STABILITY AND PHENOTYPIC PERFORMANCE OF 16 TEA CLONES (*Camellia sinensis* var. *assamica*) ACROSS TWO ENVIRONMENTS DURING THE VEGETATIVE PHASE

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ABSRACT

Tea (*Camellia sinensis* var. *assamica*) is a vital commodity in Indonesia as a raw material for the beverage industry, making early-stage clone screening essential. This study aimed to investigate the stability of growth components and characterize the morphological phenotypic performance of selected tea clones during the vegetative phase. Conducted at the Malabar (West Java) and Semugih (Central Java) plantations from December 2025 to April 2026, the experiment utilized a Randomized Complete Block Design (RCBD) with 16 treatments (15 candidate clones and one check clone, GMB 7) in three replications. Data were analysed using combined ANOVA, Tukey's HSD test (α=5%), and Principal Component Analysis (PCA). Results revealed significant genotype-by-environment (GxE) interactions for plant height and stem diameter at 3 months after planting (MAP), with variations predominantly driven by environmental factors. Clone II.13.2 was significantly shorter than GMB 7 at 3 MAP, while the stem diameters of clones TPS 93/3, TPS 87/2, II.32.15, TPS 87/1, II.6.10, and III.22.15 showed no significant difference compared to the check. Dendrogram analysis placed GMB 7 in a distinct cluster, indicating the candidate clones possess unique vegetative characteristics. Vegetative phase useful for early selection and these potential clones warrant further evaluation for future variety release.

Key words: Phenotypic stability, Tea clones, Vegetative phase.

INTRODUCTION

The tea plant (Camellia sinensis (L) O. Kuntze) is a species originating from subtropical regions, imported by the Dutch since 1684, and is currently cultivated under the ownership of state-owned enterprises, private estates, and smallholder farmers. Tea plays a crucial role in the national economy as a source of foreign exchange and for environmental conservation. The national tea export volume tends to decrease by 6.15% per year, caused by the declining rate of tea plantation area at 1.24% per year during the 2015-2023 period (Pusat Data dan Sistem Informasi Pertanian, 2024). National tea production projections indicate stability between 2025 and 2032, thus the use of environment-adaptive superior varieties in plantation intensification and rejuvenation programs can increase productivity and strengthen the competitiveness of Indonesian tea in the global market (Darmawan *et al*., 2025). These conditions encourage the Research Institute for Tea and Cinchona (RITC) to develop new superior clones with high productivity, requisite quality, and environmental adaptability.

The development of superior tea clones begins with germplasm management, mother tree selection, and yield potential and stability trials. The benefits of using cuttings from superior tea clones are the provision of seedlings in large quantities and a short time, more uniform plants, faster yielding, and higher plant productivity (Sriyadi, 2012). Genotype-by-environment (GxE) interaction or crossover is one source of variation that affects genotype performance across multiple environments in multi-location trials. Detection of GxE interactions must be further investigated regarding their causative factors because they influence the response, adaptability, and genotype response patterns due to environmental differences; thus, practical methods are needed to predict these differential response patterns (Baker, 1988). Recommendations for cultivation technology packages (genotype, cultural practices, and cultivation systems) that are stable across various environmental conditions and carry minimal risk of production decline below standard levels are highly needed by farmers (Crossa, 1990). Tea cultivation techniques require centring and/or bending stages during the early growth phase to stimulate the formation and development of lateral shoots and optimal plucking table formation. The growth rate of lateral shoots is influenced by plant growth regulators (PGR), specifically cytokinin, which can be synthesized naturally within plant tissues (Rosniawaty *et al*., 2018).

Tea germplasm has been categorized into seedling germplasm, seed production, and clonal plantation, as well as plant introduction. Identification of genetic diversity to disclose the diversity of accessions based on morpho-agronomic characteristics is important in the management of germplasm. (Wibowo and Martono 2022). The clonal planting materials tested are superior clones with high productivity potential based on previous selection stages, so that their adaptability can be studied by planting them in different locations. The variability of yield characters and yield components for initial population selection, as well as the identification of genetic diversity in germplasm based on morphological and agronomic traits for the assamica tea type, have been conducted as basic breeding materials (Khoemaeni and Sriyadi, 2011; Rahadi *et al*., 2016). Stability parameters have also been used in grouping the quality of sinensis-type tea for green tea production (Prayoga *et al*., 2023). The vegetative phase of tea plants after field transplanting is useful for the initial screening of growth component traits' adaptation, making phenotypic stability a primary supporting parameter. These data are needed as initial information to facilitate the adaptability and determination of the clones to be included for release. This study aims to investigate the stability of growth components and characterize the phenotypic performance of selected clones during the vegetative phase.

MATERIALS AND METHODS

Plant materials and study location

This study used 15 test clones (I.35.8, II.6.10, II.10.11, II.13.2, II.32.15, III.2.15, III.22.15, III.28.4, III.36.15, TPS 17/3, TPS 24/5, TPS 87/1, TPS 87/2, TPS 93/3, TPS 122/2) resulted from selection and a check clone (GMB 7). The trial was conducted in Malabar Plantation part of

PTPN 1 Regional 2 (1590 m asl), Bandung West Java from December 2025 and Semugih Plantation part of PTPN 1 Regional 3 (700 m asl), Pemalang Central Java from January 2026. The observation of vegetative characters in this study took four months after planting in the field or before frame formation (bending). There were three times observation in each location, namely in first, second, and third month after planting. Planting was conducted on December 2025 for location in Malabar Plantation, Bandung West Java and on January 2026 for Semugih Plantation, Pemalang Central Java. Precipitation and temperature were observed for supporting environment data.

Growth component characteristics of tea clones

Plant height, stem diameter, and number of shoots were observed on five plants per experimental design. The plant height was measured from ground level until top shoot by measuring tape. The stem diameter was measured on five cm above ground level by vernier calliper. The number of shoots was counted manually for fresh shoot. The increase of plant height, stem diameter, and number of shoots were counted by difference of each value in third month and first month. The observations conducted three times in 1 month after planting (MAP), 2 MAP, and 3 MAP.

