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PATCHOULI (*POGOSTEMON CABLIN* BENTH.) GERMLASM DIVERSITY AND GENETIC RELATIONSHIP IN THE COASTAL AND HIGHLAND REGIONS OF ACEH PROVINCE, INDONESIA

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SUMMARY

Patchouli (*Pogostemon cablin* Benth.) is a valuable essential oil-producing plant that considerably contributes to the global industry. Indonesia is prominent as a global leader in patchouli oil production, accounting for 80%–90% of the global market, with the Aceh Province supplying 70% of the production. The following study aimed to assess the morpho-agronomic diversity, yield, and quality of the essential oil in 14 patchouli accessions grown both in coastal and highland regions of the Aceh Province, Indonesia. The characterization of plants totaled 20 per accession, with the observed variables including quantitative traits (morphological and agronomic characters, yield components, and patchouli alcohol (PA) content) and qualitative traits (leaf and stem characteristics and branch and oil color). The results revealed significant diversity, with lowland genotypes generally exhibiting superior vegetative growth and higher oil quality. The accession AU04 recorded the highest PA content (42.8%), while AU05 produced the greatest biomass. In contrast, highland accessions, such as BM02 and BM03, showed lower PA levels but displayed adaptive traits linked to cooler environments. Cluster analysis disclosed two major clusters, largely reflecting ecological adaptation across altitude gradients. The results demonstrate that genotype × environment interaction strongly influences growth and oil. The findings provided a crucial genetic base for selecting superior accessions and developing agroecology-based conservation and cultivation strategies for patchouli.

Keywords: Patchouli (*P. cablin*), cluster analysis, plants' characterization, morpho-agronomic traits, patchouli oil, qualitative traits

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Key findings: Morpho-agronomic variations and oil quality in 14 patchouli (*P. cablin*) accessions showed the effect of environmental adaptation. The lowland accessions gave superior vegetative growth and oil quality compared with accessions from the highlands.

INTRODUCTION

The patchouli (*Pogostemon cablin* Benth.) plant is famous for producing essential oils, which hold significant economic importance and extensive application in the perfume, cosmetics, and aromatherapy sectors (Lal *et al.*, 2023; Munandar *et al.*, 2023). Indonesia is one of the recognized leading global producers of patchouli oil, with the Aceh Province serving as one of the primary centers for its cultivation (Keumalasari *et al.*, 2025). The patchouli obtained from Aceh has become the second-best in the world, capable of yielding patchouli essential oil with a patchouli alcohol (PA) content exceeding 30% (Effendy *et al.*, 2019; Ginting *et al.*, 2021).

Traditionally, this plant has been applicable in medicinal practices to address various health issues, such as colds, fevers, headaches, gastrointestinal disorders, and bites from insects and snakes (Mrisho *et al.*, 2024). The patchouli cultivation incurs considerable effects from genotypes, genetic potential, and its adaptation to the surrounding environment (Syafuruddin *et al.*, 2020; Nisa *et al.*, 2024). Furthermore, geographical location also plays a crucial role in influencing the biochemical composition and developmental processes of patchouli plants. The patchouli plants' growth and their biochemical characteristics can differ based on varying environmental conditions and cultivation sites (Setiawan *et al.*, 2021).

The patchouli exhibits various morpho-agronomic traits that are most suitable to warm and humid climates (Fatima *et al.*, 2023; Mrisho *et al.*, 2024). Aceh Province, Indonesia, experiences significant variations in agroecosystems, ranging from hot and humid coastal regions to cooler highland areas. These environmental variations may enhance the morphological and agronomic diversity among the cultivated and locally grown patchouli germplasm (Safrizal *et al.*, 2025a). Therefore,

it is vital to investigate the morpho-agronomic diversity and genetic relationship among the patchouli accessions for identifying potential genetic resources, which could serve as a sound genetic base in breeding and conservation strategies.

