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GENETIC DIVERSITY OF INDONESIAN TEA (*CAMELLIA SINENSIS* VAR. SINENSIS) CLONES IN RELATION TO MACRONUTRIENT UPTAKE AND GREEN TEA SENSORY QUALITY

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SUMMARY

Developing superior clones is crucial in boosting the market competitiveness of Indonesian green tea (*Camellia sinensis* L.). However, tea yield and quality mostly sustain influences from temperature, rainfall, and nutrient availability. In the following study, 35 clones of *C. sinensis* tea underwent assessment for genetic diversity, yield stability, and taste quality under different fertilization conditions at the Research Institute for Tea and Cinchona and the Research Center for Appropriate Technology, Bandung, Indonesia. The field experiment used a randomized block design with three replications. Genetic diversity analysis used the principal component analysis (PCA), with the leaf yield stability analyzed utilizing parametric and non-parametric measurements and flavor quality probed using a t-test. The tea clones revealed the highest genetic diversity for agro-morphological traits. In general, all clones have the same quality according to sensory evaluation. Clones I.1.93, II.4.149, and S3 have an NUE greater than 50%. After fertilization, the nitrogen and potassium levels in the tea plant leaves increased by 0.12% and 0.07%, respectively, while phosphorus decreased by 0.01%. Among the clones, 22 increased in nitrogen, 24 decreased in phosphorus, and 28 clones increased in potassium. Notably, nine clones maintained stable pekoe leaf yields across both fertilized and unfertilized conditions.

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Keywords: Tea (*C. sinensis* L.), selection, leaf yield, dry appearance, liquor color, taste quality, leaf nutrient levels

Key findings: The tea (*C. sinensis* L.) clones showed significant genetic diversity based on agro-morphological traits. Leaf nitrogen and potassium levels increased by 0.12% and 0.07%, respectively, while phosphorus decreased by 0.01%. Nine promising tea clones consistently performed better both under fertilized and unfertilized conditions.

INTRODUCTION

Tea (*Camellia sinensis* L.) is a widely consumed beverage worldwide, primarily cultivated in tropical and subtropical regions with acidic soils (pH 4.0–5.5), including major producers like Indonesia and China (Tang *et al.,* 2020; Prayoga *et al.,* 2020). The individual consumption globally of processed tea leaves reached 0.8 kg/year; therefore, increasing and improving tea production is highly crucial (Zaman *et al.,* 2022). A type of tea that is quite popular globally is green tea. For the past five years, green tea production in the world has increased by 4.21%. Hence, it is necessary to use clones with good taste based on sensory evaluation to improve the quality of green tea in Indonesia (Prayoga *et al.,* 2022).

Tea productivity and quality largely depend on environmental factors and nutrient availability. As a leaf-harvested crop, tea requires balanced macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), to support leaf development and metabolite synthesis. Nitrogen enhances leaf yield (Sitienei *et al.,* 2013), phosphorus affects quality and mineral uptake (Ding *et al.,* 2017), and potassium improves the flavor and biochemical content (Ruan *et al.,* 2013). Therefore, efficient and flexible fertilization is essential due to seasonal nutrient shifts. Unbalanced nutrients reduced the growth and leaf quality, making nutrient uptake efficiency (NUE) and optimized N application crucial (Wang *et al.,* 2020).

Genetic diversity among tea clones plays a pivotal role in determining their adaptability to environmental stressors and their potential for enhancing product quality. In several studies, genetic diversity is critical in the selection process, where broad genetic diversity makes the selection process more effective (Jolliffe, 2002; Maulana *et al.,* 2023). Tadeo *et al.* (2023) revealed that extensive genetic diversity can be applicable to developing unique tea clones. The best clones can be outcomes from exploiting genetic variations of the clones tested. Recent research underscores the importance of comprehensively understanding tea clones' genetic diversity to improve quality and productivity. By identifying superior clones with desirable taste characteristics and nutrient efficiency, the industry can secure its market position and mitigate the impact of environmental challenges. Therefore, conducting thorough investigations into tea clones' genetic variability and performance across diverse conditions is vital because most previous research in Indonesia only focused on productivity alone (Prayoga *et al.,* 2021).