Morphological characteristics in vegetative phase

Qualitative characteristics of morphological tea clones in early vegetative phase were observed according to guidelines for the conduct of test for distinctness, uniformity, and stability (PVTPP 2018). There were 12 qualitative characteristics were observed in each location according to their frequency using scores. The following are the characteristics and scores for qualitative observation:

a) Branch: presence of zigzagging = absent (1), present (9)
b) Young shoot: colour of the second leaf of two and bud stage = whitish (1), yellow green (2), light green (3), medium green (4), purple green (5)
c) Young shoot: presence of pubescence = absent (1), present (9)
d) Leaf blade: attitude = upwards (1), outwards (3), downwards (5)
e) Leaf blade: shape = very narrow elliptic (1), narrow elliptic (2), medium elliptic (3), broad elliptic (4)
f) Leaf blade: intensity of green colour = light (3), medium (5), dark (7)
g) Leaf blade: shape in cross section = folded upwards (1), flat (2), recurved (3)
h) Leaf blade: distance of venation = narrow (1), medium (2), board (3)
i) Leaf blade: shape of apex = obtuse (1), acute (2), acuminate (3)
j) Leaf blade: undulation of margin = absent or weak (1), medium (2), strong (3)
k) Leaf blade: serration of margin = weak (3), medium (5), strong (7)
l) Leaf blade: shape of base – acute (1), obtuse (2), truncate (3).

Data analysis

The data reported are the average of three replications in each environment and combined environment for plant height, stem diameter, number of shoots, and theirs increasing of growth components. The data of qualitative morphological characteristics reported are the mode of their score frequency in two environments. The number of samples in this observation are five plants per experimental design. Collection of data qualitative morphological characteristics were conducted in three replications, namely two replication in Semugih Plantation and one replication in Malabar Plantation.

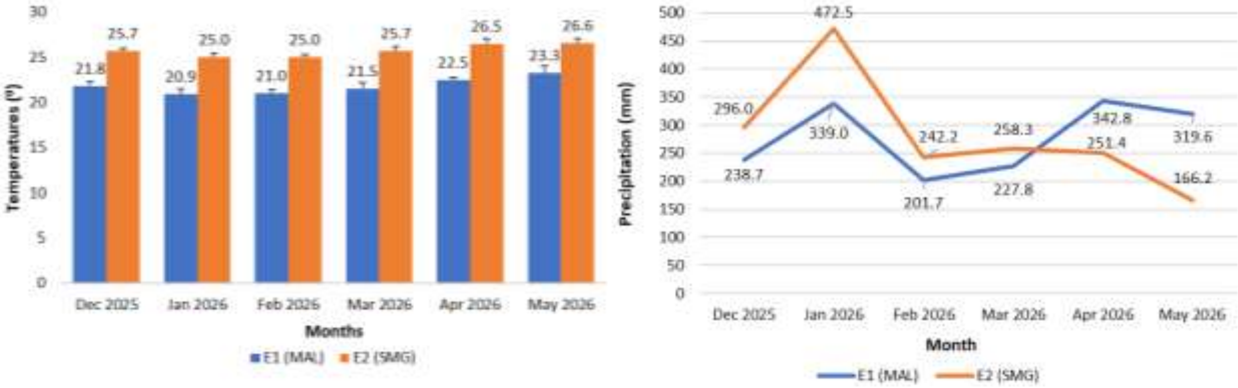
This experiment used a randomized complete block design (RCBD). Analysis of variance (ANOVA) for each environment and combined ANOVA in two environments followed by the honest significant difference test at 0.05 level was performed using the PBtools software (bbi.irri.org). The qualitative morphological characteristics explained in a dendrogram. Cluster analysis used Euclidean distance and the optimum number of clusters was determined by the average linkage methods using the PBSTAT-CL 2.2.1 software (www.pbstat.com).

RESULTS AND DISCUSSION

Agroclimatic conditions of the experimental locations

The multi-location trial sites were located at Malabar Plantation (7.212°S, 107.617°E) at an elevation of 1200 m asl, representing the highlands, and Semugih Plantation (7.153°S, 109.271°E) at an elevation of 700 m asl, representing the lowlands for tea plantations. Planting for the E1 location was in December 2025 and E2 was in January 2026. The average monthly temperature at the Malabar Plantation (E1) ranged from 20.9 to 23.3°C, and at Semugih Plantation (E2) it ranged from 25.0 to 26.6°C (Figure 1a). These results show an average monthly temperature difference ranging from 3.2 to 4.1°C between the two trial locations. Total monthly precipitation observed at 1 to 3 MAP was 768.5 mm for E1 (January-March 2026) and 751.8 mm for E2 (February-April 2026), with a difference of 16.7 mm (Figure 1b). The observation of vegetative characters was carried out during the rainy season.

Temperature and precipitation are agroclimatic factors observed to study variations in vegetative phase growth responses of the sixteen tea clones across the two trial locations. Both agroclimatic factors serve as environmental parameters in the multi-location trial. According to Dalimoenthe *et al*. (2016), climatic factors such as rainfall distribution greatly affect the production of tea; and the decline of highland tea productivity is lower than that of lowland ones. Wulansari *et al*. (2015) state that the Malabar Plantation features Andosols soil types with a compatible land capability class. Andosols soils possess high nitrogen (N) nutrient status and organic matter, whereas phosphorus (P) nutrient status ranges from low to very low. The climate changes resulted warmer and dry climates that impact for degrading optimum areas for tea cultivation because could not adaptation, so GxE interaction is useful for future tea clones selection (Tesfay *et al*., 2024).