Genetic diversity is a critical factor for developing improved varieties adapted to specific environments (Swarup *et al.*, 2021). Several previous studies have explored the morphological, yield, and quality traits of patchouli accessions using an agroforestry system (Daud *et al.*, 2024). These comprised the morphological and physiological traits of patchouli plants grown under shaded versus unshaded conditions (Setiawan and Sukamto, 2016) and the morphological variations observed in putative mutants of patchouli (Suhesti *et al.*, 2020). Others looked into the molecular identification alongside the morphological characterization of patchouli obtained from Batang Regency, Central Java Province (Yudifian *et al.*, 2022), and the analysis of morphology and productivity in patchouli mutants resulting from induced mutations (Zega *et al.*, 2024). A few had investigated morphological, physiological, and oil quality traits across altitudinal gradients within the same province. This gap limits the ability to design site-specific breeding and cultivation strategies for optimizing yield and quality.

The presented study sought to characterize the morpho-agronomic diversity of patchouli accessions from the coastal and highland regions of Aceh Province. It evaluated the yield of essential oils and PA content. Furthermore, through the use of cluster analysis, this research established a clear understanding of the genetic relationships among the various patchouli accessions. These results aim to explore the valuable insights in the management of more effective patchouli cultivation tailored to specific environmental contexts.

Table 1. Data on soil analysis of research sites for morphoagronomic characterization of 14 patchouli accessions.

No.	Accession code	Soil Analysis						
		pH	Texture	C Organic	N Total	P Available	K_exch	CEC
1	TM01	6.84	Dusty clay	1.10	0.36	15.40	0.72	18.40
2	TM02	6.61	Dusty clay	1.10	0.17	4.30	0.48	18.40
3	TM03	6.61	Dust	4.42	0.17	4.30	0.48	18.40
4	AU01	5.53	Dust	2.58	0.22	1.55	0.24	15.60
5	AU02	5.01	Dust	2.13	0.22	0.70	0.24	15.60
6	AU03	7.49	Dust	1.75	0.22	28.55	0.24	15.60
7	AU04	6.87	Sandy loam	0.77	0.15	33.50	0.17	14.80
8	AU05	6.87	Sandy loam	0.77	0.15	33.50	0.17	14.80
9	LS01	5.32	Sandy loam	1.22	0.11	7.90	0.95	28.40
10	LS02	5.32	Sandy loam	1.22	0.11	7.90	0.95	28.40
11	LS03	5.32	Sandy loam	1.22	0.11	7.90	0.95	28.40
12	BM01	5.04	Dusty clay	3.93	0.27	3.75	0.44	25.60
13	BM02	5.04	Dusty clay	3.93	0.27	3.75	0.44	25.60
14	BM03	5.04	Dusty clay	3.93	0.27	3.75	0.44	25.60

MATERIALS AND METHODS

Experimental site

The potential research on patchouli (*P. cablin*) commenced on arable lands owned by local farmers in four different regions of Aceh Province, Indonesia, i.e., Aceh Tamiang, Aceh Utara, Lhokseumawe, and Bener Meriah (Figure 1). The selection of locations and patchouli plant samples for characterization relied on the considerable findings of previous studies carried out by Safrizal *et al.* (2025b). The research sites were options based on variations in altitude, categorized into three altitudinal zones: low (0–100 masl), moderate (100–500 masl), and high (>500 masl). Soil analysis results included texture, pH, organic carbon content, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity (CEC) (Table 1).

Patchouli plant sampling and observations

In this study, we used 5-month-old patchouli plants. The selected samples should be healthy, with no symptoms of pests and disease infestations. These patchouli plants received natural cultivation on plantations owned by local farmers. Within each altitude, 20 individual plants became choices for morpho-agronomic characterization, where all

characterized accessions obtained labels with low altitude (TM01, TM02, TM03, AU04, AU05, LS01, LS02, and LS03), moderate altitude (AU01, AU02, and AU03), and high altitude (BM01, BM02, and BM03). The patchouli samples entailed harvesting at six months for assessment through production and yield-quality traits.

Experimental design and data collection

This study employed a descriptive design with a purposive sampling method (Nasruddin *et al.*, 2023), where data recording proceeded by conducting direct measurements and morphological observations of patchouli plants in their natural habitat. The selection of locations and samples depended on the diversity of patchouli accessions found at the research site, as well as the variations in agroecological conditions. The data-recording process took place directly in the field, involving the observations and documentation of plant morpho-agronomic parameters.