In the presented study, in collaboration with the Research Institute for Tea and Cinchona and the National Research and Innovation Agency, Indonesia, evaluating 35 Indonesian Sinensis clones helped identify the superior, nutrient-efficient, and high-yielding genotypes for sustainable tea cultivation. Through the examination of agro-morphological traits and nutrient profiles, the study sought to detect clones with superior qualities and stable yields under various fertilization regimes. The anticipated findings from this study will offer invaluable insights into the genetic diversity and nutrient efficiency of Indonesian tea clones, thereby contributing significantly to the advancement of sustainable cultivation practices and the enduring success of the Indonesian tea industry.

Table 1. List of 35 Sinensis tested clones.

No.	Clones	Code	No.	Clones	Code
1	I.1.70	T1	19	II.3.16	T19
2	I.1.93	T2	20	II.3.38	T20
3	I.1.100	T3	21	II.4.149	T21
4	I.1.101	T4	22	II.4.32	T22
5	I.2.34	T5	23	II.4.178	T23
6	I.2.45	T6	24	R1	T24
7	I.2.85	T7	25	R3	T25
8	I.2.188	T8	26	S1	T26
9	I.4.113	T9	27	S2	T27
10	II.1.3	T10	28	S3	T28
11	II.1.32	T11	29	SGMBA	T29
12	II.1.38	T12	30	Yabukita	T30
13	II.1.60	T13	31	GMBS 1	T31
14	II.1.76	T14	32	GMBS 2	T32
15	II.1.98	T15	33	GMBS 3	T33
16	II.2.43	T16	34	GMBS 4	T34
17	II.2.108	T17	35	GMBS 5	T35
18	II.2.146	T18			

MATERIALS AND METHODS

The latest research comprises three main phases: green tea processing, sensory evaluation, and nutrient uptake efficiency. The experiment commenced at the Research Institute for Tea and Cinchona (RITC), Bandung, West Java, Indonesia (RITC, 2006). The breeding material comprised 35 clones of Sinensis tea procured from the RITC germplasm. All the clones originated from Pasir Sarongge, Cianjur District, West Java, Indonesia, except the clone Yabukita, which was introduced from Japan (Table 1).

Green tea processing

Green tea processing continued using steaming. As many as 500 g of p+3 shoots (pekoe + three leaves, harvested manually) sustained steaming at ~200 °C for five minutes under four bar pressure. The steamed buds underwent air-drying for one hour, then pan-drying at 100 °C for 14 minutes. The leaves' rolling manually took 15 minutes before finally drying them using a tray dryer (mesh 14: 1.4 mm wire holes) at 100 °C for 30 minutes (Prayoga *et al.,* 2021).

Nutrient uptake efficiency (NUE)

Nutrient uptake efficiency evaluation constituted comparing leaf yield before and after fertilization. The plucking time range was 60 days after fertilization. The plucking succeeded with a professional using pruning shears. The fertilizer dosage applied was according to the Tea Plant Cultivation Technical Manual, with 250 kg/ha urea (N), 60 kg/ha TSP (P_2O_5), and 60 kg/ha ZK (K_2O) applied per plant (Jolliffe, 2002). The nutrient uptake efficiency calculation followed the method of Prayoga *et al.* (2020):

$$\mathrm{NUE} = \frac{\mathrm{Ydf} - \mathrm{Yef}}{\mathrm{F}} \mathrm{x} 100\%$$

Where NUE = the nutrient uptake efficiency (%), Ydf = the yield after fertilization (kg/ha), Yef = the yield before fertilization (kg/ha), and F = the weight of applied fertilizers (kg/ha).

Moreover, the N, P, and K content of the tea plants acquired testing in the leaves before and after fertilization. The analysis of the N, P, and K content of leaves used the titrimetry method, referring to the Technical Instructions for Chemical Analysis of Soil, Plants, Water, and Fertilizers (Institute ISR, 2009).

Sensory evaluation

Three expert panelists performed sensory evaluation following the Indonesian National Standard SNI 3945:2016. Brewing two grams of tea from 35 clones used 100 ml of boiling water at 96 °C–98 °C before leaving for 10 minutes, following Prayoga *et al.* (2022). Then, separating the tea solution from the infused leaf followed. Evaluated parameters included dry appearance (1–5), liquor color (1–5), taste (21–49), aroma (1–5), and infused leaf (1–5). The total taste properties entailed calculation based on the formula according to Prayoga *et al.* (2021), as follows:

$$TVGT = (VDA \times 3) + (VLC \times 3) + (VT \times 1) + (VA \times 2) + (VIL \times 2)$$

Where TVGT = the total value of green tea, VDA = the value of dry appearance, VLC = the value of liquor color, VT = the value of taste, VA = the value of aroma, and VIL = the value of infused leaf.