(a) (b)

Note: E1) Malabar plantation in Bandung, West Java; E2) Semugih plantation in Pemalang, Central Java; The raw data is downloaded from https://power.larc.nasa.gov/data-access-viewer

Figure 1. Diagram of average monthly temperature (a) and graphic of total monthly precipitation (b) in two test locations from December 2025 until May 2026

Combined ANOVA and contribution of variation for clone performances

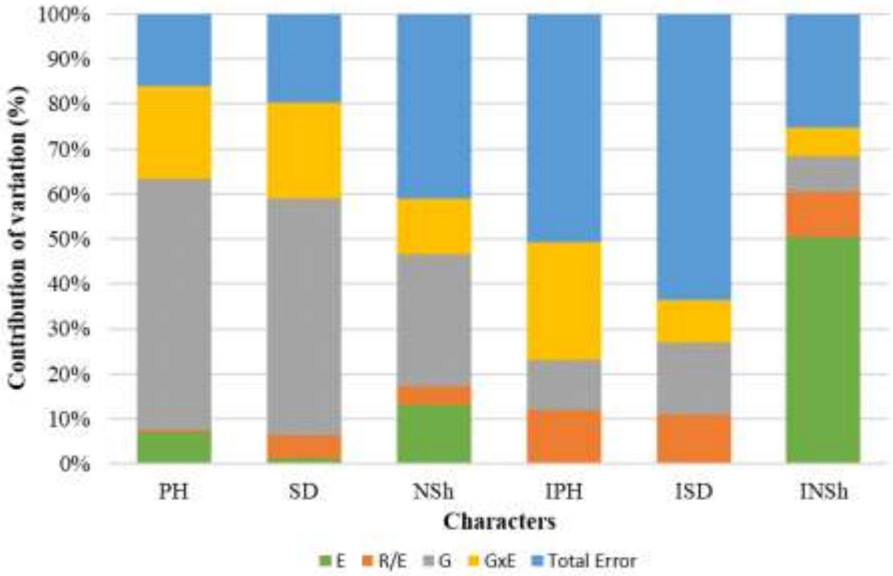
The combined analysis of variance (ANOVA) indicated significant mean difference responses for the effects of environment/location (E), genotype (G), and GxE interaction on plant height characteristics (1, 2, and 3 MAP), and the number of shoots at 1 MAP. The response of the source of variation in the combined analysis of variance for the tested characters is presented in Table 1. The low coefficient of variation for the plant height character indicates environmental homogeneity and a relatively high level of observation precision. A significant genotype response implies that the combined mean performance of the clones varies. A significant environmental response shows that differences in trial location conditions influence clone performance. The significant GxE interaction effect indicates the presence of phenotypic crossover among clones across the two environments. GE interaction of tea plant should be properly analysed. Thus, for the identification of new genotypes for commercial release, it is necessary to test different genotypes in different environments over several years to evaluate their adaptability and stability (Mullualem *et al.*, 2024). The lowland-grown clones have advantages over highland clones with suitable light intensities and warmer temperatures for improving catechin synthesis. However, tea clones may thrive at higher altitudes through a distinct mechanism from lowland tea clones. Light exposure significantly influences flavonoid metabolism in tea plants (Murdiono *et al.*, 2025).

Table 1. Probability values of the combined analyses of variance for plant height, stem diameter, and number of shoots for 16 tea clones were evaluated at two environments.

Characters	Location (E)	Replication / Location (R/E)	Genotype (G)	Genotype*Location (GxE)	CV (%)
Plant height					
1 MAP	**	ns	**	**	11.40
2 MAP	**	ns	**	**	9.71
3 MAP	**	ns	**	**	9.36
Stem diameter					
1 MAP	ns	*	**	**	11.05

2 MAP	ns	**	**	**	10.02
3 MAP	ns	**	**	**	9.67
Number of shoots					
1 MAP	**	*	**	*	16.99
2 MAP	**	**	**	ns	17.23
3 MAP	**	ns	**	ns	20.11
Increase of plant height on 3 MAP	ns	*	ns	*	49.74
Increase of stem diameter on 3 MAP	ns	*	ns	ns	47.51
Increase of number of shoots on 3 MAP	ns	**	ns	ns	86.65

Note: * and **) Significant at $p<0.05$ and $p<0.01$, respectively; ns) Not significant at $p<0.05$; CV) Coefficient of variation; MAP) Month after planting.



Note: PH) Plant height (cm); SD) Stem diameter (mm); NSh) Number of shoots; IPH) Increase of plant height (cm); ISD) Increase of stem diameter; INSh) Increase of number of shoots

Figure 2. The source of variation contribution for growth component characters on 3 MAP

The variation and phenotypic performance of clones are influenced by environmental factors, genetic factors, and their interactions. Analysing of environmental factors comprise the variation sources of location (E), replication nested within location (R/E), and total error. The total variation contribution (G + E + GxE) for the tested characters at 3 MAP consists of environmental factors (E) varying from 23.6% to 85.7%, genetic factors (G) varying from 8.1% to 55.7%, and GxE factors varying from 6.3% to 26.3% (Figure 2). The highest environmental factor contribution was shown by the increase in shoot number character, while the lowest was for plant height, whereas the opposite applied to the genetic factor. The highest GxE interaction factor contribution was shown by the plant height increase character, and the lowest by the increase in shoot number. These difference response useful for studying main factor that influence clones performances, so we could precision selection.

The quantitative character performance of the test clones at the two locations is relatively influenced by environmental factors. The source of variation regarding testing location differences is influenced by variations in edaphic and agroclimatic factors. The source of variation for replications nested within environments is influenced by microclimate variations and soil fertility levels within and between experimental plots. Total error variance represents unintended errors and is expected to have a small sum of squares to enhance testing precision. The dominance of the genetic factor on the phenotypic plant height of tea clones indicates that variations are primarily caused by differences in test clone means and possess high potential heritability values. Tea plants require a continual supply of macronutrients for growth and development due to in young leaves, it's significant correlation between the levels of macronutrients N, P, and K and the main biochemical components, i.e., free amino acid (FAA), caffeine (CAF) and tea polyphenols (TP) among the 87 tea varieties in China (Zaman *et al*., 2022).

