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Study on yield and chemical constituent of *Pogostemon Cablin* (Blanco) Benth collected from different regions in Aceh Province, Indonesia

Izarul Machdar[1,2*], Dinda Ariefa Luthfiah[1], Husni[3], Wahyu Rinaldi[1]

[1] Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Jalan Teungku Syech Abdur Rauf, Darussalam, Banda Aceh 24415, Indonesia
[2] Atsiri Research Center, Universitas Syiah Kuala, Darussalam, Banda Aceh, Indonesia
[3] Department of Mechanical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Jalan Teungku Syech Abdur Rauf, Darussalam, Banda Aceh 24415, Indonesia
* Corresponding author's e-mail: machdar@usk.ac.id

ABSTRACT

Patchouli essential oil serves as a crucial raw material in the fragrance and cosmetic industries. Since the late 19th century, the patchouli plant has been cultivated across various regions of Indonesia's Aceh Province, with notable variations in oil yields and chemical composition depending on environmental conditions and geographic locations. This study examined the yields and chemical constituents of patchouli oil from five regions in Aceh Province, namely Sabang, Aceh Besar, Aceh Jaya, Aceh Selatan, and Gayo Lues. Oil extraction was performed using laboratory steam distillation, followed by gas chromatography-mass spectrometry analysis of sesquiterpene hydrocarbon compounds. This analytical approach allowed for precise identification and quantification of the oil's chemical components. The analysis revealed that Sabang produced the highest oil yield at 4.05%, while other regions ranged from 2.2% to 2.9%. Specifically, Aceh Besar yielded 2.2%, Aceh Jaya 2.6%, Aceh Selatan 2.9%, and Gayo Lues 2.6%. Four major sesquiterpene hydrocarbon compounds were identified: β-patchoulene, caryophyllene, α-guaiene, and aciphyllene. Total sesquiterpene hydrocarbon content varied significantly across regions, with Gayo Lues showing the highest concentration at 84.78%, followed by Aceh Selatan (74.32%), Aceh Besar (68.34%), Aceh Jaya (63.73%), and Sabang (60.83%). Although Sabang demonstrated superior oil yield, Gayo Lues exhibited the highest sesquiterpene hydrocarbon content. This inverse relationship between oil yield and sesquiterpene concentration suggests that environmental factors significantly influence the plant's chemical composition and oil production. Based on these findings, Gayo Lues emerges as the recommended location for mass cultivation of patchouli plants, offering optimal conditions for producing essential oil with high sesquiterpene concentration, which is particularly valuable for the fragrance industry.

Keywords: patchouli essential oil, oil yield, chemical constituent, patchouli alcohol

INTRODUCTION

Pogostemon cablin (Blanco) Benth., commonly known as patchouli plant or *nilam* in Indonesian and Malay, belongs to the family of Lamiaceae. Patchouli essential oil (PEO) is commonly extracted by steam distillation of dried leaves dan stems of the patchouli plant [van Beek and Joulain, 2018]. The PEO has been widely used in the primary perfume industries [Jain et al., 2022, 1985; Annonis, 2007]. The oil also showed moderate antioxidant and antimicrobial activities [Dechayont et al., 2017]. The patchouli plant is native to the Philippines, grows wild in Southeast Asia [Swamy and Sinniah, 2015], and has been primarily cultivated in Indonesia [Rinaldi et al., 2022]. According to the Indonesian Central Bureau of Statistic [BPS, 2023], the total patchouli cultivation area amount to 16,000 ha dispersed across 16 provinces of the total 37 provinces in Indonesia, and the total PEO production is around 2,600 ton. Aceh Province contributed approximately 15% of the total PEO production from Indonesia.

Tracing back history, the practice of exporting PEO from Aceh began at the end of the 19th century, reaching its peak in the early 20th century, as documented by Dutch researchers in ”Atjeh Patchouli-Olie” [Spoon, 1932]. During this period, PEO produced in the Aceh was exclusively shipped to Singapore and partially to Penang (Malaysia). In these trading hubs, the PEO would undergo mixing and refinement with other PEOs before being re-exported to other countries under the label ”Singapore oil” rather than ”Aceh oil.” The trade routes and marketing strategies for PEOs from West and East Java followed a distinctly different path from their Aceh counterparts. These regions established their unique distribution channels and marketing approaches, operating independently of the Singapore-centered trade network. The distinction in trade routes was paralleled by differences in oil quality, with Java’s PEO exhibiting a more moderate aroma compared to Aceh’s product. These variations in quality and aromatic properties can be attributed to the distinct growing conditions, particularly soil composition and climate, which naturally favored patchouli cultivation in Aceh over Java.

Research has consistently demonstrated that the chemical composition of PEO varies significantly based on geographic location and environmental conditions. Swamy and Sinniah [2015] documented substantial variations in chemical profiles across different cultivation sites, highlighting the importance of terroir in patchouli production. This finding was further supported by Lal et al. [2023], who established a clear correlation between environmental factors and both essential oil yield and key component concentrations. Numerous studies conducted on PEO samples from various regions of China have identified nine primary compounds that constitute the oil’s chemical profile [Hu et al., 2006; Li et al., 2011, Huang et al., 2018]. These are α-guaiene, β-guaiene, ε-guaiene, β-patchoulene, caryophyllene, seychellene, spathulenol, patchouliol, and pogostone. Some of these compounds serve as important markers for evaluating oil quality and authenticity, as their relative concentrations can vary significantly based on growing conditions and cultivation practices [Huda et al., 2024].

