not a complete assessment of soil nutrient reserves, and the higher 15–30 cm values indicate the importance of depth when interpreting sampling results.

Repeated soil tests at consistent depths, paired with leaf sampling at a standard tissue stage, would provide more reliable information on changes in K status than either measure used in isolation.

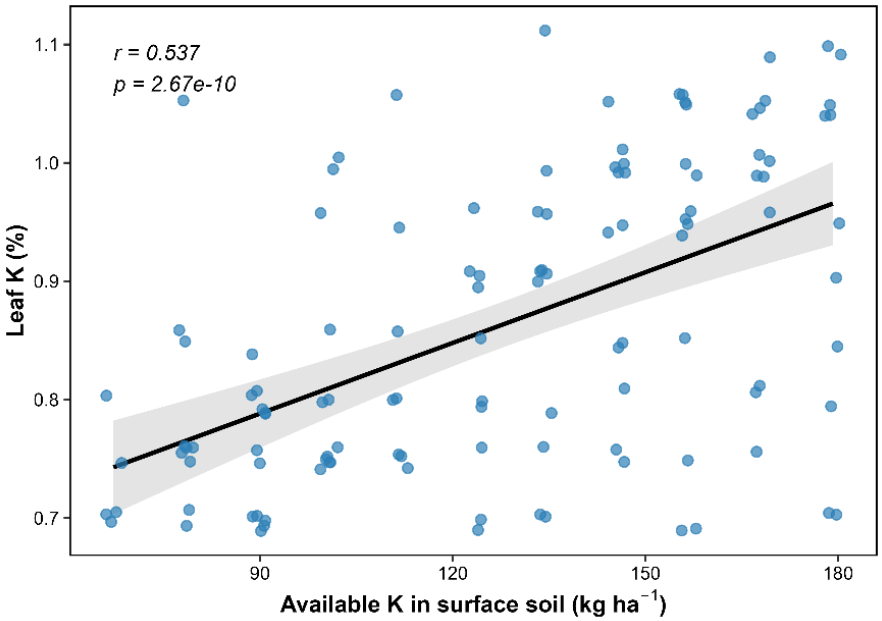


Fig. 2. Relationship between available K in surface soil (0–15 cm; kg ha⁻¹) and mature-leaf K concentration (%) at 120 tea-garden locations in Agro-Ecological Unit 20, Wayanad. Pearson r = 0.54 (p < 0.001); the solid line indicates the fitted linear trend, with a shaded uncertainty band

Evidence from fertiliser trials provides context for management options. The meta-analysis of Xi *et al*. (2023) associated potassium fertilisation with higher tea yield and quality across a range of experimental settings. More broadly, a synthesis of fertilisation studies found that application frequency can influence tea yield and bud development under varying cultivation conditions (Yu *et al*., 2025). Earlier South Indian experience also highlighted the value of coordinating potassium with nitrogen and other nutrients in plantation systems (Ranganatha & Natesan, 1985; Verma & Pund, 2014). Comparable soil-test-based targeted-yield nutrient prescriptions have also been evaluated for groundnut in the southern lateritic soils of Kerala (Karthu *et al*., 2025). These findings support locally calibrated, balanced K programmes and trials comparing the timing and distribution of potassium applications rather than a single uniform field prescription.

The sustainability of potassium supply also depends on interactions among soil nutrient pools and biological processes. In a pot experiment involving tea, Wei *et al*. (2025) found increased soil available K and leaf K when mineral nutrient sources were combined with a plant growth-promoting bacterial inoculant and biochar. Such approaches provide experimental directions for nutrient-mobilisation research, but plantation-scale applicability depends on soil properties, management and economic feasibility. In Wayanad, the practical sequence is to identify K-limited gardens with paired soil–leaf evidence and then test fertiliser schedules or alternative nutrient strategies under local field conditions.