Observed traits

The morpho-agronomic traits of patchouli plants observed during the study included plant height (cm), the number of branches, book length (cm), crown width (cm), stem diameter (cm), and the number of leaves.

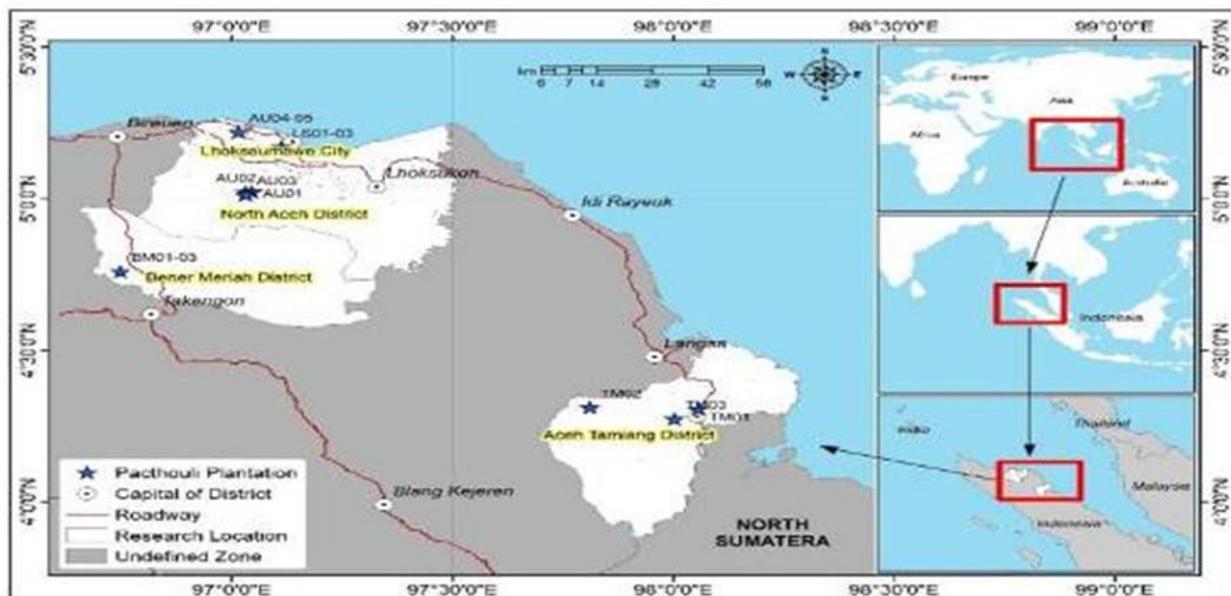


Figure 1. The study site.

Recording ensued for leaf area, length, width, and length \times width ratio using the portable laser leaf area meter type CI-202 (cm). Other traits measured comprised petiole length (cm), chlorophyll content using a SPAD-502 meter, fresh and dry weights (g), root length (cm), root fresh and dry weights (g), patchouli alcohol (%) using SNI 2385:2019 National Standardization Agency (BSN), stem and branch morphology, and color of the leaf, the upper and lower leaf surfaces, old leaves, young branches, and the oil.

Data analysis

All the data underwent descriptive analysis by computing the means and standard deviations of the recorded morpho-agronomic traits in patchouli accessions. Additionally, cluster analysis helped categorize patchouli accessions based on the similarity of morpho-agronomic traits, utilizing the NTSYS software version 2.20 (Bakry *et al.*, 2024). The similarity coefficient used was Euclidean distance. The cluster analysis method applied was the UPGMA (unweighted pair group method with arithmetic mean).

RESULTS AND DISCUSSION

Quantitative morphological traits of patchouli leaves

The results about leaf morphological traits in 14 patchouli accessions appear in Table 2. Leaf characteristics play a crucial role in photosynthesis and plant metabolism, which ultimately influences plant growth and development and the production of secondary metabolites. The data offered a detailed overview of the leaf morphological diversity found in each patchouli accession.