Phenotypic performance in vegetative stage

The plant height responses of the 16 clones at the two test locations up to 3 MAP are shown in Table 2. Based on observations, the average total plant height of the clones at Malabar Plantation (E1) at 1, 2, and 3 MAP was 47.44 cm, 49.95 cm, and 51.75 cm, respectively. The plant heights of clones I.35.8 (G01), II.13.2 (G04), and III.28.4 (G08) was significantly lower compared to GMB 7, while other candidate clones did not significantly different compared to GMB 7 at 1, 2, and 3 MAP in E1. At Semugih Plantation (E2), the average total plant heights at 1, 2, and 3 MAP were 52.56 cm, 54.92 cm, and 57.16 cm, respectively. The plant height of all candidate clones was not significantly different compared to GMB 7 at 1 MAP. Clone I.35.8 (G01) was significantly lower compared to GMB 7, whereas the other candidate clones showed no significant difference compared to GMB 7 at 2 and 3 MAP in E2.

Based on observations, the combined grand means plant heights across both locations at 1, 2, and 3 MAP were 50.00 cm, 52.44 cm, and 54.46 cm, respectively. The plant heights of clones I.35.8 (G01), II.13.2 (G04), and III.28.4 (G08) was significantly lower compared to GMB 7, while the other candidate clones showed no significant difference compared to GMB 7 at 1, 2, and 3 MAP for the combined analysis of both trial locations. Observation results explain that variations in plant height among the 16 clones are influenced by differences in genetic material and test environments. The grand means plant height of clones in the highlands (E1) is relatively lower than in the lowlands (E2). Plants growing at high altitudes generally experience slower growth rates than those at lower altitudes. This is influenced by environmental factors such as lower temperatures, reduced nutrient availability, and decreased photosynthetic efficiency (Jeyakumar *et al*., 2020). The accumulation of nutrients in tea leaves at higher altitudes may reflect the plants' limited ability to utilize the absorbed nutrients for growth rather than increased uptake alone (Murdiono *et al*., 2025). Plant height is an important agronomic trait related to apical dominance, plant architecture, yield, lodging, cultivation, and harvesting. Plant height it is mostly controlled by pleiotropic interactions, which present potential risks of creating undesirable changes in other important traits (Miao *et al*., 2024).

Table 2. Variation among tea clones on plant height in two environments

Genotype		1 MAP (cm)			2 MAP (cm)			3 MAP (cm)		
		E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$
G01	I.35.8	38.20 p	34.73	36.47 p	40.37 p	35.87 p	38.12 p	41.97 p	37.50 p	39.73 p
G02	II.6.10	53.56	63.57	58.56	55.63	65.67	60.65	57.23	67.50	62.37
G03	II.10.11	44.33	56.07	50.20	46.40	58.27	52.33	49.93	59.97	54.95
G04	II.13.2	30.90 p	48.77	39.83 p	32.60 p	49.83	41.22 p	33.83 p	55.90	44.87 p
G05	II.32.15	53.63	62.20	57.92	56.50	64.20	60.35	57.53	66.60	62.07
G06	III.2.15	44.43	63.13	53.78	47.03	65.67	56.35	48.67	67.23	57.95
G07	III.22.15	56.60	43.80	50.20	58.33	49.10	53.72	59.20	51.50	55.35
G08	III.28.4	33.27 p	41.57	37.42 p	36.77 p	42.77	39.77 p	37.87 p	45.10	41.48 p
G09	III.36.15	42.97	54.10	48.53	44.90	56.13	50.52	46.33	58.07	52.20
G10	TPS 17/3	47.00	41.07	44.03	49.67	44.23	46.95	52.50	47.03	49.77
G11	TPS 24/5	48.60	40.40	44.50	51.53	42.57	47.05	54.67	43.50	49.08
G12	TPS 87/1	54.50	56.47	55.48	57.30	57.80	57.55	59.60	58.93	59.27
G13	TPS 87/2	51.83	57.80	54.82	54.63	59.40	57.02	56.23	61.17	58.70
G14	TPS 93/3	56.90	69.63	63.27	60.30	70.77	65.53	62.47	72.53	67.50
G15	TPS 122/2	47.60	54.20	50.90	50.63	60.70	55.67	51.57	63.47	57.52
G16	GMB 7	54.67	53.40	54.03	56.67	55.77	56.22	58.47	58.60	58.53
Grand mean		47.44	52.56	50.00	49.95	54.92	52.44	51.75	57.16	54.46
HSD 0.05		13.99	20.16	11.77	12.75	17.82	10.51	12.30	18.17	10.52
Pr > F		**	**	**	**	**	**	**	**	**

Note: **: Significant at p<0.01; p). Significantly lower compared to GMB 7 check clone based on HSD 0.05; E1) Malabar Plantation in Bandung West Java; E2) Semugih Plantation in Pemalang Central Java; $\bar{x}$) The average of combination two environments E1 and E2; MAP) Month after planting.

The responses of stem diameter of the 16 clones at the two test locations up to 3 months after transplanting are presented in Table 3. At Malabar Plantation (E1), the average total stem diameter of the clones at 1, 2, and 3 MAP was 5.04 mm, 5.43 mm, and 5.62 mm, respectively. Clones II.13.2 (G04), III.2.15 (G06), III.28.4 (G08), and III.36.15 (G09) was significantly lower compared to GMB 7 at 1 MAP in E1. Clones I.35.8 (G01), II.13.2 (G04), III.2.15 (G06), III.28.4 (G08), and III.36.15 (G09) was significantly lower compared to GMB 7 at 2 and 3 MAP in E1. The stem diameters of the other candidate clones did not significantly differ from GMB 7. At Semugih Plantation (E2), the average total stem diameters at 1, 2, and 3 MAP were 5.24 mm, 5.63 mm, and 5.84 mm, respectively. Clones I.35.8 (G01) and III.28.4 (G08) had significantly lower compared to GMB 7 at 1 MAP in E2. Clones I.35.8 (G01), III.28.4 (G08), and TPS 122/2 (G15) was significantly lower compared to GMB 7 at 2 and 3 MAP in E2. The other candidate clones were not significantly different compared to GMB 7 in E2.