TVGT score classification was according to the following categories: < 50 = baddest, 50–59 = bad, 60–69 = fair, 70–79 = good, 80–89 = premium, and 90–99 = special.

Antioxidant activity testing used the radical scavenging activity (RSA) method, where measurements employed the DPPH (2,2-diphenyl-1-picrylhydrazyl) based on Al-Obaidi and Sahib (2015).

Statistical analysis

The breeding material comprised 35 clones of Sinensis tea procured from the RITC germplasm. This research proceeded in a randomized complete block design with three replications. The principal component analysis (PCA) engaged the Past3 software (Norwegia) and examined the relationships among 35 tea clones based on quality, nutrient uptake efficiency (NUE), and leaf yield. Data scrutiny employed the analysis of variance (ANOVA) and Tukey's HSD test (5%) with PKBT Stat 3.1 (Indonesia). Nutrient content differences before and after fertilization underwent testing using a t-test (5%) in SPSS 16.0 (United States of America).

The parametric and non-parametric stability models served for identifying stable tea clones. For linear regression, the study followed the Eberhart and Russell (1966) model, with stability as shown by the regression slope (*bi*) of 1 and a variance deviation (S^2di) of 0. The mean-variance component (θi) and GE variance component ($\theta_{(i)}$) estimates employed Plaisted and Peterson (1959) and Plaisted (1960), respectively. Wricke's ecovalence (Wi^2), Shukla's stability variance, and coefficient of variation (CVi) relied on Wricke (1962), Shukla (1972), and Francis and Kannenberg (1978), respectively.

Non-parametric stability (S [i]) followed the approach of Nassar and Huhn (1987); NP(i) was from Thennarasu (1995), with Kang's KR based on Kang (1988). Yield and stability variances incurred equal weighing (1) to identify the high-yielding and stable tea clones. STABILITYSOFT was the program used for the analysis (Pour-Aboughadareh *et al.,* 2019). The tea clones' grouping utilized the dendrogram from stability rankings.

RESULTS

Genetic variation in clones

The beneficial study examines the relationship among the leaf yield, antioxidant activity, organoleptic traits, and NUE of tea clones using the principal component analysis (PCA). Table 2 presents the eigenvalues of all the tested tea parameters. Only the components with eigenvalues ≥ 1 were useful, as explained by the significant cumulative variation (Maulana *et al.,* 2023).

The first five principal components (PCs) explained 76.72% of the total variation among 35 tea clones (Table 2). The PCA revealed PC1 (24.27%) as influenced by the total value (TV), PC2 (19.58%) by inhibition and AA, PC3 (14.03%) by multiple traits, PC4 (9.81%) by NUE, and PC5 (9.04%) by leaf yield. These findings identified the traits driving genetic diversity among the tea clones.

The PCA biplot showed the relationships among the traits (Figure 1). The antioxidant active (AA) and inhibition, stem diameter (ST) and plant height (PH), and

Table 2. Trait values influencing the diversity of 35 tea clones.

Traits	PC1	PC2	PC3	PC4	PC5
Leaf yield	0.026	0.033	0.196	-0.336	**0.578**
Nutrient uptake efficiency (NUE)	-0.099	0.009	-0.055	**0.762**	-0.101
Inhibition	-0.158	**0.502**	-0.314	-0.040	-0.114
Antioxidant activity (AA)	-0.158	**0.502**	-0.315	-0.040	-0.114
Dry appearance (DA)	0.150	0.156	-0.445	0.158	**0.473**
Liquor color (LC)	0.381	0.026	0.118	0.320	0.097
Taste	0.434	0.137	-0.062	-0.175	-0.328
Aroma	0.387	-0.202	-0.033	-0.110	-0.305
Infused leaf (IL)	0.364	0.247	-0.038	-0.010	0.327
Total value (TV)	**0.540**	0.105	-0.102	0.024	-0.091
Plant height (PH)	-0.008	0.428	0.444	0.003	-0.204
Stem diameter (ST)	-0.019	0.385	**0.467**	-0.047	0.010
Number of branch (NB)	0.096	0.082	0.342	0.361	0.198
Eigenvalue	3.155	2.545	1.824	1.275	1.175
Variability (%)	24.267	19.576	14.033	9.807	9.038
Cumulative (%)	24.267	43.843	57.876	67.683	76.721

PC = principal component; Numbers in bold indicate a discriminant of > 0.5 or < 0.5 that contributed to the variance.