A recorded variability in leaf morphology emerged among the observed patchouli accessions. The patchouli accession AU04 displayed the most leaves (321.05) and the broadest leaf area (41.50 cm²), reflecting its substantial biomass and photosynthetic capacity. Conversely, the accession BM03 exhibited the lowest performance across several variables, including leaf area, length, and width. The accession LS01 resulted in the longest leaf, which enhances gas exchange efficiency, while accession TM03 demonstrated the highest chlorophyll content. The ratios of

Table 2. Leaf dimensions and chlorophyll content in the patchouli accessions.

Accession code	Leaf number	Leaf area	Leaf length	Leaf width	Leaf length × width ratio	Leaf stalk length	Chlorophyll content
TM01	284.57±1.9	40.29±2.2	9.48±6.9	7.01±1.4	1.30±5.7	3.03±1.4	50.93±3.93
TM02	319.81±20.16	38.88±0.94	8.90±0.48	6.88±0.36	1.29±0.04	2.83±0.13	47.40±8.37
TM03	280.76±11.20	39.05±0.56	9.23±0.43	6.67±0.32	1.38±0.03	2.74±0.06	58.87±5.84
AU01	318.19±38.44	39.73±5.64	9.19±1.12	7.33±0.60	1.25±0.14	2.82±0.25	49.50±2.87
AU02	298.52±29.39	39.66±3.29	9.01±0.99	7.67±0.46	1.17±0.14	2.95±0.22	46.33±2.07
AU03	293.40±16.42	32.88±3.17	8.82±0.98	6.97±0.58	1.26±0.12	2.87±0.23	42.05±1.41
AU04	321.05±20.42	41.50±5.18	9.81±1.24	7.41±0.62	1.32±0.12	2.70±0.24	40.51±3.57
AU05	310.29±9.66	39.81±2.52	9.91±0.99	7.32±0.82	1.35±0.05	2.80±0.0	41.68±1.88
LS01	204.62±18.06	39.73±2.81	9.92±0.60	7.37±0.46	1.35±0.02	2.87±0.29	40.36±4.48
LS02	224.62±18.06	36.07±2.82	9.05±0.91	6.76±0.72	1.32±0.02	2.52±0.14	45.26±6.45
LS03	201.65±10.65	40.97±1.70	9.17±0.71	7.29±0.53	1.26±0.03	2.81±0.58	56.90±11.38
BM01	230.48±23.44	23.5±0.00	7.54±0.0	5.57±0.0	1.35±0.0	1.94±0.16	40.69±3.38
BM02	245.00±32.43	30.76±0.00	8.85±0.0	6.45±0.0	1.37±0.0	2.33±0.22	40.44±2.59
BM03	216.43±12.38	19.49±0.00	7.09±0.0	5.07±0.0	7.43±0.0	2.17±0.13	42.10±5.31

leaf length to width varied, reflecting differences in leaf shape, ranging from elongated (BM03) to nearly round (AU02) leaves. Additionally, petiole length varied among the accessions. Hijrah *et al.* (2024) investigated the diversity of morphological, agronomic, and quality traits in soybean, and their findings revealed that morphological characteristics posed significant diversity, except for hypocotyl color, flower, and leaf size.

Environmental factors, particularly the altitude in growing the plants, affect leaf characteristics. Suhesti *et al.* (2020) mentioned leaves appeared as the critical trait influencing overall productivity in patchouli genotypes. The leaves serve as the primary organ for capturing light, also necessary for photosynthesis in plants. The size and thickness of leaves can impact the biomass generated by the plants (Zega *et al.*, 2024). The lowland area patchouli accessions (TM02 and AU05) demonstrated more leaves than those from the highland regions, such as BM03, which had fewer and smaller leaves, likely due to lower temperatures and limited exposure to sunlight. The results revealed some patchouli accessions have the potential for further development in cultivation programs. Among the investigated patchouli accessions, the genotype AU04 showed the

best performance with the potential to be a leading candidate for biomass production.

Yield and quality traits of the patchouli oil

The data on the yield of patchouli oil and its quality traits are available in Table 3. The patchouli accessions involved evaluation through different variables to determine the potential of each accession for biomass production and the quality of patchouli oil. The results illustrated the genetic diversity among the accessions, as well as their physiological responses to varying environmental conditions. These results will serve as a foundation for the selection of high-yielding accessions with optimal PA content, which is essential for the advancement of sustainable patchouli cultivation.