Management needs to consider the wider tea rhizosphere, not only the dose of mineral potassium. Jiang *et al*. (2024) compared fertilisation systems in tea and found associated differences in root exudate metabolites, microbial indicators and rhizosphere properties. Together with the tea nutrient-amendment experiment of Wei *et al*. (2025), this work suggests that the biological and physical environment of the root zone can modify the effectiveness of nutrient inputs. For high-rainfall tea gardens, comparisons of soil-test-guided K rates, application timing and placement can be combined with measurements of soil reaction, leaf K and harvested-shoot yield. Such an integrated field approach would connect the regional K baseline to agronomic benefits while recognising differences among individual plantations.

4. Limitations of the Study

This single-season observational survey describes K status at sampled tea gardens in November 2025 and does not resolve seasonal variation, plantation-wide sampling representativeness or causal processes underlying the soil-depth pattern. Soil pH, texture, cation-exchange capacity, K fractions, fertiliser history, crop genotype, bush age, leaf yield and direct K-leaching fluxes were not included in the reported dataset. Soil K values expressed per hectare depend on the soil mass or depth conversion adopted for the soil test, and the 120/240 kg ha⁻¹ descriptive boundaries are not interchangeable with all local advisory rating systems. Foliar diagnostic thresholds also depend on tissue stage and reference population. The reported grouped statistical summaries and the correlation characterise broad patterns, while raw paired observations and complete model diagnostics would allow more detailed evaluation of depth differences and garden-level nutrient responses.

5. Conclusion

The tea gardens surveyed across the Wayanad Central Plateau exhibited substantial heterogeneity in available soil potassium and a consistent tendency towards higher extractable K in the 15–30 cm layer than in the 0–15 cm layer. Mean surface K was 127.59 kg ha^{-1}, and 40% of surface samples fell below the survey's 120 kg ha^{-1} boundary. Mature-leaf K averaged 0.86%, with values ranging from 0.70% to 1.10%. A moderate positive correlation (r = 0.54) linked surface soil K with leaf K across the 120 gardens. These findings establish a regional baseline for integrated soil and foliar potassium diagnosis and identify a practical basis for prioritising site-specific fertiliser evaluation. Further field studies can determine how soil K distribution, seasonal nutrient uptake and potassium application schedules influence tea growth and productivity under Wayanad conditions.

Acknowledgements

The authors acknowledge the Department of Soil Science and Agricultural Chemistry, Kerala Agricultural University, for providing laboratory infrastructure and logistical support for the field survey.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

The authors declare no known competing financial or non-financial interests that could have influenced the work reported in this study.

References

Arun, E. V., Raj, K. K., Rani, B., Leno, N., Gopinath, P. P., & Nisha, M. S. (2025). Soil and plant molybdenum status in coconut palms of the Southern Coastal Plain (AEU 1), Kerala, India. *International Journal of Plant & Soil Science, 37*(12), 248–256. https://doi.org/10.9734/ijpss/2025/v37i125889

Chandran, P., Ray, S. K., Bhattacharyya, T., Srivastava, P., Krishnan, P., & Pal, D. K. (2005). Lateritic soils of Kerala, India: Their mineralogy, genesis, and taxonomy. *Australian Journal of Soil Research, 43*(7), 839–852. https://doi.org/10.1071/SR04128

Chen, L., Chen, Y., & Ao, J. (2025). Tea plantation slope position modulates nutrient and heavy metal allocation in tea plant organs: Implications for health risks and sustainable plantation management. *Frontiers in Agronomy, 7*, Article 1670025. https://doi.org/10.3389/fagro.2025.1670025

Dutta, R., Stein, A., Smaling, E. M. A., Bhagat, R. M., & Hazarika, M. (2010). Effects of plant age and environmental and management factors on tea yield in northeast India. *Agronomy Journal, 102*(4), 1290–1301. https://doi.org/10.2134/agronj2010.0091

Greeshma, R., Binitha, N. K., & Nideesh, P. (2026). Assessment of potassium fractions in the northern laterite soils of Kerala: Mediated by influence of potassium solubilising fungi and insoluble potassium sources. *Asian Journal of Soil Science and Plant Nutrition, 12*(1), 312–320. https://doi.org/10.9734/ajsspn/2026/v12i1661