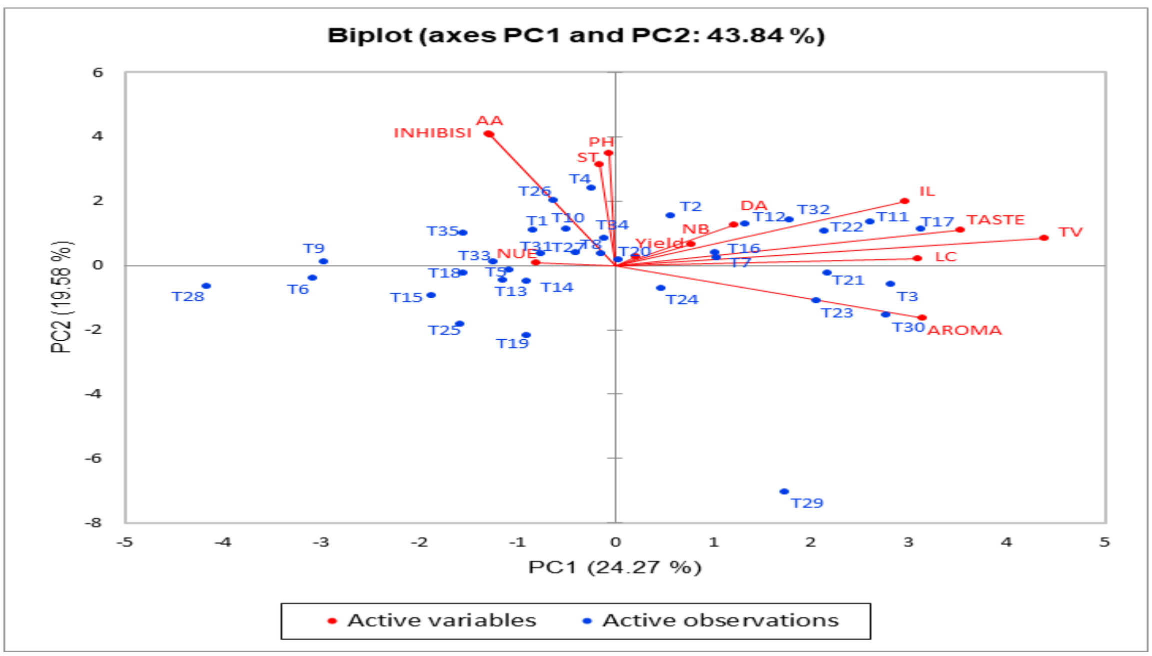

Figure 1. Principal component analysis (PCA) biplot of 35 tea clones based on agro-morphological traits. For tea clones code, see Table 1, and for trait codes, see Table 5.

dry appearance (DA) and infused leaf (IL) have significant positive correlations, as shown by sharp vector angles. Other considerable links include IL-taste, taste-TV, TV-LC, and LC-aroma. Clones T3, T22, T23, and T24 were close to the trait of aroma, indicating the highest aroma. The tea clone T21 lies near LC, suggesting high AA. Other groupings were T30 (TV), T11 (taste), T12 and T32 (IL), T2 and T7 (DA), T20 and T27 (AA/inhibition), and T10 (NUE). Tea clones opposite a trait vector were likely to have low values for the said trait.

Table 3. Analysis of variance for 35 Sinensis tea clones and t-test of nutrient content in the leaves.

Characters	F_{count}	F_{table} 5%	F_{table} 1%	CV (%)
Quality parameters				
Dry appearance	1.87*	1.6	1.95	5.97
Liquor color	3.32**	1.6	1.95	7.44
Taste	1.08ns	1.6	1.95	6.04
Aroma	1.30ns	1.6	1.95	9.28
Infused leaf	1.32ns	1.6	1.95	3.63
Total Value	1.58ns	1.6	1.95	4.21
Nutrient uptake efficiency				
Weight per hectare (F0)	2.26**	1.6	1.95	27.00
Weight per hectare (F1)	1.53ns	1.6	1.95	23.13
The difference in weight per hectare (F1-F0)	8.73**	1.6	1.95	38.13
Average Weight per hectare	1.69*	1.6	1.95	24.54
NUE	8.73**	1.6	1.95	38.13
t-test of nutrient content in leaves				
Nutrient	t_{count}	t_{table}	Mean	SD
Nitrogen (N) (%)	3.23*	2.03	-0.12	0.21
Phosphorus (P) (%)	2.16*	2.03	0.01	0.17
Potassium (K) (%)	4.33*	2.03	-0.07	0.09

* = significantly different at $P < 0.05$, ** = significantly different at $P < 0.01$, ns = not significantly different, CV = coefficient of variation, F0 = Before fertilization application, F1 = After fertilization application.