A considerable variation occurred both in the yield and quality of patchouli oil accessions. The patchouli accession AU05 exhibited the highest fresh weight (1517.12 g) and dry weight (1208.75 g), suggesting a significant potential for biomass production. The accession AU04 demonstrated superior root weight and the maximum PA content (42.80%), becoming identified as the prime candidate for producing high-quality patchouli oil. Accession BM03 ranked the lowest in nearly all the observed traits, including fresh and dry

Table 3. Yield and oil quality characters in the patchouli accessions.

Accession code	Fresh weight	Dry weight	Root length	Root fresh weight	Root dry weight	PA content
TM01	1208.85±4.8	962.32±5.2	38.43±3.1	226.37±7.3	200.43±7.5	36.82±1.5
TM02	1314.14±52.8	1066.60±66.8	40.40±2.6	230.18±6.6	200.09±9.5	38.7±0.0
TM03	1256.56±34.2	979.50±17.3	40.48±2.6	239.21±8.01	195.81±6.7	39.39±0.0
AU01	1334.55±92.3	901.43±94.8	44.67±3.6	183.60±14.2	127.73±12.7	31.18±7.2
AU02	1310.01±104.1	909.28±176	44.19±3.4	237.03±21.5	206.57±23.2	32.29±0.0
AU03	1304.63±58.6	1051.50±56.5	42.29±2.0	240.54±20.9	199.82±23.6	36.97±0.0
AU04	1321.79±42.6	1087.25±38.6	40.67±2.3	260.35±8.2	221.08±27.7	42.80±0.0
AU05	1517.12±28.1	1208.75±29	39.86±1.7	178.72±14	145.67±13.2	42.60±0.0
LS01	1074.49±28.1	718.41±55.7	41.38±2.2	165.24±12.6	129.07±14.7	42.37± 0.0
LS02	1141.86±35.3	765.48±46.2	41.67±2.1	251.03±5.5	205.72±29.2	41.15 ±0.0
LS03	1032.85±144.1	618.89±140.3	37.95±2.9	215.00±23.6	170.63±21.8	40.69±0.0
BM01	974.36±41.6	632.59±56.7	27.86±1.8	160.09±6.5	113.45±29.4	30.20±0.0
BM02	1069.91±88.6	673.10±80.3	27.67±2.0	176.33±21.1	113.61±30.8	30.68±0.0
BM03	853.75±98.2	444.30±56.5	28.24±2.3	144.63±12.8	89.01±3.1	30.27±7.2

weights and PA content, indicating its limited production capacity. These results were similar to the findings of Huang *et al.* (2016), who reported three patchouli accessions (from the northernmost region of China) exhibited the lowest PA content, whereas other accessions displayed higher PA contents. The results further revealed the accession AU01 possessed the longest root length, signifying an enhanced capability for nutrient absorption, while the accession BM02 had the shortest roots. These investigations affirm the significant role of root morphological characteristics in facilitating the growth and development of patchouli plants. Mrisho *et al.* (2025) stated that patchouli roots develop an extensive and branched root system, allowing them to penetrate deep into the soil in mature plants that grow without interference.

The variation in PA content observed among patchouli accessions reflects the influence of the genotype × environment interaction. Environmental parameters, particularly altitude-related temperature and light intensity, typically regulate terpenoid biosynthesis, including the formation of patchouli alcohol. Lowland conditions provide higher temperatures and greater light intensity, which boost photosynthetic activity and energy production (ATP, NADPH). These factors increase the availability of metabolic

precursors for the mevalonate and methylerythritol phosphate pathways, thereby stimulating the synthesis of sesquiterpenes such as PA. This explains why the accession AU04 showed the highest PA content (42.8%) under lowland conditions. In contrast, the cooler climate of highland regions (BM02 and BM03) limits enzymatic activity and metabolic flux in secondary metabolite biosynthesis, leading to reduced PA accumulation. Highland accessions with lower PA contents demonstrated traits that support stress tolerance, such as slower growth and smaller biomass, which may be advantageous under low-temperature or resource-limited environments.

