RESEARCH ARTICLE

Agromorphological traits associated with high yield potential in 21 Robusta coffee accessions from Indonesia

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ABSTRACT

Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) is typically grown in mid-altitude areas, although some varieties are well adapted to higher elevations. This study aimed to identify vegetative and generative morphological traits determining high yield in 21 local coffee accessions from Pagar Alam Regency, South Sumatra, Indonesia. Agronomic traits and yield were analysed using ANOVA and multivariate approaches. The results showed that vegetative architecture, particularly long primary branches and numerous secondary branches, was a key determinant of high yield. One superior accession, characterized by extensive branching, exhibited outstanding generative performance, including high 100-bean weight, optimal seed production, and a high percentage of normal fruits. Strong positive correlations between vegetative and generative traits highlight the importance of agromorphological characteristics for early identification of superior accessions. These findings provide a practical framework for selecting superior Robusta coffee accessions in breeding programs.

Key words: Accessions, *Coffea canephora*, high yield, morphological traits, Robusta coffee.

INTRODUCTION

Coffee is among the most significant agricultural commodities worldwide, serving both as a vital source of income for millions of smallholder farmers and as a major driver of global trade and rural development (Wright et al., 2024). Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) is widely cultivated in Indonesia, particularly at mid-altitudes (200-800 m a.s.l.), where ecological conditions are favourable for its growth (Widaningsih, 2023). However, its productivity is strongly influenced by environmental factors such as climate variability, elevation, and agricultural practices (Fain et al., 2018; Ahmed et al., 2021; Sarmiento-Soler et al., 2022; Kath et al., 2023). These pressures have stimulated the development of locally adapted genotypes with enhanced resilience to heat, drought, poor soil conditions, and diseases (González-Orozco et al., 2024; Guambi et al., 2024).

According to FAO, Indonesia ranks as the world's fourth largest coffee producer and exporter, following Brazil, Vietnam, and Colombia. National coffee production during the 2023-2024 period ranged from approximately 755.4 to 810.0 thousand tons (BPS-Statistics Indonesia, 2025). In 2020, Indonesia accounted for around 7.42% of global coffee production (750.9 thousand tons), placing it behind Colombia (7.74%), Vietnam (16%), and Brazil (31.4%) (Center for Agricultural Data and Information Systems, 2023). Robusta coffee predominates in Indonesia, representing 72.71% of total production, while Arabica accounts for 27.29%. South

Sumatra Province is a major smallholder coffee-producing region, with dry coffee bean production reaching 219.6 thousand tons in 2024 (BPS-Statistics Indonesia, 2025).

Adaptation to local agroecological conditions gives rise to unique agronomic traits that often distinguish local varieties or clones. Previous studies have shown that Robusta coffee clones respond differently to inputs such as organic fertilizer, influencing physiological traits like chlorophyll and proline content (Sulistiono et al., 2021). These locally adapted genotypes are referred to as accessions, each characterized by distinct genetic and phenotypic attributes (Huang et al., 2020).

In South Sumatra, Indonesia, the Pagar Alam Highlands are recognized for their diverse Robusta coffee accessions, several of which exhibit superior yield potential and adaptability (Syafaruddin et al., 2020). These genetic resources are highly valuable for breeding programs aiming to develop improved varieties with high yield, climate tolerance, and disease resistance (Akpertey et al., 2019; Kiwuka et al., 2021; Campuzano-Duque and Blair, 2022; Verleysen et al., 2023).

Agromorphological and yield traits such as plant height, stem diameter, number of productive branches, berry size, and yield per plant are essential selection criteria in coffee breeding (Filla et al., 2023; Paredes-Espinosa et al., 2023). Evaluating these traits helps identify accessions with high agronomic performance under specific environmental conditions. Therefore, morphological and yield assessments are fundamental for selecting elite coffee genotypes.

Evidence from other crops also highlights the importance of trait identification in breeding. For example, previous studies demonstrated that identifying morphological traits closely associated with high yield in hemp (*Cannabis sativa* L.) greatly supports the breeding and selection of superior plants (Chaisan et al., 2025). Similarly, in coffee, identifying key agronomic traits and classifying them into clusters represents a crucial step, given the high morphological diversity between species (Robusta and arabica), among clones, and even within a single species. Accurate identification of morphological traits and kinship grouping provides a strong foundation for breeding programs, particularly for Robusta coffee, as it facilitates the determination of suitable cross-breeding parents and the development of superior varieties (Rubiyo et al., 2022). Conversely, neglecting these agronomic traits hinders the development of varieties that are both adaptive and productive, or that remain stable under diverse environmental conditions (Akpertey et al., 2019; Paixão et al., 2022).

Although numerous studies have focused on Robusta, information on the relationship between vegetative and generative traits in local Indonesian Robusta remains limited. Studies on Robusta coffee in other producing countries have mainly addressed agronomic performance, genetic diversity, and breeding potential. For instance, Kiwuka et al. (2021) assessed agronomic traits of Robusta coffee in Uganda, while Campuzano-Duque and Blair (2022) examined genetic diversity and population structure in *Coffea canephora*. However, studies specifically exploring the relationships between vegetative and generative traits in locally adapted Indonesian Robusta accessions remain limited. This gap hinders a deeper understanding of how morphological and yield traits are interconnected in Robusta, particularly in local accessions with superior potential. Addressing this knowledge gap is essential to accelerate the development of more targeted, adaptive, and sustainable breeding programs.

Given this background, the present study aimed to evaluate 21 Robusta coffee accessions from the Pagar Alam Highlands based on their agromorphological and yield characteristics, with the goal of identifying superior candidates for varietal development. We hypothesize that specific accessions will demonstrate superior performance under local conditions, thereby contributing to improved productivity, climate resilience, and the long-term conservation of coffee genetic resources.