Hajiboland, R. (2017). Environmental and nutritional requirements for tea cultivation. *Folia Horticulturae, 29*(2), 199–220. https://doi.org/10.1515/fhort-2017-0019

Hisham, M. M., Chandran, J., & Gopinath, P. P. (2025). RAISINS: Integrating R and AI for agricultural data analysis. *Journal of Sustainable Technology in Agriculture, 1*(1). https://doi.org/10.5281/zenodo.15622128

Huang, W., Lin, M., Liao, J., Li, A., Tsewang, W., Chen, X., Sun, B., Liu, S., & Zheng, P. (2022). Effects of potassium deficiency on the growth of tea (*Camelia sinensis*) and strategies for optimizing potassium levels in soil: A critical review. *Horticulturae, 8*(7), Article 660. https://doi.org/10.3390/horticulturae8070660

Jackson, M. L. (1973). *Soil chemical analysis*. Prentice-Hall of India. https://spices.res.in/opac/cgi-bin/koha/opac-detail.pl?biblionumber=179

Jiang, Y., Lin, X., Wang, H., Muhammad, W., Xu, Y., & Lin, W. (2024). Evaluation of fertilization on microbial assembly, metabolites of root exudates and rhizosphere soil in tea plant. *Scientia Horticulturae, 338*, Article 113812. https://doi.org/10.1016/j.scienta.2024.113812

Kamau, D. M., Spiertz, J. H. J., & Oenema, O. (2008). Carbon and nutrient stocks of tea plantations differing in age, genotype and plant population density. *Plant and Soil, 307*(1–2), 29–39. https://doi.org/10.1007/s11104-008-9576-6

Karthu, P. V., Visveswaran, S., Rani, B., & Raj, K. K. (2025). Nutrient management for targeted yield for the groundnut crop in lateritic soils. *Journal of Scientific Research and Reports, 31*(5), 327–335. https://doi.org/10.9734/jsrr/2025/v31i53031

Li, N., Shen, B., Bassiony, A., Liu, Y., Li, J., & Ruan, L. (2026). Soil weathering and nutrient dynamics in response to land-use change following forest conversion to tea plantations. *Plants, 15*(5), Article 747. https://doi.org/10.3390/plants15050747

Marschner, P. (Ed.). (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Neeshma, N., Raj, K. K., Gopinath, P. P., Rani, B., Leno, N., Visveswaran, S., & Fairoosa, F. K. T. (2026). Disambiguation of multiple nutrient deficiency stresses in coconut using compositional nutrient diagnostic norms powered by machine learning algorithms. *Scientific Reports, 16*, Article 13713. https://doi.org/10.1038/s41598-026-40501-x

Raj, K. K., Pandey, R. N., Singh, B., Talukdar, A., Meena, M. C., & Chobhe, K. A. (2020). Evidences for the use of ^{14}C content in the root exudates as a novel application of radiocarbon labelling for screening iron deficiency tolerance of soybean (*Glycine max* (L.) Merr.) genotypes. *Journal of Radioanalytical and Nuclear Chemistry, 326*(1), 487–496. https://doi.org/10.1007/s10967-020-07284-5

Ranganatha, V., & Natesan, S. (1985). Potassium nutrition of tea. In R. D. Munson (Ed.), *Potassium in agriculture* (pp. 981–1022). American Society of Agronomy. https://doi.org/10.2134/1985.potassium.c42

Ruan, L., Cheng, H., Ludewig, U., Li, J., & Chang, S. X. (2022). Root foraging strategy improves the adaptability of tea plants (*Camellia sinensis* L.) to soil potassium heterogeneity. *International Journal of Molecular Sciences, 23*(15), Article 8585. https://doi.org/10.3390/ijms23158585

Singh, A. K., & Pathak, S. K. (2018). Potassium in tea (*Camellia sinensis* (L) O. Kuntze) cultivation from soil to cup quality: A review. *Agricultural Reviews, 39*(1), 40–47. https://doi.org/10.18805/ag.R-1731