Nutrient uptake efficiency

The analysis of variance showed significant ($P \leq 0.01$) differences among the 35 *C. sinensis* clones for weight per hectare before and after fertilization, as well as the nutrient uptake efficiency (NUE) (Table 3). Among the tea clones, the average yield per hectare also differed substantially ($P \leq 0.05$). Tukey's HSD test confirmed notable differences in weight change and NUE (Table 5). Clone I.1.93 excelled all other clones with the highest values for weight gain (237.18 kg/ha) and NUE (64.10%).

Plant leaf nutrient analysis displayed significant variations in macronutrients such as nitrogen, phosphorus, and potassium levels (Table 3). On average, nitrogen and potassium increased by 0.12% and 0.07%, respectively, while phosphorus decreased by 0.01%, and the t-test confirmed these trends (Table 5). According to the leaf analysis, nitrogen enhancement succeeded in 22 tea clones, phosphorus decline resulted in 24 clones, and a rise in potassium occurred in 28 clones. The results suggested more efficient absorption of nitrogen and potassium than phosphorus in the tested tea clones.

Tea leaf yield under different conditions

Leaf yield stability refers to a clone's ability to perform consistently across diverse environments. Stability analysis assesses the genotype by environment interactions and determines that a clone is broadly stable or specifically adapted (Pour-Aboughadareh *et al.,* 2022). This study used various parametric and non-parametric models to identify the tea clones with the highest and most stable leaf yields under fertilized and non-fertilized conditions.

Evaluating tea clone leaf yield consistency used the following methods. Cluster analysis, as shown in the dendrogram (Figure 2), grouped the tea clones based on stability rankings. Clones with similar ratings achieved clustering together. However, the dendrogram revealed four groups, i.e., unstable-medium yield (blue), unstable-low yield (green), stable-high yield (red), and stable-medium yield (yellow).

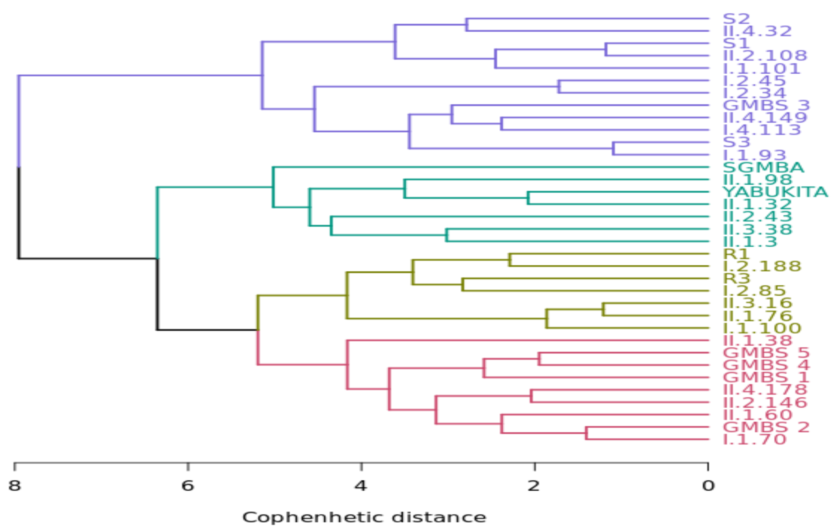

Figure 2. Dendrogram for grouping Sinensis tea clones based on leaf yield under two different conditions.

Sensory evaluation

The application of N, P, and K had a nonsignificant effect on taste, aroma, infused leaf, and overall quality (Table 3); however, they affected the dry appearance and liquor color. Based on Tukey's HSD test, tea clones II.1.60 and Yabukita significantly differed for dry appearance, with scores of 3.27 (1-5) and 4.03 (1-5), respectively (Table 4). Several tea clones, including clone Yabukita, showed notably better liquor color (4.13–4.40, bright greenish-yellow), while clone I.2.45 scored 4.03 (reddish yellow/fairly bright). Clone Yabukita was superior for both traits of dry appearance and liquor color and had a premium taste score of 83.00.