These observations align with the findings of Rachmaniah and Nugraha (2018) and Ritawati *et al.* (2021), who confirmed patchoulis grown in lowlands possess higher oil contents than patchoulis cultivated in highlands. Rinaldi *et al.*'s (2022) findings further revealed a correlation between altitude and the patchouli oil yield, denoting higher altitudes have an association with increased oil production. These findings suggested the accessions AU05 and AU04 (Aceh Utara) were notable as potential genotypes worth recommending for further development in patchouli cultivation.

Table 4. Qualitative morphological characterization of patchouli leaves.

Accession code	Leaf color	Stem shape	Branch shape	Leaf surface		Branch color		Oil color
				Upper	Old branch	Young branch	Lower	
TM01	Green	Round	Rectangular	Green	Purple	Purple	Pale green	Yellow
TM02	Purplish green	Round	Round	Purplish green	Purple	Purple	Mild maroon	Brownish yellow
TM03	Green	Round	Rectangular	Green	Purple	Purple	Pale green	Yellow
AU01	Purplish green	Round	Rectangular	Purplish green	Purple	Purple	Pale green	Yellow
AU02	Green	Round	Round	Green	Purple	Purple	Pale green	Yellow
AU03	Green	Round	Round	Green	Purple	Purple	Pale green	Yellow
AU04	Green	Round	Round	Green	Purple	Purple	Mild maroon	Brownish yellow
AU05	Purplish green	Round	Rectangular	Purplish green	Purple	Purple	Pale green	Brownish yellow
LS01	Purplish green	Round	Round	Purplish green	Purple	Purple	Pale green	Yellow
LS02	Purple	Round	Round	Purple	Purple	Purple	Pale green	Yellow
LS03	Green	Round	Rectangular	Green	Purple	Purple	Pale green	Yellow
BM01	Green	Round	Rectangular	Green	White	Purple	Pale green	Light Yellow
BM02	Purplish green	Round	Round	Purplish green	White	Purple	Mild maroon	Yellow
BM03	Green	Round	Rectangular	Green	White	Green	Green	Light Yellow

Qualitative morphological characterization of patchouli leaves

The qualitative morphological analysis of the different patchouli accessions appears in Table 4. The qualitative morphological characterization of the leaves revealed considerable variations among patchouli accessions, particularly for leaf color, branch shape, and oil color. The differences in leaf color were ascribable to both genetic diversity and environmental responses. Predominantly, leaf colors ranged from green to purplish green, and the one accession (LS02) exhibited a deep purple color. Accessions from Aceh Utara and Lhokseumawe displayed a tendency toward purplish-green leaf coloration, which could suggest a higher accumulation of anthocyanins in these regions, potentially as a reaction to environmental stressors. However, all the accessions exhibited a round-stem shape, indicating uniformity of this trait within the studied patchouli collection. Still, variations were evident in the branch shape. Most branches were round; although, certain

accessions (from Aceh Tamiang and Bener Meriah) presented rectangular branch shapes. This variation in branch morphology may correlate with the plant's lateral growth capacity and structural resilience.

In patchouli accessions, the leaf surface generally appeared green or purplish green, aligning with the coloration of both the upper and lower leaves. However, nonsignificant differences resulted in this characteristic among the studied accessions, implying a potential low variability for this trait. The coloration of both old and young branches in most accessions was purple, except for three patchouli accessions from Bener Meriah (BM01, BM02, and BM03), which exhibited white, old branches. This alteration in color can serve as an indicator of lignification levels and tissue age. Haryanti *et al.*'s (2024) findings disclosed the color transition in patchouli explants shifts from green to yellowish or pale white, signifying damage to photosynthetic pigments.

The colors of patchouli oil vary from yellow and light yellow to brownish yellow and slightly maroon. However, these colors gained

influences from the presence of chemical compounds, such as patchouli alcohol (PA) and other phenolic substances. Patchouli accessions exhibiting brownish-yellow or slightly maroon oil (AU04, AU05, and TM02) may possess higher concentrations of bioactive compounds. A yellow color in patchouli oil signifies a high PA content, whereas a brown color indicates a low PA content (Pawestri and Fitri, 2019). Generally, the patchouli accessions from Bener

Meriah (BM) demonstrated unique traits regarding branch and oil colors. The results proposed the potential of the diverse genetic resources, which can be considerable candidates for breeding and cultivation initiatives.