MATERIALS AND METHODS

Study site and plant material
From a coffee plantation with a population of 8000 trees, 21 accessions of Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) were selected based on their superior traits, including high productivity (> 2 kg tree^{-1} yr^{-1}), stable yields, and resistance to pests and diseases. The study was conducted over the course of 2020 (January-December) and covered two growing and harvest seasons. Harvest observations were based on yield stability, assessed using production consistency data from previous years. The plantation is located in Pagar Alam Regency, South Sumatra, Indonesia. The coffee plots were situated in several villages within the subdistricts of North Dempo and South Pagar Alam.

Each of the 21 Robusta coffee accessions was cultivated in distinct plots characterized by specific conditions such as geographic location, elevation, plant age, propagation method, productivity, and agronomic traits. The details of the plantation sites for each accession are presented in Table 1. Most of the 21 Robusta coffee accessions observed were propagated by seeds, except for accessions D2, D3, and D4, which were propagated by non-apical grafting using plagiotropic branches as the scion. The plants were generally considered old; however, their productivity remained relatively high (> 2 kg beans tree^{-1} yr^{-1}). The advanced age of these accessions indicates long-term survival under local agroecological conditions.

Table 1. Geographic location (coordinates and elevation) of each Robusta coffee accession plot.

Accession number	Accession code	Coordinates	Elevation (m a.s.l.)
1	R1	4°4'42.4" S, 103°9'20.0" E	1194
2	R2	4°4'41.8" S, 103°9'21.6" E	1190
3	R3	4°4'46.1" S, 103°9'20.2" E	1191
4	R4	4°4'44.5" S, 103°9'18.9" E	1226
5	R5	4°4'38.5" S, 103°9'18.9" E	1220
6	W1	4°4'57.6" S, 103°9'42.9" E	1168
7	W2	4°4'58.4" S, 103°9'40.8" E	1185
8	D1	4°5'31.0" S, 103°9'43.1" E	1103
9	D2	4°5'31.5" S, 103°9'43.6" E	1099
10	D3	4°5'31.3" S, 103°9'43.1" E	1103
11	D4	4°5'31.6" S, 103°9'43.6" E	1099
12	DV	4°5'9.4" S, 103°10'36.1" E	1005
13	YD1	4°4'48.3" S, 103°10'6.2" E	1091
14	YD2	4°4'48.1" S, 103°10'6.3" E	1095
15	HL1	4°5'7.8" S, 103°10'16.3" E	1104
16	HL2	4°5'8.1" S, 103°10'16.3" E	1102
17	MH1	4°6'7.0" S, 103°9'50.6" E	1247
18	MH2	4°6'7.7" S, 103°9'50.7" E	1246
19	F	4°5'58.7" S, 103°9'50.0" E	1213
20	PD1	4°4'25.3" S, 103°10'2.9" E	1212
21	PD2	4°4'28.6" S, 103°10'2.3" E	1214

Experimental site and environmental conditions

The field experiment was conducted in Pagar Alam District (4°01'-4°05' S, 103°09'-103°10' E; 700-1200 m a.s.l.), South Sumatra Province, Indonesia. The region has a humid tropical highland climate, with daily temperatures ranging from 20 to 26 °C and a distinct dry season between June and August. Annual rainfall was 2325 mm (2017) and 2413 mm (2018), distributed across 151-158 rainy days (Table 2).

Table 2. Climatic conditions of the study area in Pagar Alam Regency, South Sumatra, Indonesia (2017-2018).

Year	Annual rainfall	Rainy days	Wettest month (rainfall)	Dry season
	mm	d	mm	
2017	2325	158	Feb (320)	Jun-Aug
2018	2413	151	Nov (390)	Jun-Aug

Soils in the experimental plots are classified as Ultisols, moderately acidic (pH 4.7-5.2) with moderate to high cation exchange capacity (23-37 cmol$_{(+)}$ kg^{-1}). Organic C ranged from 5.6% to 10.3%, while available P varied from very low to very high (6.6-77.7 mg kg^{-1}). The soils were predominantly sandy to sandy loam in texture (Table 3). These characteristics were considered in evaluating plant growth and yield performance.

Table 3. Selected soil properties of the experimental plots. CEC: Cation exchange capacity.

Property	Range
pH (H$_2$O)	4.71-5.23
Organic C, %	5.55-10.32
Total N, %	0.47-0.88
C/N ratio	11.05-19.44
Available P, mg kg^{-1}	6.62-77.65
Exchangeable K, cmol$_{(+)}$ kg^{-1}	0.54-1.74
Exchangeable Ca, cmol$_{(+)}$ kg^{-1}	6.60-18.60
CEC, cmol$_{(+)}$ kg^{-1}	23.31-36.62
Texture	Sandy to sandy loam

Morphometric traits characterization

Sample trees for each accession were selected using a purposive non-probability sampling method. The experiment consisted of three replicates, with one plant observed per replicate. The observed variables were categorized into vegetative and generative traits. Vegetative traits included plant age (yr), plant height (cm), trunk circumference (cm), crown width measured in both north-south and east-west directions (cm), leaf length (cm), leaf width (cm), lengths of primary and secondary branches (cm), number of primary and secondary branches, diameters of primary and secondary branches (cm), and internode length (cm). Generative traits included the number of clusters and number of fruits on both primary and secondary branches, fruit length (mm), fruit width (mm), fruit thickness (mm), fruit weight (g), number of seeds per 100 g, percentage of normal seeds (%), percentage of single seeds (%), and percentage of triple seeds (%).