DISCUSSION

The principal component analysis (PCA) served to analyze the genetic variations among the tea clones based on agro-morphological traits. This method helps classify the genotypes and identify the traits and reduces the variables to support selection (Jolliffe, 2002; Maulana *et al.,* 2022, 2023). Principal components (PCs) with eigenvalues ≥ 1 explained 76.72% of the total variation (Table 2).

The five PCs captured the key trait variations. High contribution values, especially PC1, were evident with trait loadings > 0.5 (Table 5), indicating significant genetic influence, reflecting distinct agro-morphological abilities in each clone (Maulana *et al.,* 2023). This supports findings that PC1 > 0.5 implies a dominant genetic control (Bouargalne *et al.,* 2022). The PCA plot also revealed trait correlations, and the acute vector angles indicated significant positive relationships, and obtuse angles expressed negative relationships (Maxiselly *et al.,* 2024).

Among the 35 tea clones, the traits of dry appearance and liquor color varied significantly. In general, dry appearance and liquor color attained great influences from chlorophyll, which is the green substance in leaves that influences the manifestation of dry appearance and liquor color (Ošťádalová *et al*., 2015). Clone Yabukita showed the highest adaptation to fertilization and scored the topmost values for dry appearance, liquor color, and taste (83.00 points). Steaming likely enhanced these traits, aligning with practices in Japanese tea production (Ikeda, 2018; Prayoga *et al.,* 2023). Since soil fertility is manageable, good agricultural practices support climate adaptation. Evidence-based strategies and resilient breeding can help

Table 4. Average value of green tea quality parameters in 35 Sinensis tea clones.

Clones	Dry appearance	Liquor color	Taste	Aroma	Infused leaf	Total value
I.1.70	4.00	3.50	40.00	4.00	4.17	78.83
I.1.93	3.90	3.93	40.33	4.13	4.27	80.63
I.1.100	3.73	4.40	41.67	4.00	4.27	82.60
I.1.101	3.77	3.77	39.67	4.03	4.23	78.80
I.2.34	3.57	3.70	40.00	4.03	4.13	78.13
I.2.45	3.73	3.07	39.33	3.67	4.13	75.33
I.2.85	3.93	3.67	41.00	4.43	4.20	81.07
1.2.188	3.93	3.53	40.00	4.00	4.27	78.93
I.4.113	3.93	3.63	38.00	3.80	4.03	76.37
II.1.3	3.67	3.73	40.67	4.13	4.10	79.33
II.1.32	3.87	4.13	42.33	4.17	4.33	83.33
II.1.38	3.77	4.20	41.00	4.17	4.23	81.70
II.1.60	3.27	3.67	41.33	4.17	4.00	78.47
II.1.76	3.50	4.17	38.33	4.17	4.07	77.80
II.1.98	3.97	3.67	38.00	3.90	4.13	76.97
II.2.43	3.73	4.13	40.00	4.40	4.23	80.87
II.2.108	3.93	4.03	43.67	4.17	4.33	84.57
II.2.146	3.90	3.90	37.67	3.80	4.20	77.07
II.3.16	3.50	3.60	38.67	4.00	4.23	76.43
II.3.38	3.63	3.63	40.67	4.03	4.33	79.20
II.4.149	3.97	4.37	40.33	4.10	4.33	82.20
II.4.32	3.57	4.03	41.33	4.33	4.30	81.40
II.4.178	3.77	4.23	40.00	4.17	4.33	81.00
R1	3.83	3.77	40.67	4.00	4.23	79.93
R3	3.67	4.00	36.67	4.00	4.17	76.00
S1	4.00	3.47	39.33	3.70	4.37	77.87
S2	3.70	3.57	41.00	4.13	4.17	79.40
S3	3.53	3.50	38.00	3.43	4.07	74.10
SGMBA	3.70	3.67	40.67	4.67	4.03	80.17
Yabukita	4.03	4.23	41.00	4.33	4.27	83.00
GMBS 1	3.93	3.67	40.00	3.93	4.13	78.93
GMBS 2	3.90	4.03	42.33	3.87	4.33	82.53
GMBS 3	3.67	4.00	39.67	3.67	4.07	78.13
GMBS 4	3.93	3.77	40.00	4.03	4.20	79.57
GMBS 5	3.77	3.93	39.00	3.67	4.20	77.83
HSD 5%	0.77	0.97	-	-	-	-
Avrage	3.78	3.84	40.07	4.04	4.20	79.39
Minimum	3.27	3.07	36.67	3.43	4.00	74.10
Maximum	4.03	4.40	43.67	4.67	4.37	84.57

Numbers followed by the same letter are not significantly different at HSD = 5%.

maintain quality in stressed conditions (Ahmed *et al.,* 2019).