The results about the morphological distinctions in trubus, leaves, stems, branches, leaf surfaces, and leaf undersides of various patchouli accessions have details in Figure 2.

Accession code	Trubus	Stem	Branch	Upper Leaf surface	Lower leaf surface
TM01 TM03 LS03 AU01 AU05 LS01 AU02 AU03 LS02 BM02					
TM02 AU04					
BM01, BM03					

Figure 2. Qualitative morphology of trubus, stem, branches, leaf surface, and leaf underside.

This illustration aims to enhance the characterization data by demonstrating significant phenotypic variations among the

accessions, particularly in the color, shape, and structure of plant tissues. The grouping based on morphological characteristics revealed

significant disparities among the patchouli accessions. Accessions TM01, TM03, LS03, AU01, AU05, LS01, AU02, AU03, LS02, and BM02 exhibited the same morphological patterns across all observed parameters, while accessions TM02 and AU04 formed a distinct group. In contrast, the patchouli accessions, BM01 and BM03, displayed quite pronounced morphological differences versus the other groups.

The observed morphological variations showed genetic diversity among the examined patchouli accessions. The substantial group, comprising the accessions TM01, TM03, LS03, AU01, AU05, LS01, AU02, AU03, LS02, and BM02, enunciated a relatively high level of morphological uniformity. However, this uniformity may refer to the geographical closeness and interchange of planting materials across the regions, resulting in genetic homogenization.

The placement of patchouli accessions TM02 and AU04 in a separate group highlighted phenotypic variation that could be in association with local adaptation and specific selection pressures in their respective regions of origin. For achieving optimal plant growth and development, the adaptation to environmental variations is essential (Prayoga *et al.*, 2024). The further assessment of BM01 and BM03 implies accessions from Bener Meriah exhibited more distinctive morphological traits, likely shaped by the unique agroecological conditions of the area. This differed from those of other lowland areas in Aceh, such as variations in altitude and cooler temperatures.

These observations align with the theory of phenotypic variation, which posits that environmental differences can influence the plant's morphological traits, even from the same species (Yogendra *et al.*, 2024). Consequently, the selection aimed at identifying superior accessions makes it vital to

consider these unique traits to acquire genotypes more well-suited to the specific conditions of the development area. Overall, this qualitative morphological assessment offers an initial overview of the diversity found among the patchouli accessions of Aceh, serving as a basis for subsequent genetic and agronomic analyses and further improvement.

Analysis of morpho-agronomic diversity

Cluster analysis sought to categorize the patchouli cultivation sites according to the similarity of the observed morpho-agronomic traits of the plants. This methodology seeks to uncover patterns of phenotypic similarity among the locations, which could reveal the effect of environmental factors on plant trait variations. Tahir *et al.* (2019) also employed cluster analysis to assess the genetic diversity of each patchouli mutant genotype, thereby allowing for a more precise estimation of the selection direction. The illustrated outcomes of the cluster analysis appeared in a dendrogram, which depicts the relationship among the patchouli accessions procured from various cultivation sites (Figure 3).

The classification succeeded in its determination by the similarity coefficient represented on the horizontal axis, with values ranging from 0.60 to 0.94 (Figure 3). The results indicated the patchouli accessions entailed dividing into two primary groups at a coefficient of approximately 0.70. The first group, comprising the accessions BM01 and BM03 obtained from the Bener Meriah highlands, emerged notably distinct from the other group, suggesting a significant difference in morpho-agronomic traits compared with patchouli accessions from other regions. These distinctions likely reflect adaptation to environmental conditions, such as lower temperature and lower sunlight intensity in the highlands. Regarding production and quality assessment, these accessions demonstrated potential for low PA levels. The different regions with considerable environmental variations can influence plant growth and patchouli oil quality (Souhoka *et al.*, 2020). Machdar *et al.* (2025) cited both environmental