Yield observations

Coffee productivity was assessed based on the annual yield of fresh fruit (cherry) per tree, expressed in kilograms per tree per year (kg tree^{-1} yr^{-1}). The measurement was carried out by collecting all harvested coffee cherries from each sampled tree throughout a full harvest season. The beans were then dried to a standard moisture content (approximately 12%-13%) before being weighed. This variable reflects the actual productivity performance of the coffee plants under the cultivation treatments applied.

Data analysis

To explore the structure of variation and assess interrelationships among morphological, agronomic, and yield-related traits of coffee accessions, statistical analyses were applied. ANOVA was conducted to compare mean values among accessions, with statistical significance determined at $p < 0.05$. Principal component analysis (PCA) was performed to reduce dimensionality and identify the most influential traits contributing to overall variability. Hierarchical cluster analysis (HCA) was used to classify accessions into groups based on trait similarity. Visualization of results was performed using biplots and heatmaps with dendrograms. All statistical analyses were carried out using R software (version 4.2.3; R Foundation for Statistical Computing, Vienna, Austria) with the packages *factoextra*, *pheatmap*, and *stats*.

RESULTS

Vegetative trait variation in 21 coffee accessions

ANOVA revealed significant differences ($p < 0.01$) across all vegetative traits among the coffee accessions (Table 4), indicating considerable genetic diversity and highlighting the unique vegetative strengths of each genotype. This diversity includes (1) age, (2) plant height, (3) stem diameter, (4) crown area from north to south, (5) leaf size, (6) number of primary and secondary branches, and (7) branch size, length and diameter.

Table 4. ANOVA and Tukey's HSD test for vegetative traits of coffee accessions. CV: Coefficient of variation. Means followed by different letters in the same column are significantly different at $p < 0.05$ according to Tukey's HSD test.

Accession code	Plant age	Plant height	Stem circumference	Crown width E-W direction	Crown width N-S direction	Leaf length	Leaf width	Primary branch length	Secondary branch length	Number of primary branches	Number of secondary branches	Primary branch diameter	Secondary branch diameter	Branch segment length
	yr	cm	cm	m	m	cm	cm	cm	cm	nr plant^{-1}	nr plant^{-1}	mm	mm	cm
R4	60[a]	102[i]	61.0[b]	65.00[a]	62.0[a]	20.2[b-f]	8.33[c-e]	136.75[b]	77.00[a]	6[c]	16[l]	14.90[b]	6.37[f]	7.67[b]
MH1	50[b]	168[b-e]	81.0[a]	44.50[d]	48.3[c]	20.9[a-f]	10.09[a-c]	149.00[a]	68.50[f]	4[e]	32[g]	10.85[f]	6.05[i]	6.00[h]
MH2	50[b]	184[ab]	61.0[b]	49.50[c]	47.0[d]	21.0[a-f]	9.94[a-d]	119.00[h]	70.75[e]	4[e]	35[f]	10.76[g]	7.53[b]	5.67[i]
R1	41[c]	180[a-c]	62.2[b]	28.30[fg]	29.3[i]	20.0[c-f]	8.13[c-e]	81.47[s]	61.00[p]	5[d]	10[q]	10.59[h]	7.08[c]	7.33[c]
D1	40[c]	165[c-f]	51.3[c]	30.20[ef]	28.3[j]	18.2[d-f]	7.01[e]	86.50[r]	61.05[o]	4[e]	13[n]	7.81[t]	4.61[s]	6.67[e]
W1	40[c]	170[b-e]	66.0[b]	55.20[b]	58.1[b]	24.8[ab]	11.20[ab]	121.75[f]	76.50[b]	6[c]	15[m]	10.04[j]	6.32[g]	6.02[g]
PD1	33[d]	175[a-d]	36.0[e]	43.40[d]	40.1[e]	24.9[a]	11.36[a]	92.50[q]	61.25[n]	4[e]	52[b]	10.90[e]	5.85[m]	5.67[i]
DV	30[e]	165[c-f]	40.0[e]	27.07[g]	24.8[p]	21.2[a-f]	9.92[a-d]	132.25[d]	62.75[l]	6[c]	45[c]	10.56[i]	4.59[t]	6.67[e]
F	30[e]	165[c-f]	40.0[e]	18.13[k]	25.2[n]	20.1[b-f]	9.10[a-e]	130.75[e]	73.50[c]	5[d]	40[d]	13.47[c]	6.62[e]	4.67[m]
R3	30[e]	188[a]	38.0[e]	32.00[e]	25.0[o]	20.3[a-f]	8.97[b-e]	132.25[d]	55.50[s]	5[d]	12[o]	11.22[d]	5.99[j]	5.33[j]
R5	30[e]	155[e-h]	42.0[de]	48.00[c]	21.0[q]	17.7[ef]	7.10[e]	99.00[o]	62.33[m]	8[a]	13[n]	19.64[a]	10.10[a]	7.00[d]
W2	30[e]	150[f-h]	34.0[ef]	21.00[ij]	19.4[r]	20.5[a-f]	8.10[c-e]	96.25[p]	51.25[u]	4[e]	12[o]	9.05[o]	4.94[r]	6.12[f]
YD1	30[e]	167[c-e]	42.0[de]	27.20[g]	25.2[n]	17.5[f]	8.42[c-e]	99.50[m]	64.25[j]	5[d]	37[e]	9.83[k]	5.68[o]	3.67[n]
PD2	25[f]	160[d-g]	40.0[e]	16.60[k]	17.1[s]	22.3[a-e]	8.44[c-e]	100.25[l]	58.00[r]	5[d]	30[h]	9.20[n]	7.04[d]	5.00[l]
YD2	20[g]	149[f-h]	24.0[g]	26.10[gh]	27.2[l]	19.5[c-f]	7.81[de]	101.25[k]	64.00[k]	7[b]	29[i]	9.24[m]	5.42[p]	5.67[i]
HL2	17[h]	160[d-g]	27.0[fg]	23.70[hi]	26.5[m]	19.0[d-f]	7.74[de]	104.50[i]	65.75[h]	4[e]	96[a]	9.37[l]	5.91[l]	5.33[j]
HL1	15[h]	144[gh]	34.0[ef]	18.90[jk]	27.4[k]	19.4[d-f]	7.92[c-e]	92.50[q]	67.50[g]	2[f]	26[j]	8.88[p]	5.28[q]	7.33[c]
R2	6[i]	141[h]	20.3[g]	21.50[ij]	21.0[q]	17.7[d-f]	8.61[c-e]	134.50[c]	53.25[t]	5[d]	5[r]	8.20[q]	5.71[n]	4.67[m]
D4	4[ij]	184[ab]	51.0[c]	30.20[ef]	29.5[h]	17.5[f]	7.19[e]	104.25[j]	59.75[q]	4[e]	15[m]	6.43[u]	4.38[u]	5.67[i]
D3	3[j]	176[a-d]	49.0[cd]	27.17[g]	32.0[f]	22.4[a-d]	8.42[c-e]	99.25[n]	65.25[i]	4[e]	11[p]	8.18[r]	6.18[h]	5.12[k]
D2	2[j]	172[a-d]	42.0[de]	28.50[fg]	30.2[g]	24.1[a-c]	8.86[c-e]	119.75[g]	71.75[d]	4[e]	17[k]	8.04[s]	5.92[k]	8.00[a]
Significance	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
CV, %	3.22	3.19	5.86	2.79	0	7.37	8.38	0	0	0	0	0	0	0