According to observation, the combined grand means stem diameters across both locations at 1, 2, and 3 MAP were 5.14 mm, 5.53 mm, and 5.73 mm, respectively. Stem diameters of clones I.35.8 (G01), II.13.2 (G04), III.2.15 (G06), III.28.4 (G08), III.36.15 (G09), and TPS 17/3 (G10) was significantly lower than GMB 7 at 1 MAP. Stem diameters of clones I.35.8 (G01), II.13.2 (G04), III.2.15 (G06), III.28.4 (G08), III.36.15 (G09), TPS 17/3 (G10), TPS 24/5 (G11), and TPS 122/2 (G15) was significantly lower compared to GMB 7 at 2 and 3 MAP. Other candidate clones not specified based on the combined analysis had stem diameters that not significant different compared to GMB 7 across combined environment. Clones I.35.8 (G01), II.13.2 (G04), and III.28.4 (G08) exhibited plant heights and stem diameters significantly lower compared to GMB 7 at all observation times and locations. Clones II.6.10 (G02), II.10.11 (G03), II.32.15 (G05), III.22.15 (G07), TPS 87/1 (G12), TPS 87/2 (G13), and TPS 93/3 (G14) are potential clones in vegetative phase due to their plant height and stem diameter values were not significant different compared to GMB 7. The variations of both characters are predominantly controlled by genetic factors exceeding 50%. Rosniawaty *et al*. (2018) state that the treatment 50% and 75% concentrations of coconut water is not significant different to 60 ppm Benzyl Amino Purine treatment for stem diameters in vegetative phase.

Table 3. Variation among tea clones on stem diameter in two environments

Genotype		1 MAP (mm)			2 MAP (mm)			3 MAP (mm)		
		E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$
G01	I.35.8	4.59	4.16p	4.38p	4.87p	4.50p	4.68p	5.07p	4.59p	4.83p
G02	II.6.10	5.33	5.53	5.43	5.54	6.03	5.79	5.74	6.29	6.01
G03	II.10.11	4.88	5.79	5.34	5.58	6.24	5.91	5.77	6.43	6.10
G04	II.13.2	3.57p	5.59	4.58p	3.93p	5.94	4.94p	4.14p	6.21	5.17p
G05	II.32.15	5.69	5.95	5.82	5.98	6.17	6.07	6.14	6.54	6.34
G06	III.2.15	4.21p	5.93	5.07	4.47p	6.19	5.33p	4.67p	6.40	5.53p
G07	III.22.15	5.11	4.95	5.03	5.53	5.57	5.55	5.69	5.77	5.73
G08	III.28.4	3.05p	3.81p	3.43p	3.71p	4.31p	4.01p	3.90p	4.48p	4.19p
G09	III.36.15	3.83p	5.26	4.54p	4.18p	5.67	4.93p	4.37p	5.88	5.13p
G10	TPS 17/3	4.87	4.57	4.72p	5.38	4.90	5.14p	5.56	5.07	5.32p
G11	TPS 24/5	5.61	4.59	5.10	6.03	4.76	5.39p	6.23	5.00p	5.61p
G12	TPS 87/1	5.75	5.18	5.46	6.05	5.63	5.84	6.23	5.80	6.02
G13	TPS 87/2	6.07	5.63	5.85	6.45	6.18	6.32	6.71	6.41	6.56
G14	TPS 93/3	6.57	6.21	6.39	6.87	6.51	6.69	7.06	6.75	6.90
G15	TPS 122/2	5.38	4.62	5.00	5.71	4.74p	5.22p	5.87	4.93	5.40p
G16	GMB 7	6.14	6.09	6.11	6.61	6.71	6.66	6.80	6.92	6.86

Grand mean	5.04	5.24	5.14	5.43	5.63	5.53	5.62	5.84	5.73
HSD 0.05	1.64	1.81	1.17	1.37	1.95	1.14	1.42	1.91	1.14
Pr > F	**	**	**	**	**	**	**	**	**

Note: **) Significant at p<0.01; p). Significantly lower compared to GMB 7 check clone based on HSD 0.05; E1) Malabar Plantation in Bandung West Java; E2) Semugih Plantation in Pemalang Central Java; $\bar{x}$) The average of combination two environments E1 and E2; MAP) Month after planting.

The shoots number responses of the 16 clones at the two test locations up to 3 months after transplanting are shown in Table 4. Based on observations, the average total number of shoots at Malabar Plantation (E1) at 1, 2, and 3 MAP was 5.7, 5.9, and 5.7, respectively. The fluctuating value of shoot numbers in several clones was caused by dry shoot conditions and their relatively slow addition. All candidate clones in E1 had shoot numbers that were not significantly different compared to GMB 7 at 1 and 2 MAP. The response of shoot number not significant different in E1 at 3 MAP. At Semugih Plantation (E2), the average total number of shoots at 1, 2, and 3 MAP was 4.7, 5.3, and 6.8, respectively. Clone TPS 93/3 (G14) was significantly higher compared to GMB 7 in E2 at 1 and 2 MAP. All candidate clones in E2 displayed shoot numbers that were not significantly different compared to GMB 7 at 3 MAP.

The combined grand means number of shoots across both locations at 1, 2, and 3 MAP was 5.2, 5.6, and 6.3, respectively, demonstrating an increase each month. Clone TPS 93/3 (G14) was significantly higher compared to than GMB 7 at 1 and 2 MAP, while the others not significant. The shoot numbers of all candidate clones were not significantly different compared to GMB 7 at 3 MAP. Generally, with the number of shoots at 3 MAP, frame formation can be carried out through bending to increase the number of primary shoots. The number of shoots is an important trait in the vegetative phase because a higher number of active shoots indicates a potential of secondary and tertiary branches, signifying that the tea clone is productive. The increment of shoot number is influenced by cytokinin content, and Benzyl Amino Purine treatment increases the number of tea shoots (Rosniawaty *et al*., 2018).