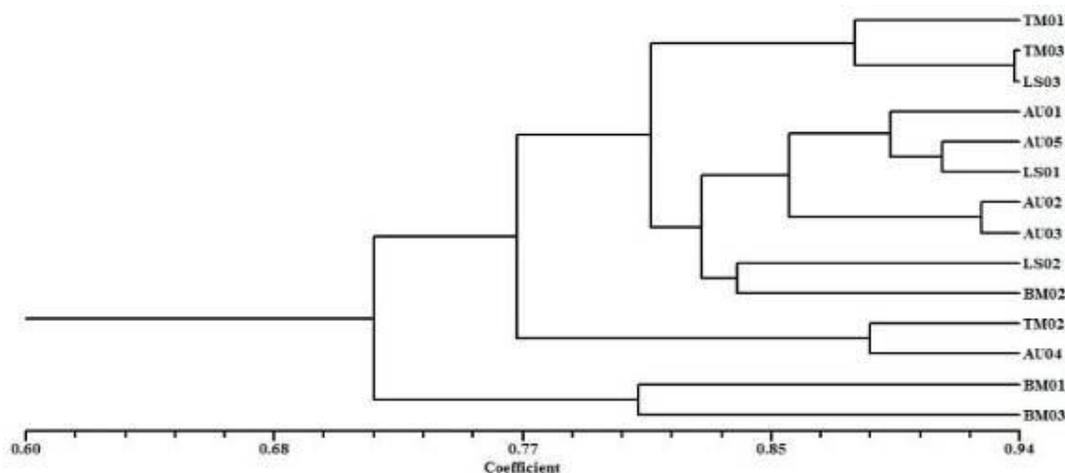


Figure 3. Dendrogram of morphoagronomic diversity analysis.

factors that impact the overall oil yield and influence the concentration and proportion of other key biochemical components.

The second group comprises the patchouli accessions from Aceh Tamiang (TM01, TM02, TM03), Aceh Utara (AU01, AU02, AU03, AU04, and AU05), and Lhokseumawe (LS01, LS02, LS03), along with one accession from Bener Meriah (BM02). In this group, it was evident that several accessions from various locations form relatively close subclusters; for instance, TM01, TM03, and LS03 reached grouping together at the coefficient nearing 0.94, which signifies a high degree of character similarity despite their different origins. Similar patterns were also noticeable in the subclusters AU05 and LS01, as well as AU02 and AU03. Patchouli accessions within this subcluster typically revealed considerable vegetative growth, yielding high fresh and dry biomass, although the PA content showed variability. According to Lee *et al.* (2020), PA contents vary depending on the harvested period, cultivated location, and the experimental conditions.

The subclusters AU05–LS01 and AU02–AU03 illustrated that accessions from Aceh Utara and Lhokseumawe possess closely related characteristics, even though these patchouli accessions came from two distinct districts. This may indicate the dissemination of similar plant material in geographically

neighboring regions. In these accessions, oil production was generally moderate, with fluctuations in PA content that could have acquired effects from interactions of genotypes and environmental factors. Accessions TM02, AU04, and BM02, categorized into separate subclusters, exhibited unique variations that can serve as potential genetic resources for breeding initiatives. Notably, the accession AU04 demonstrates considerable growth traits and competitive essential oil yield, positioning it as an excellent candidate for further development.

Briefly, the cluster analysis detailed geographical factors that do influence the variation in morpho-agronomic traits; their location did not solely constrain the phenotypic distribution of patchouli plants. Consequently, conservation and breeding approaches should consider specific characteristics of patchouli accessions rather than focusing exclusively on their geographical origins. This observation implies variations in altitude and geographical position do not completely dictate morpho-agronomic differences, as there exists a phenotypic overlap across the different locations. Nevertheless, patchouli accessions originating from Bener Meriah appear to form a distinct cluster, which may indicate a particular adaptation to the highland agroecological environment.

CONCLUSIONS

Altitude significantly affects the morphological characteristics, yield, and quality of the patchouli oil. Lowland accessions, AU04 and AU05, demonstrate superior vegetative traits and PA content, positioning them as excellent candidates for commercial cultivation and breeding programs. Studying various patchouli accessions can enhance breeding, conserve genetics, and identify optimal growing areas, improving both productivity and oil quality.

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