The PCA analysis revealed that the cumulative contribution of the principal components (PCs) increased substantially in the early PCs. The first five PCs explained approximately 70% of the total variation, while the first nine PCs accounted for 89% of the morphological variability among accessions. This indicates that most of the variation can be represented by a relatively small number of components, allowing subsequent analyses to focus on the major PCs (Figure 1).
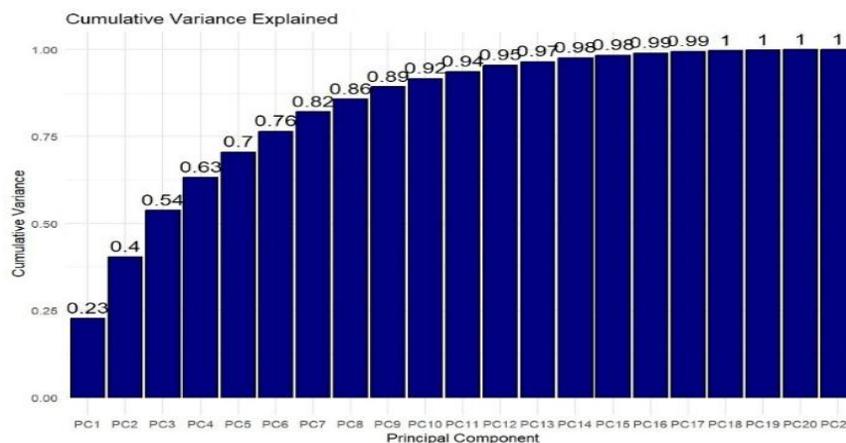
Figure 1. Cumulative variance (%) explained by the first five principal components (PCs) of vegetative traits in 21 Robusta coffee accessions.