Table 4. Variation among tea clones on number of shoots in two environments

Genotype		1 MAP			2 MAP			3 MAP		
		E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$
G01	I.35.8	4.5	3.7	4.1	5.1	4.5	4.8	5.3	5.5	5.4
G02	II.6.10	6.8	5.0	5.9	6.9	5.7	6.3	6.4	6.0	6.2
G03	II.10.11	5.2	4.8	5.0	5.4	5.1	5.3	4.9	6.3	5.6
G04	II.13.2	4.1	5.3	4.7	4.3	5.7	5.0	3.9	7.1	5.5
G05	II.32.15	6.9	5.5	6.2	7.0	5.5	6.2	6.5	7.2	6.9
G06	III.2.15	5.3	5.3	5.3	5.8	6.3	6.0	6.3	7.9	7.1
G07	III.22.15	6.8	4.5	5.6	7.0	4.9	5.9	6.1	7.1	6.6
G08	III.28.4	4.0	3.0	3.5	4.9	3.3	4.1	3.8	4.9	4.4
G09	III.36.15	5.9	4.7	5.3	6.0	5.5	5.7	5.5	7.8	6.7
G10	TPS 17/3	5.7	3.7	4.7	6.2	4.2	5.2	6.1	6.5	6.3
G11	TPS 24/5	5.9	3.9	4.9	6.1	4.7	5.4	6.8	5.5	6.2
G12	TPS 87/1	5.2	5.3	5.3	5.4	5.8	5.6	5.3	7.1	6.2
G13	TPS 87/2	6.2	4.7	5.4	6.4	5.6	6.0	5.9	6.5	6.2

G14	TPS 93/3	6.8	6.8a	6.8a	7.1	7.8a	7.4a	7.4	9.4	8.4
G15	TPS 122/2	5.4	4.9	5.1	5.6	5.3	5.5	4.8	7.4	6.1
G16	GMB 7	5.9	3.9	4.9	6.0	4.5	5.3	6.0	6.9	6.5
Grand mean		5.7	4.7	5.2	5.9	5.3	5.6	5.7	6.8	6.3
HSD 0.05		2.9	2.4	1.8	2.7	3.1	2.0	3.8	3.8	2.6
Pr > F		**	**	**	*	**	**	ns	*	**

Note: * and **) Significant at $p<0.05$ and $p<0.01$, respectively; ns) Not significant at $p<0.05$; a) Significantly higher compared to GMB 7 check clone based on HSD 0.05; E1) Malabar Plantation in Bandung West Java; E2) Semugih Plantation in Pemalang Central Java; $\bar{x}$) The average of combination two environments E1 and E2; MAP) Month after planting.

The response regarding the increase in growth components of the clones across two locations is presented in Table 5. All variables exhibited no significant effect. The increase in plant height at E1 varied from 2.60 cm (G07) to 6.07 cm (G11), and at E2 it ranged from 2.77 cm (G01) to 9.27 cm (G15). The grand means increments in plant height at E1, E2, and their combination were 4.32 cm, 4.61 cm, and 4.46 cm, respectively. The plant height increase of clone TPS 17/3 (G10) was relatively higher compared to the grand means at both E1 and E2. The increase in stem diameter at E1 varied from 0.41 mm (G02) to 0.89 mm (G03), and at E2 it ranged from 0.31 mm (G15) to 0.83 mm (G16). The grand mean increments in stem diameter at E1, E2, and their combination were 0.58 mm, 0.60 mm, and 0.59 mm, respectively. The stem diameter increases for clones III.22.15 (G07), TPS 87/2 (G13), and GMB 7 (G16) were relatively higher than the grand means at both E1 and E2. The increase in the number of shoots at E1 varied from -0.60 (G15) to 0.87 (G11), and at E2 it ranged from 1.00 (G02) to 3.07 (G09). The grand means increments in shoot number at E1, E2, and their combination were 0.04, 2.15, and 1.09, respectively. The shoot number increments for clones III.2.15 (G06), TPS 93/3 (G14), and GMB 7 (G16) were relatively higher than the grand means at E1 and E2. Based on the combined average across the two environments, clones TPS 17/3 (G10) and GMB 7 (G16) demonstrated a relatively higher increase in plant height, stem diameter, and shoot number compared to the overall grand means. Observational results indicated that the increase in growth components at E1 (highlands) lower than E2 (lowlands). Generally, these findings suggest that clone growth during the vegetative phase adapts well to lowland conditions. Rosniawaty *et al*. (2018) reported that the high metabolism of tea plants in lowlands necessitates additional cytokinin to stimulate and enhance shoot growth.

Table 5. The increase of growth components characteristics in 3 MAP

Genotype		IPH (cm)			ISD (mm)			INSh		
		E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$	E1 (MAL)	E2 (SMG)	$\bar{x}$
G01	I.35.8	3.77	2.77	3.27	0.47	0.43	0.45	0.87	1.87	1.37
G02	II.6.10	3.67	3.93	3.80	0.41	0.76	0.58	-0.40	1.00	0.30
G03	II.10.11	5.60	3.90	4.75	0.89	0.63	0.76	-0.33	1.53	0.60
G04	II.13.2	2.93	7.13	5.03	0.57	0.61	0.59	-0.20	1.87	0.83
G05	II.32.15	3.90	4.40	4.15	0.45	0.59	0.52	-0.40	1.73	0.67
G06	III.2.15	4.23	4.10	4.17	0.46	0.47	0.47	1.07	2.67	1.87
G07	III.22.15	2.60	7.70	5.15	0.58	0.81	0.70	-0.67	2.67	1.00
G08	III.28.4	4.60	3.53	4.07	0.85	0.67	0.76	-0.23	1.93	0.85