Nitrogen uptake efficiency improved post-fertilization, indicating better absorption and reduced excess. Adequate macronutrient availability enhanced growth and quality. In Japan, over 500 kg/ha of nitrogen boosts amino acids for better flavor; however, its overuse risks acidification and pollution (Ikeda, 2018). Mitigation includes controlled-release fertilizers, inhibitors, and biochar for higher pH and efficiency (Wang *et al.,* 2020).

Phosphorus uptake declined, while potassium incurred enhancement, with a similar trend observed in past studies (Li *et al.*, 2015). Their opposing efficiency reflects different plant responses. Though low phosphorus may not limit plant growth, its role in fertility and quality remains vital. Low phosphorus (P) availability can affect tea

Table 5. Nutrient uptake efficiency (NUE) and nutrient content in the leaves of 35 Sinensis tea clones.

Clones	Weight (kg ha^{-1})				NUE (%)	Nitrogen Content (%)		Phosphorus Content (%)		Potassium Content (%)	
	F0	F1	Difference	Average		F0	F1	F0	F1	F0	F1
I.1.70	464.90	559.35	94.44	512.13	25.53	2.79	2.98	0.157	0.149	0.643	0.684
I.1.93	237.47	474.64	237.18	356.05	64.10	2.48	3.10*	0.116	0.129	0.604	0.788*
I.1.100	461.69	505.04	43.35	483.36	11.72	3.26	3.37*	0.185	0.147*	0.656	0.667*
I.1.101	429.13	468.18	39.06	448.65	10.56	3.32	3.08	0.143	0.143	0.688	0.848*
I.2.34	294.67	310.53	15.87	302.60	4.29	2.82	2.77	0.156	0.134*	0.877	0.853
I.2.45	301.75	314.64	12.89	308.20	3.48	2.97	2.78	0.144	0.139*	0.757	0.658
I.2.85	398.90	463.38	64.48	431.14	17.43	2.66	2.86*	0.152	0.145*	0.775	0.775
1.2.188	471.61	535.00	63.40	503.30	17.14	3.20	3.13	0.197	0.164*	0.710	0.854*
I.4.113	303.81	487.41	183.61	395.61	49.62	2.48	2.77*	0.146	0.162	0.879	0.948*
II.1.3	293.39	353.75	60.37	323.58	16.31	2.30	2.59*	0.125	0.152	0.842	0.753
II.1.32	286.99	350.34	63.35	318.67	17.12	2.65	2.74*	0.149	0.121*	0.727	0.747*
II.1.38	379.38	472.67	93.29	426.02	25.21	2.84	2.97*	0.147	0.134*	0.667	0.718*
II.1.60	419.52	503.50	83.99	461.51	22.70[f]	2.94	3.15*	0.160	0.148*	0.702	0.801*
II.1.76	506.52	559.16	52.63	532.84	14.23	3.04	3.02	0.158	0.143*	0.714	0.761*
II.1.98	314.72	384.43	69.71	349.58	18.84	2.83	2.83	0.148	0.136*	0.665	0.683*
II.2.43	313.08	426.13	113.05	369.61	30.55	2.61	2.88*	0.139	0.151	0.626	0.631*
II.2.108	414.52	428.97	14.44	421.75	3.90	3.01	2.88	0.145	0.131*	0.725	0.759*
II.2.146	453.55	529.27	75.71	491.41	20.46	2.70	2.85*	0.134	0.132*	0.656	0.686*
II.3.16	513.19	559.58	46.40	536.39	12.54	2.66	2.86*	0.152	0.135*	0.892	0.955*
II.3.38	226.97	344.25	117.28	285.61	31.70	2.45	2.42	0.134	0.151	0.601	0.795*
II.4.149	259.35	458.45	199.09	358.90	53.81	2.51	2.79*	0.127	0.132	0.664	0.784*
II.4.32	370.72	422.47	51.75	396.60	13.99	2.74	2.89*	0.151	0.136*	0.836	0.915*
II.4.178	540.03	610.90	70.86	575.46	19.16	2.97	2.98*	0.165	0.164*	0.675	0.742*
R1	434.56	488.75	54.19	461.66	14.64	2.64	2.78*	0.127	0.145	0.583	0.677*
R3	368.03	437.13	69.09	402.58	18.67	2.98	2.88	0.180	0.151*	0.702	0.845*
S1	396.87	413.53	16.65	405.20	4.50	2.74	2.56	0.188	0.145*	0.990	1.090*
S2	378.96	493.04	114.08	436.00	30.83	2.66	2.93*	0.143	0.141*	0.806	0.764
S3	267.37	484.78	217.41	376.08	58.76	2.33	3.13*	0.157	0.145*	0.897	1.230*
SGMBA	314.02	391.24	77.21	352.63	20.87	2.81	2.77	0.166	0.161*	0.673	0.740*
YABUKITA	251.46	357.71	106.25	304.58	28.72	3.09	3.17*	0.182	0.169*	0.638	0.653*
GMBS 1	448.23	546.26	98.03	497.25	26.50	2.83	2.96*	0.148	0.138*	0.607	0.797*
GMBS 2	468.77	559.58	90.82	514.18	24.54	2.89	2.80	0.131	0.129*	0.626	0.702*
GMBS 3	253.43	459.00	205.57	356.22	55.56	2.57	2.85*	0.146	0.145*	0.735	0.863*
GMBS 4	406.59	495.83	89.25	451.21	24.12	2.85	2.97*	0.142	0.156	0.589	0.784*
GMBS 5	382.02	465.37	83.36	423.70	22.53	2.76	2.94*	0.132	0.153	0.775	0.642
HSD 5%	341.18	-	114.2	346.83	30.87	-	-	-	-	-	
Average	372.18	460.41	88.23	416.29	23.85	2.782	2.898	0.116	0.151	0.144	-0.006
Minimum	226.97	310.53	12.89	285.61	3.48	2.300	2.420	-0.240	0.116	0.121	-0.043
Maximum	540.03	610.90	237.18	575.46	64.10	3.320	3.370	0.800	0.197	0.169	0.027