The wide range of vegetative traits observed among coffee accessions suggests strong potential for targeted selection and future breeding efforts. Among the 21 accessions evaluated, only four—R3, MH1, MH2, and R4—demonstrated superior agronomic traits. These include taller plant height, longer branches, and a greater number of branches. Such traits are commonly associated with high-performing varieties and are often used as key indicators in the selection, improvement, or conservation of coffee germplasm (Figure 2).
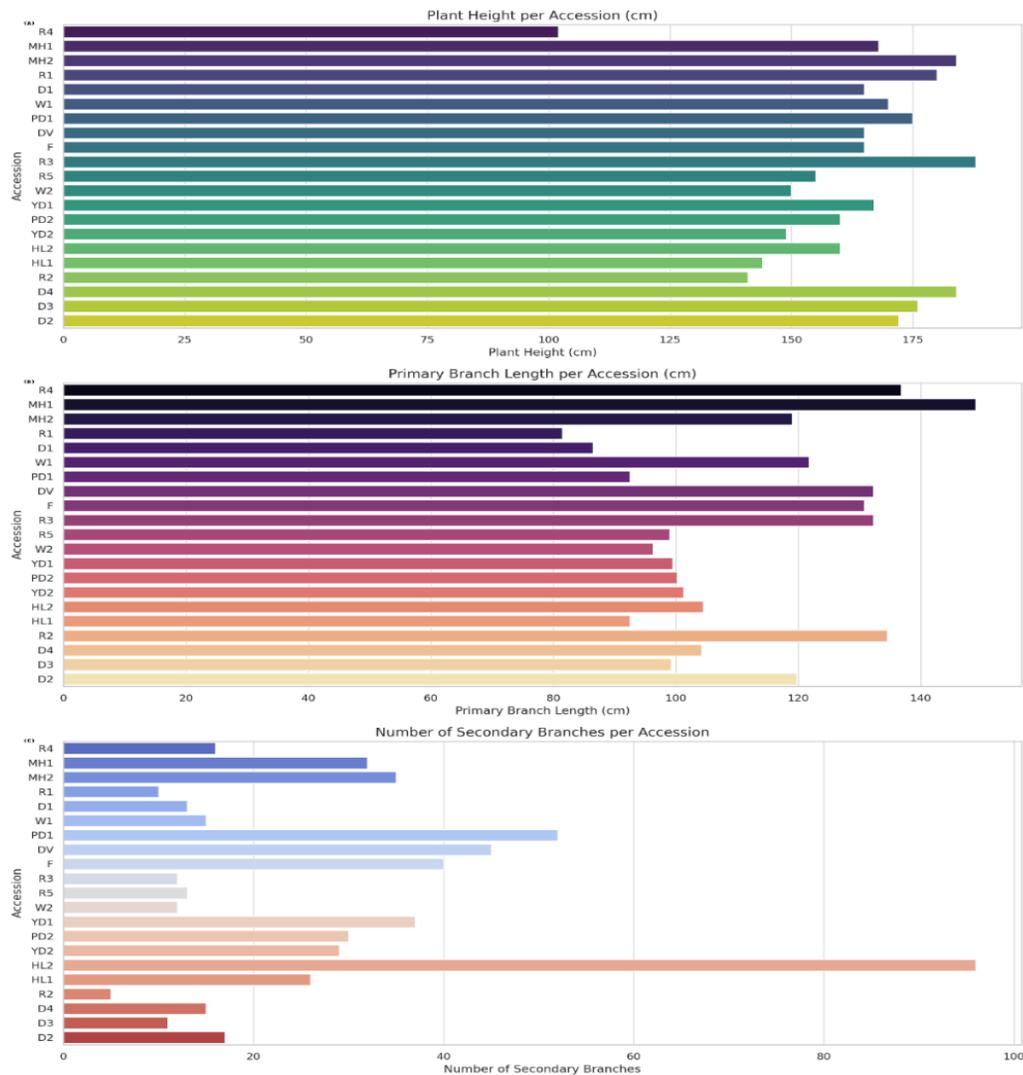
Figure 2. Variation in vegetative traits of 21 Robusta coffee accessions: Plant height (A), primary branch length (B), and number of secondary branches (C). Bars = mean ± SE (n = 3).

The graphical comparison of plant height, primary branch length, and secondary branch number (Figure 2) reveals clear vegetative variation among 21 coffee accessions. Accessions R3, MH1, MH2, R4, and R5 showed superior plant height and branching architecture, while D2, D3, and R2 displayed lower values. This variation reflects genetic diversity and supports the selection of superior genotypes for breeding or conservation. The high secondary branch count in HL2 and the long primary branches in MH1 and R4 enhance canopy development and yield potential, making these traits valuable for field selection.

Characteristics of generative properties

Analysis of generative traits across 21 coffee accessions revealed highly significant differences ($p < 0.01$) for all measured variables (Table 5). Accession MH2 showed prominent generative characteristics compared to other accessions, namely providing the highest yield with significant differences ($p < 0.01$) in seed production and number of fruits per primary branch (Table 4). The highest seed production in MH2 was supported by the highest number of normal seeds, normal seed percentage (94%), with minimal single-seeded fruits. It appears that the agronomic performance of the generative variable that determines seed productivity is the number of fruits per primary branch. This characteristic can be a superior trait for coffee accessions or varieties for high productivity purposes.

Table 5. ANOVA and Tukey's HSD test for generative traits of coffee accessions. CV: Coefficient of variation. Means followed by different letters in the same column are significantly different at $p < 0.05$ according to Tukey's HSD test.