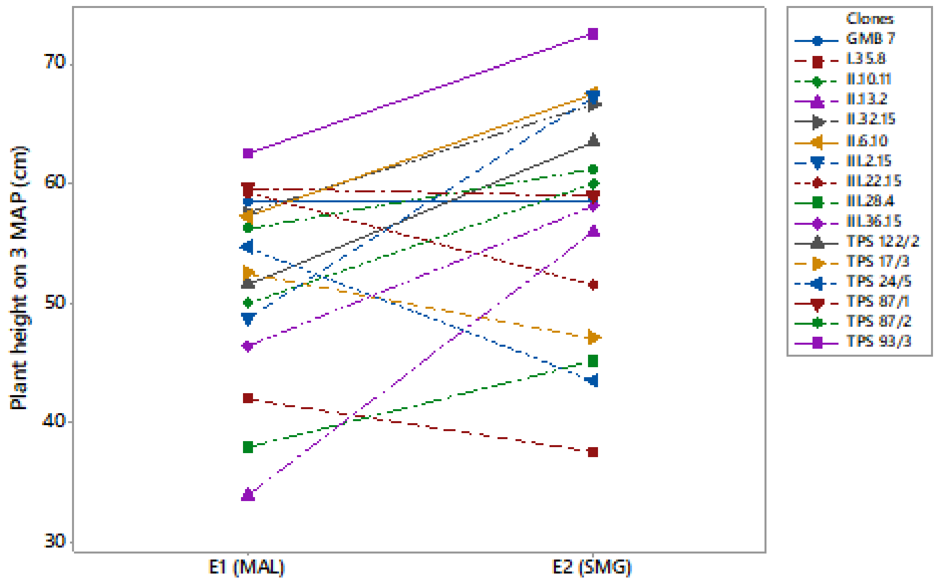
G09	III.36.15	3.37	3.97	3.67	0.55	0.62	0.58	-0.33	3.07	1.37
G10	TPS 17/3	5.50	5.97	5.73	0.69	0.51	0.60	0.40	2.80	1.60
G11	TPS 24/5	6.07	3.10	4.58	0.61	0.41	0.51	0.87	1.67	1.27
G12	TPS 87/1	5.10	2.47	3.78	0.49	0.62	0.55	0.13	1.73	0.93
G13	TPS 87/2	4.40	3.37	3.88	0.64	0.77	0.71	-0.33	1.80	0.73
G14	TPS 93/3	5.57	2.90	4.23	0.49	0.53	0.51	0.60	2.60	1.60
G15	TPS 122/2	3.97	9.27	6.62	0.49	0.31	0.40	-0.60	2.53	0.97
G16	GMB 7	3.80	5.20	4.50	0.66	0.83	0.75	0.13	3.00	1.57
Grand mean		4.32	4.61	4.46	0.58	0.60	0.59	0.04	2.15	1.09
HSD 0.05		5.42	7.87	4.58	0.76	0.94	0.58	2.93	2.84	1.96
Pr > F		ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: ns) Not significant at p<0.05; IPH) Increase of plat height; ISD) Increase of stem diameter; INSh) Increase of number of shoots; E1) Malabar Plantation in Bandung West Java; E2) Semugih Plantation in Pemalang Central Java; $\bar{x}$) The average of combination two environments E1 and E2

Gxe interaction analysis

A significant response regarding the effect of GxE interaction was observed in the characters of plant height and stem diameter at 1, 2, and 3 MAP, shoot number at 1 MAP, and the increase in plant height at 3 MAP (Table 1). The clone crossover exhibited an inconsistency in clone rankings across environments, indicating the GxE interaction. A distinct crossover pattern for plant height at 3 MAP was caused by inconsistencies in the rank order of the clones (Figure 3). Based on the ranking of plant height at 3 MAP in location E1, clones TPS 87/1 (G12), III.22.15 (G07), and GMB 7 (G16) were among the top five ranks, whereas in E2, their rankings fell below eight, indicating specific adaptation to the highlands. Conversely, clones III.2.15 (G06) and TPS 122/2 (G15) secured positions within the top five ranks in location E2, but fell below rank 10 in E1, demonstrating specific adaptation to the lowlands. Clones TPS 93/3 (G14) and II.32.15 (G05) adapted well to both highlands and lowlands, as they consistently remained in the top five ranks.

Furthermore, regarding stem diameter rankings across the two environments, clones TPS 24/5 (G11) and TPS 87/1 (G12) achieved the top five ranks in E1, but exhibited contrasting results in E2. Based on the GxE interaction ranking results for plant height and stem diameter, clone TPS 93/3 (G14) is considered a potential clone due to its consistency in the top three ranks, indicating robust adaptation in both locations. Clones I.35.8 (G01) and III.28.4 (G08) did not achieve maximal adaptation across the two locations, as they consistently occupied the bottom four ranks during the vegetative phase. The observational results of the GxE interaction elucidate that genetic and environmental factors play an active, mutual role in clone adaptability during the three months post-transplanting. Rank inconsistency represents a definitive response to GxE interaction; therefore, a clone achieving top-ranking responses in a specific environment demonstrates specific adaptation, whereas a consistent ranking signifies general adaptation. These potential clones warrant further evaluation according to yield adaptability for future variety release. Cultivar adaptability based on GxE interactions is beneficial for recommending optimal technical culture technology packages. There were significant GxE variations and dynamic changes of macronutrients (N, P and K) levels for many elite tea varieties in young and mature leaves, throughout the spring, summer, and autumn seasons (Zaman *et al*., 2022).



Note; E1) Malabar Plantation in Bandung West Java; E2) Semugih Plantation in Pemalang Central Java

Figure 3. Interaction line plot graphic of plant height on 3 MAP

Clone kinship based on morphological characteristics

Kinship relationships among clones can be analysed using clustering analysis methods. The employed cluster analysis utilized the Euclidean dissimilarity method alongside the average linkage clustering method (Figure 4). The grouping was based on qualitative and quantitative morphological characters at 3 MAP. The cluster analysis results revealed that the 16 clones were divided into two main groups based on the cophenetic distance at a cut point value of 10. Clones grouped within the same cluster demonstrate a closer degree of kinship. The check clone, GMB 7, was grouped in cluster 1 (C-1), while all candidate clones were grouped in cluster 2 (C-2). This indicates that the candidate clones exhibit a distant kinship relationship relative to the check clone due to their differing morphological characteristics, thereby possessing potential uniqueness. The uniqueness of each candidate clone serves as a vital asset in breeding programs and one of the variety release prerequisites.