Numbers followed by the same letter are not significantly different at HSD = 5%. F0 = Before fertilization application, F1 = After fertilization application, NUE = Nutrient uptake efficiency, * = significant increase in nitrogen and potassium, a significant decrease in phosphorus.

genotypes both physiologically and biochemically. Phosphorus plays a key role in energy metabolism, root development, and the synthesis of nucleic acids and secondary metabolites. Its deficiency reduces shoot growth, nutrient uptake, and the accumulation of quality-related compounds, such as catechins and theaflavins (Zhang *et al.,* 2023). Potassium influences leaf yield and quality, depending on the soil potassium content. A mixed-effects model revealed that quality depends upon applied and available K, while leaf yield gained more influences from tea genotype types (Xi *et al.,* 2023). Nutrient impact on secondary metabolism varies regionally, emphasizing tailored nutrient management. The availability and type of nutrients significantly influence secondary metabolic activity in tea plants, particularly impacting the production of quality compounds like catechins and tannins. Specifically, macronutrients like N, P, and K are crucial in tea plant growth and the synthesis of these desirable metabolites (Luo *et al.,* 2024).

Leaf yield per hectare varied among the 35 clones, as affected by fertilization being a major yield driver (Tabu *et al.,* 2015). Being a quantitative trait, leaf yield reflects gene-environment interactions. Nutrients support the growth of young tea shoots by increasing photosynthesis, protein synthesis, and energy transport. Phenotypic expression includes environmental variation (Stansfield, 1991). Rahadi *et al.'s* (2016) findings revealed the yield-related diversity ranging from 27.77% *to* 51.83% coefficient of variation. Similarly, shoot weight attained alterations by the PCA in Sri Lankan tea clones (Kottawa-Arachchi *et al.,* 2017).

Parametric and non-parametric analysis grouped the tea clones into four dendrogram-based clusters, i.e., unstable medium yield (blue), unstable low yield (green), stable high yield (red), and stable medium yield (yellow) (Figure 2). This approach effectively identified the promising barley genotypes (Vaezi *et al.,* 2019) and has also been applicable in crops like rice, soybean, and sweet potato (Wijaya *et al.,* 2022; Utami *et al.,* 2023; Maulana *et al.,* 2022). The tea clones in the red cluster showed promise for stable leaf yields under various conditions, while the tea clones in the green cluster performed poorly. Therefore, unstable tea clones may require environment-specific development strategies.

CONCLUSIONS

Tea clones displayed broad agro-morphological diversity. In general, all clones have the same quality in terms of taste value. Clones I.1.93, II.4.149, and S3 have an NUE greater than 50%. Leaf analysis showed that macronutrients, such as nitrogen and potassium, increased, while phosphorus decreased in the leaves.

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