Accession code	Number of clusters on primary branches	Number of clusters on secondary branches	Number of fruits on primary branches	Number of fruits on secondary branches	Fruit length (mm)	Fruit width (mm)	Fruit thickness (mm)	Weight of 100 fresh beans (g)	Weight of 100 dry parchment coffee beans (g)	Weight of 100 dry green coffee beans (g)	Seed production (fresh fruit) (kg tree⁻¹ yr⁻¹)	Normal seeds (%)	Single-seeded fruits (%)	Three-seeded fruits (%)
R4	21.50c	12.50f	32.00l	28.00o	12.08a-c	16.52c-f	15.09a	221.56c-h	54.43de	49.61c-f	3.52e	63.33c-e	36.33a-c	0.33ab
MH1	18.25e	11.75g	32.00k	30.00k	12.26a-c	18.98a-c	14.55e	272.35a-c	70.94a	63.07a	4.30c	75.00a-d	25.00b-e	0.00b
MH2	17.50h	12.75e	39.50a	38.00b	11.48c	18.00a-e	13.81a	215.78d-i	65.96ab	56.85a-c	10.11a	94.00a	5.33e	0.67a
R1	8.67s	16.33a	38.67b	34.67d	12.34a-c	14.45fg	14.45e	160.99ij	44.63fg	39.95e-h	3.00l	90.67ab	9.33de	0.00b
D1	17.25i	10.25l	30.75n	29.16l	11.86bc	18.96a-c	12.89a	230.37b-g	63.89a-c	54.89a-d	3.52e	72.33a-e	27.67a-e	0.00b
W1	18.00f	10.50k	26.50t	26.00s	11.92bc	15.58d-g	13.00a	176.65g-j	52.39d-f	32.33h	4.02d	58.00de	42.00ab	0.00b
PD1	15.50p	13.00d	34.50h	26.12r	13.56ab	16.78c-f	15.72a	239.66a-e	60.41b-d	51.33b-e	5.01b	47.33e	52.67a	0.00b
DV	16.50k	9.25o-i	23.50u	21.50t	13.49ab	18.96a-c	15.41a	241.49a-e	69.91a	60.38ab	3.06j	73.33a-e	26.67a-e	0.00b
F	20.25c	14.25b	36.25f	32.50g	13.75ab	18.69a-d	15.10a	255.25a-e	63.99ab	54.22a-d	3.00l	79.67a-d	20.33b-e	0.00b
R3	19.50d	11.25i	37.00d	30.75f	12.39a-c	17.70a-e	15.97a	216.39d-f	55.84c-e	48.12c-f	3.12f	59.67de	40.33ab	0.00b
R5	17.00j	13.00d	29.67p	32.67f	11.22c	14.89e-g	12.86a	155.01j	40.35g	34.01gh	3.07i	68.33a-e	31.67a-e	0.00b
W2	17.50h	11.11j	33.45l	26.25q	11.17c	13.40g	12.84a	170.59h-j	48.58e-g	39.22e-h	3.11g	87.67a-c	12.33c-e	0.00b
YD1	16.23m	11.75g	30.25o	30.50j	12.08a-c	17.39b-f	13.73a	233.10b-f	67.96ab	57.85a-c	3.01k	77.67a-d	22.33b-e	0.00b
PD2	16.25l	12.50f	36.50e	38.25a	13.61ab	18.89a-c	14.68a	270.64a-d	66.61ab	56.67a-c	3.00l	67.67a-e	32.33a-d	0.00b
YD2	17.75g	12.50f	28.50r	28.67m	12.07a-c	18.39a-d	12.98a	234.03b-f	73.06a	45.41d-f	2.82m	72.33a-e	27.67a-e	0.00b
HL2	15.00q	9.67n	29.50q	32.00h	12.96a-c	18.37a-d	14.68a	224.67b-h	65.49ab	55.07a-d	2.72n	74.00a-d	26.00b-e	0.00b
HL1	15.00q	11.50h	34.00i	30.00k	13.97a	20.23ab	15.72a	261.36a-d	72.75a	62.36a	3.10h	65.67b-e	34.33a-d	0.00b
R2	23.00a	14.11c	37.75c	36.00c	13.47ab	15.61d-g	14.96a	200.65e-j	52.21d-f	43.29e-g	2.32q	73.67a-e	26.00b-e	0.33ab
D4	14.75r	10.50k	36.00g	33.75e	11.19c	16.71c-f	12.96a	180.15f-j	54.34de	48.71c-f	2.52o	74.67b-d	25.33b-e	0.00b
D3	15.75o	12.75e	31.00m	28.50n	12.85a-c	20.52a	14.60a	279.66a-b	69.11ab	54.93b-d	2.50p	58.00de	42.00ab	0.00b
D2	16.05n	9.75m	27.21s	26.50q	12.27a-c	20.48ab	14.81a	290.89a	70.53a	58.57a-c	2.23r	53.33de	46.67ab	0.00b
Significance	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
CV, %	0	0	0	0	4.94	5.68	7.24	7.9	4.93	6.63	0	0	29.6	33.2

Three other accessions, namely MH1, ML1, and DV, also exhibited prominent coffee yield traits, as indicated by the weight of 100 dry green coffee beans (Table 4). These generative traits may serve as agronomic markers for identifying superior coffee varieties. These results highlight MH2, MH1, ML1, and DV as promising accessions for superior fruit and seed traits, supporting their potential use in breeding programs. The coffee fruit performance for each accession is shown in Figure 3.

Figure 3. Variation in fruit size and shape of fresh Robusta coffee from 21 accessions under field conditions in the Pagar Alam Highlands.

Heatmap analysis of agronomic traits

The relationship between vegetative and generative traits among the 21 coffee accessions reveals a meaningful pattern that can inform breeding strategies. Accessions with superior vegetative performance—such as MH1, MH2, R3, R4, and R5—also tended to show favourable generative outcomes, particularly MH2 and MH1 (Figure 4).
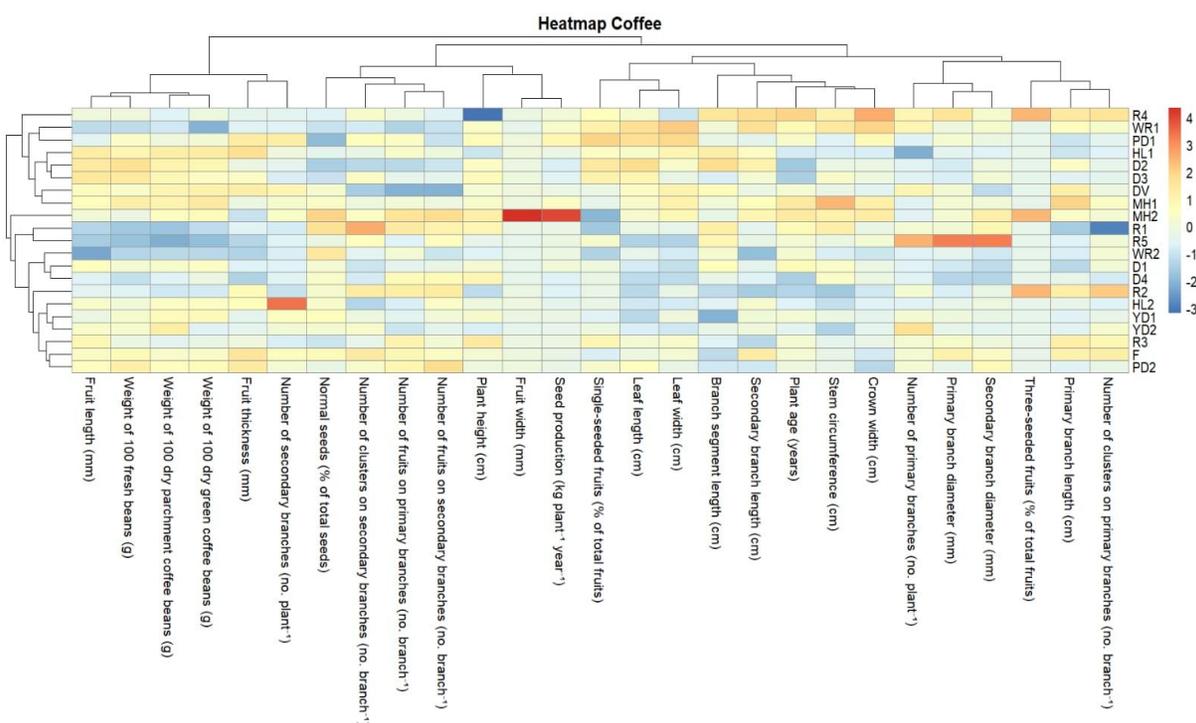
Figure 4. Heatmap of agronomic performance of 21 Robusta coffee accessions, with hierarchical clustering based on trait similarity.