The selection of tea accessions for crossing parents utilizes accessions that represent each group and are not closely related, based on the cluster analysis results, to prevent narrow variability and the accumulation of undesirable recessive genes in the progenies (Wahyudin *et al*., 2024; Rahadi *et al*., 2016). Maxiselly *et al*. (2024) state a high genetic diversity within the sinensis-type tea collection accessions at the Research Institute for Tea and Cinchona (RITC), which possess the potential to be developed into new candidate clones. The information on kinship relationships based on morpho-agronomic in tea clone characteristics has a number of weaknesses due to environmental influences, so molecular markers can be used due to more accurate and not influenced by environmental factors and plant development (Wibowo and Martono 2022). The different tea clones possess unique genetic markers that correlate with catechin levels and other antioxidants. For instance, specific gene regions called QTLs (Quantitative Trait Loci) have been linked to tea plants' catechin content and antioxidant activity and can be used as a marker to identify and select tea clones with high catechin and antioxidant levels (Hazra *et al*., 2020).

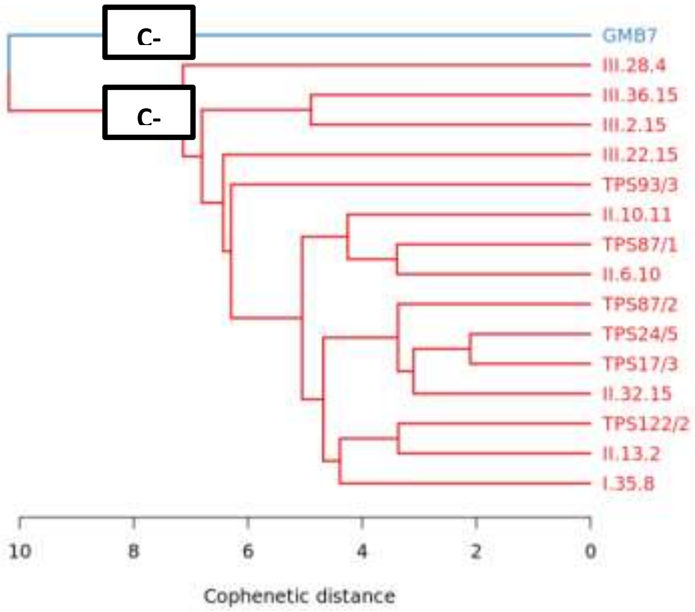


Figure 4. Dendogram of the 16 tea clones based on morphological characteristics

General discussion

The stability and uniqueness of clones during the vegetative phase demonstrate the phenotypic diversity of candidate clones in adapting to two environments with distinct agroclimatic characteristics. Clones II.32.15 (G05) and TPS 93/3 (G14) exhibited general adaptation across both environments, with clone TPS 93/3 (G14) performing superiorly in both. Clone TPS 87/1 (G12) is a specifically adapted clone in the highlands (E1), and clone III.2.15 (G06) is specifically adapted in the lowlands (E2). Clones I.35.8 (G01) and III.28.4 (G08) are inferior clones as they failed to adapt maximally in either environment. The check clone, GMB 7, displayed clear differences in qualitative and quantitative morphological characteristics and high mean consistency across all tested characters at 3 MAP, with no candidate had significant higher value. Significant differences in elevation influenced the phenotypic performance of the tea clones, resulting in distinct adaptability for each clone. The growth components value relatively higher in lowlands due to a considerable temperature difference of approximately 4°C, which stimulated the metabolism of tea plants during vegetative phase. Morphological characters are important in differentiation tea accessions and these differences are attributed to variations in the genetic constitution or environmental factors on the genotype of each accession (Dargah *et al*., 2023).

The distribution of rainfall is very important in rain-fed tea production, thus optimizing water resources is a must. Microclimate modification such as the establishment of shading plants and planting of tolerant clones are important to maintain stable productivity growth especially during El Nino (Fatawa *et al*., 2023). The shading plants could maintain soil humidity around tea crop 10% higher and crop temperature 7-9 °C lower compared to without shading. The recommendation of several shade plants such as *Acacia pruinose*, *Acacia auriculiformis*, *Albizzia falcataria*, *Calliandra calothrysus*, *Cassia siamea*, *Erythrina lithosperma*, *Leucaena leucocephala*, and *Grevillea robusta* (Rokmah *et al*., 2022). The drought-tolerant of tea clones including GMB 1, GMB 2, GMB 4, GMB 7, GMB 8, GMB 9, GMB 10, GMB 11, and TRI 2025 which have a deep root system (Purwaningrum 2006). The clones that resistant and adaptive to heavy rainfall namely PGL-4, PGL-9, PGL-10, PGL-11, PGL-12, and PGL-16 with production potential over 1 ton of tea per month (Yuliana 2013). Different tea clones possess distinct genetic compositions that leads to variations in the levels of key anti-oxidant compounds, such as catechins, theaflavins and polyphenols. In another hand, environmental factors, such as different altitudes, along with distinct light intensities and temperature, interact with genetic traits, further influencing anti-oxidant activity, so genetic and environment mutually influential for tea quality (Murdiono *et al*., 2025). Prayoga *et al*. (2023) state that clones I.1.101, I.2.34, I.2.85, II.1.3, II.1.60, R1, S2, GMBS 3, and GMBS 4 exhibited stable green tea quality under both panning and steaming processing methods.

CONCLUSION

The phenotypic performance variation of test clones in vegetative phase is influenced by genetic, environment, and GxE interactions. Clones II.32.15 and TPS 93/3 exhibited general adaptation across highlands and lowlands, with clone TPS 93/3 performing superiorly in both environment. Clone TPS 87/1 have specific adaptation in highlands at Malabar plantation and III.2.15 is specifically adapted in lowlands at Semugih plantation. Clones I.35.8 and III.28.4 are inferior clones due to could not well adaptation in two environments. Clones II.6.10, II.10.11, II.32.15, III.22.15, TPS 87/1, TPS 87/2, and TPS 93/3 are potential clones in vegetative phase due to their plant height and stem diameter not significant different compared to GMB 7. All candidate clones are unique due to had differences morphological characteristics with GMB 7 according to distant kinship relationship. The potential clones could evaluated further and the beneficial of observation in vegetative phase we could precision selection for next stage.

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