Singh, H., Barman, M., Das, D., Rao, K. K., Sarkar, D., Raj, K. K., Sharma, V. K., & Das, T. K. (2025). Identifying optimal extractants for plant-available potassium that remain effective despite soil moisture fluctuations. *Journal of Soil Science and Plant Nutrition, 25*(4), 8496–8511. https://doi.org/10.1007/s42729-025-02646-y

Sun, Y., Wu, Z., Xing, A., Zhang, H., Xu, X., Gong, Z., Zhao, Z., Liu, S., Chen, X., Li, X., & Wang, Y. (2024). Potassium alleviates fluoride accumulation and enhances fluoride tolerance in *Camellia sinensis*. *Industrial Crops and Products, 219*, Article 119062. https://doi.org/10.1016/j.indcrop.2024.119062

Tang, S., Zhou, J., Pan, W., Sun, T., Liu, M., Tang, R., Li, Z., Ma, Q., & Wu, L. (2023). Effects of combined application of nitrogen, phosphorus, and potassium fertilizers on tea (*Camellia sinensis*) growth and fungal community. *Applied Soil Ecology, 181*, Article 104661. https://doi.org/10.1016/j.apsoil.2022.104661

Tseng, W.-Y., & Lai, H.-Y. (2022). Comprehensive analysis revealed the specific soil properties and foliar elements respond to the quality composition levels of tea (*Camellia sinensis* L.). *Agronomy, 12*(3), Article 670. https://doi.org/10.3390/agronomy12030670

Verma, D. P., & Pund, S. A. (2014). Potassium—the key nutrient for tea grown in latosols of south India: Glimpses of seven decades of potassium research. *International Journal of Tea Science, 10*(1–2), 41–52. https://doi.org/10.20425/ijts.v10i1and2.4779

Wang, Y., & Wu, W.-H. (2013). Potassium transport and signaling in higher plants. *Annual Review of Plant Biology, 64*, 451–476. https://doi.org/10.1146/annurev-arplant-050312-120153

Wei, W., Li, K., Li, C., Wang, S., Li, L., Xie, J., Li, T., Zhou, Z., Zhang, S., & Wang, G. (2025). Enhancing soil phosphorus and potassium availability in tea plantation: The role of biochar, PGPR, and phosphorus- and potassium-bearing minerals. *Agronomy, 15*(6), Article 1287. https://doi.org/10.3390/agronomy15061287

Xi, S., Chu, H., Zhou, Z., Li, T., Zhang, S., Xu, X., Pu, Y., Wang, G., Jia, Y., & Liu, X. (2023). Effect of potassium fertilizer on tea yield and quality: A meta-analysis. *European Journal of Agronomy, 144*, Article 126767. https://doi.org/10.1016/j.eja.2023.126767

Yang, Q., Gao, S., Zhao, X., Lian, X., Xie, Y., Lu, X., Zhang, Y., Qi, S., Yang, Y., & Yang, T. (2025). Over-expression of CsHAK4 from tea plant (*Camellia sinensis* L.) negatively regulates high salt tolerance in transgenic *Arabidopsis*. *Plant Science, 360*, Article 112734. https://doi.org/10.1016/j.plantsci.2025.112734

Yu, Y., Wang, J., Lou, R., Wu, W., Wang, Z., Jiang, Q., Wang, Y., & Zhou, J. (2025). Optimizing fertilization under varying cultivation conditions: Insights from a meta-analysis on tea yield and quality. *Journal of Environmental Management, 392*, Article 126808. https://doi.org/10.1016/j.jenvman.2025.126808

Zhang, M., Wang, Y., Li, Q., Wang, Q., Ma, S., Jia, X., Zhang, Q., & Ye, J. (2026). Influence of tea stand age on leaf biochemical components, mineral elements, and rhizosphere soil properties in Wuyi Rougui (*Camellia sinensis* (L.) Kuntze). *Horticulturae, 12*(2), Article 217. https://doi.org/10.3390/horticulturae12020217

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/170384