For instance, MH2, which exhibited strong vegetative architecture (e.g., long primary branches and a high number of secondary branches), also recorded outstanding generative performance, including the highest number of fruits on secondary branches, high fresh bean weight, and superior seed production (fresh fruits) with 94% normal seeds. This suggests that optimal vegetative structure—especially extensive branching—may enhance assimilate distribution and support better fruit set and seed development. Similarly, MH1, characterized by long primary branches and well-balanced canopy structure, produced the heaviest 100 dry green beans (63.07 g), indicating efficient seed filling, likely supported by its vegetative vigour.

Overall, these findings suggest that vegetative traits—particularly plant height, primary branch length, and number of secondary branches—can serve as early indicators of generative potential. Strong vegetative development not only supports canopy expansion but also facilitates fruit and seed formation, making it a reliable selection criterion in field-based coffee breeding programs.

The heatmap in Figure 4 provides a comprehensive visualization of the variation in vegetative and generative traits across 21 coffee accessions. Traits are clustered based on similarity, while accessions are grouped according to their overall performance patterns. Warmer colours (red) indicate higher standardized values, whereas cooler tones (blue) reflect lower values.

Accessions such as MH2, MH1, and R2 exhibit a higher concentration of red in both vegetative and generative traits, indicating strong performance across multiple parameters—including fruit number, seed production, and branching characteristics. For example, MH2 stands out for seed production, normal seed percentage, and fruit number, consistent with prior findings.

The clustering pattern also reveals trait groupings: Vegetative parameters such as plant height, branch length, and leaf size tend to cluster together, suggesting they are co-related. Likewise, generative traits such as fruit size, bean weight, and seed characteristics form a separate cluster. This heatmap confirms the correlation between vegetative vigour and reproductive potential. The number of secondary branches shows a strong positive correlation with 100-bean weight both with and without parchment, as well as with the fresh weight of 100 coffee beans without parchment. Similarly, the number of nodes per cluster on secondary branches is strongly and positively correlated with seed yield. In addition, other major vegetative traits—such as canopy length, stem diameter, plant age, number of clusters on primary branches, and the diameters of primary and secondary branches—form a strong cluster, indicating that branching traits, plant age, and canopy architecture are interrelated and collectively influence yield (Figure 5). These correlations highlight the importance of these traits as reliable criteria for selection in coffee breeding programs.
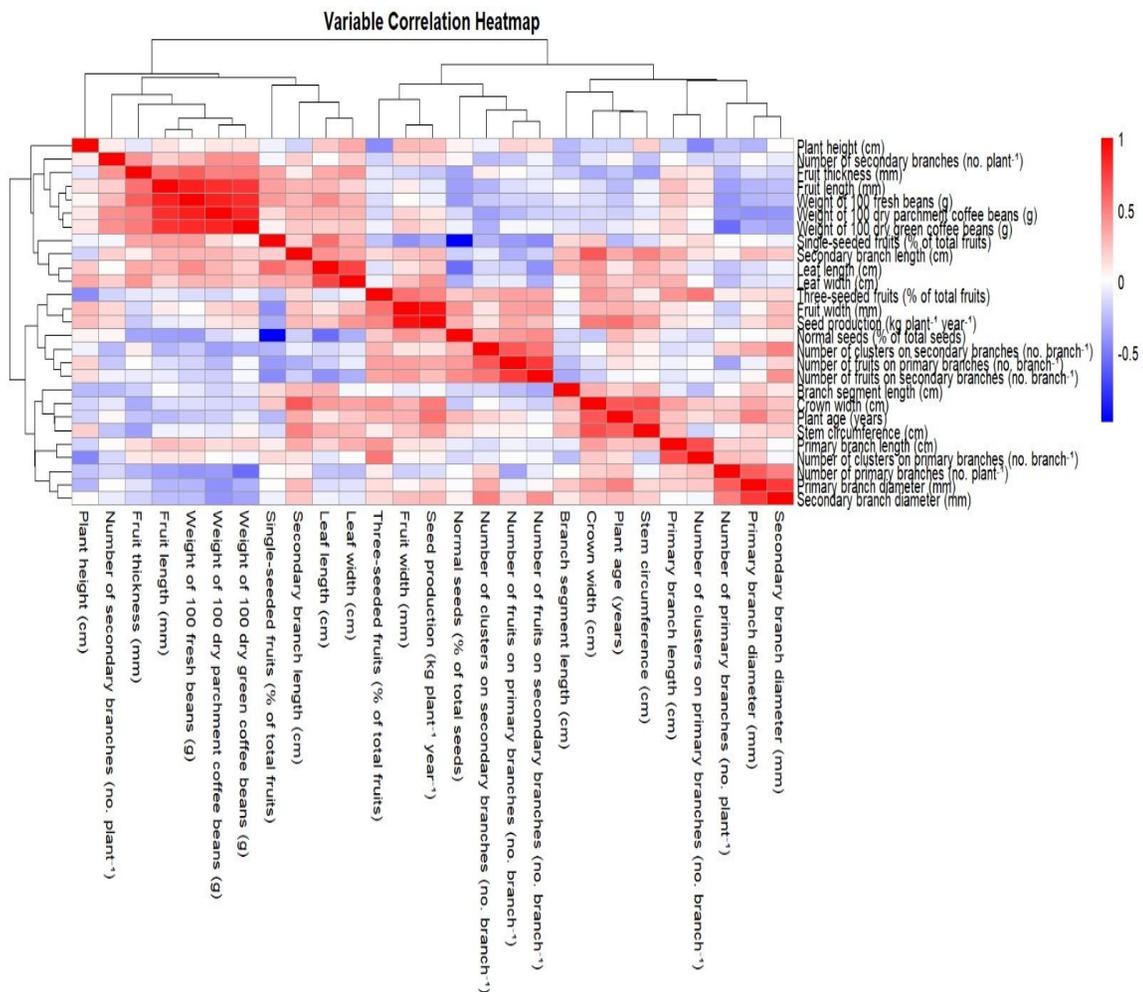
Figure 5. Heatmap of correlation coefficients among morphological, agronomic, and yield traits of 21 Robusta coffee accessions. Positive = red, negative = blue; colour intensity shows correlation strength.

DISCUSSION

The analysis showed that several vegetative traits—such as primary branch length, stem diameter, and a moderate number of secondary branches—can serve as early indicators for identifying superior Robusta coffee accessions. These traits were strongly correlated with generative traits, including the dry weight of 100 beans (with and without parchment), seed production, and the percentage of normal seeds.

Accessions such as MH2 and MH1 illustrated these relationships; MH2 combined a high fresh bean weight with a high percentage of normal seeds, suggesting efficient photosynthate allocation and reproductive success. The MH1, on the other hand, displayed a high 100-dry bean weight, indicating effective seed formation and filling. These examples highlight how vegetative traits can directly predict yield and quality outcomes.

Trait clustering patterns provided further evidence of this link. For instance, accessions with high seed production clustered with fruit diameter and plant height, while those with high fresh or dry bean weights clustered with the number of secondary branches. This indicates that selecting for specific vegetative traits can indirectly enhance yield and bean quality in breeding programs.

These findings are in line with previous studies on coffee. Gebreselassie et al. (2024) demonstrated strong correlations between traits such as the number of secondary branches, primary branch length, and canopy diameter with arabica coffee yield. Similarly, Akpertey et al. (2019) reported that plant height, stem diameter, and the number of lateral branches were closely associated with productivity. Giles et al. (2018) also highlighted the importance of stem diameter and internode length in distinguishing coffee genotypes.

Such associations indicate that morphological traits can serve as proxies for yield potential, but their genetic basis is often complex. In this context, Ferrão et al. (2024) showed that morphological traits related to yield in *Coffea canephora* are largely under polygenic control, with nonadditive gene actions contributing to hybrid vigour. In addition, Sulistiono et al. (2021) found that differences among clones extended beyond morphology to physiological attributes, such as leaf chlorophyll and proline content.

Morphological diversity observed here supports the findings of Alemayehu et al (2022), who emphasized that agronomic traits such as fruit shape, branching pattern, plant growth habit, and stem structure are important in differentiating accessions. This diversity also aligns with rapid screening tools based on phenotypic heatmaps (Zhai et al., 2024) or chemical profiling (Santos et al., 2025).

The close association between vegetative traits and yield capacity is further reinforced by eco-physiological studies. Max et al. (2022) linked high productivity with C assimilation, leaf hydraulics, and stomatal efficiency, while Suela et al. (2023) highlighted the role of node and internode counts in determining flowering and productivity.

Overall, this study demonstrates that vegetative traits are reliable early selection indicators. They provide a practical framework for identifying superior genotypes, improving yield and quality, and conserving valuable genetic resources. Accessions MH2 and MH1, in particular, emerge as promising parents for breeding programs, in line with phenotypic selection approaches suggested by Alkimim et al. (2020). To the best of our knowledge, this study provides the first evidence of a strong relationship between primary branch length and 100-bean weight in local Robusta coffee from Pagar Alam, offering a novel and practical insight for more targeted and efficient breeding.

CONCLUSIONS

Vegetative architecture, particularly long primary branches and a moderate number of secondary branches, showed strong positive correlations with generative traits such as 100-bean weight, seed production, and the percentage of normal fruits in the evaluated Robusta coffee accessions. Accessions MH2 and MH1 emerged as promising candidates for breeding due to their superior vegetative and generative traits under the conditions of this study. These results indicate that vegetative traits may serve as potential early selection markers in Robusta coffee improvement. However, further studies involving a wider range of genotypes and environments are required to validate their broader applicability.

Author contribution
Conceptualization: E.R., H.S. Methodology: E.R., H.S., D. Software: E.F., W.S. Validation: E.W., D.P., B.H., S.A. Formal analysis: E.F., W.S. Investigation: E.R., H.S., N.P.E., S.A. Resources: E.R., E.F., W.S., Sak.S., Sae.S., H.S., D. Data curation: E.F., W.S., H.S.

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