Understanding regional variations is crucial for optimizing patchouli cultivation and ensuring consistent oil quality. Different environmental conditions not only affect the overall oil yield but also influence the concentration and proportion of these key chemical constituents. This variability emphasizes the importance of conducting systematic qualitative and quantitative analyses of PEO products from different cultivation regions within Aceh Province. The present study aims to evaluate these variations across different regions of patchouli cultivation in Aceh, providing valuable insights into the relationship between environmental factors and oil composition. This research will contribute to a broader understanding of patchouli cultivation in Indonesia, helping to identify optimal growing conditions and improve production practices. The findings will also establish important benchmarks for quality control and help guide future cultivation site selection throughout the Indonesian archipelago.

MATERIALS AND METHODS

Plant material preparation

Patchouli plant samples were collected from five distinct regions across Aceh province: Sabang, Aceh Besar, Aceh Jaya, Aceh Selatan, and Gayo Lues. The geographical distribution of these sampling locations is illustrated in Figure 1. Each region represents unique environmental conditions and cultivation practices that could potentially influence the plant’s chemical composition and oil yield. The harvesting process focused on collecting fully mature plants, including leaves and stems but excluding root systems. The maturity of the plants was carefully assessed based on plant age (seven months) to minimize variations that could affect the final analysis results. After harvesting, the plant materials underwent a controlled drying process under shade conditions for three days. This method was chosen over direct sun exposure to prevent potential degradation of volatile compounds and ensure optimal preservation of the essential oils. The drying process continued until the samples reached a constant weight, indicating that the moisture content had stabilized at an appropriate level for distillation. Following the drying phase, the plant material was manually processed into uniform pieces measuring 2–3 centimeters in length. This size reduction is crucial for ensuring consistent steam penetration during the distillation process and maximizing oil extraction efficiency. The manual

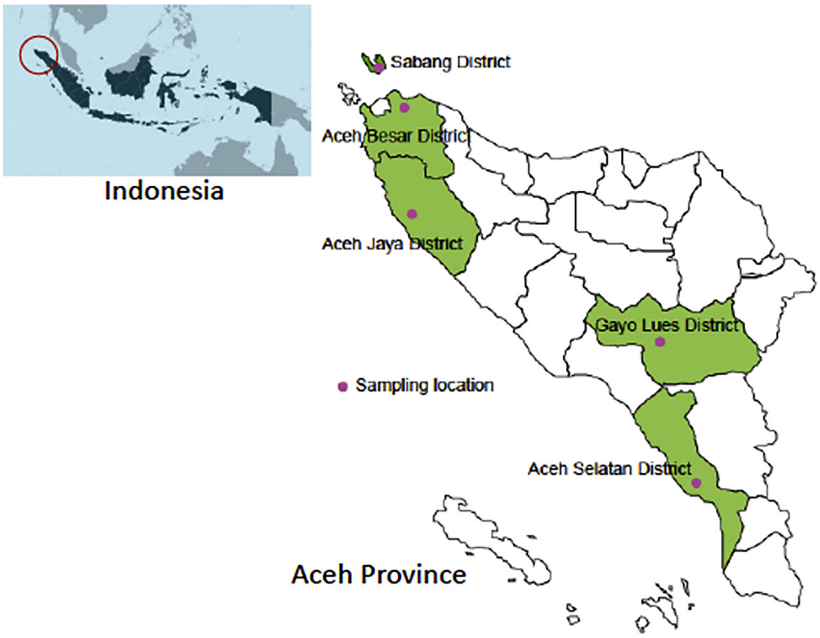

Figure 1. Sample locations

chopping method was preferred over mechanical processing to minimize the loss of volatile compounds that might occur with excessive heat or mechanical stress. This sampling and preparation methodology was designed to minimize variables that could affect the final analysis, ensuring that any observed differences in oil yield and composition could be attributed primarily to regional variations rather than processing inconsistencies.

Extraction of PEO

Extraction of PEO was performed using a laboratory steam distillation unit. The apparatus comprised three main components: a 10-litre steam generator drum, a glass column designed to hold 1 kg of processed plant material (dried and chopped leaves and stems), and a condenser equipped with a Florentine vessel specifically designed to facilitate the separation of PEO from water condensate. The complete experimental setup is visually documented in Figure 2, while the detailed process conditions are presented in Table 1.

The extraction process was conducted under carefully controlled conditions, maintaining a consistent steam loading rate of approximately 7 L/m²-min for a duration of 4 hours. To maintain the purity of the extracted oil, a purification step was implemented using hydrophobic fabric (monyl screen polyester). This material effectively separated any residual water contamination from the PEO prior to GC-MS analysis. To ensure statistical reliability and validate the reproducibility of results, all extraction procedures were performed in duplicate. The yield calculation followed a straightforward methodology, expressing the ratio between the weight of obtained PEO and the initial weight of the dried raw material. This calculation provides a clear percentage yield that can be used for comparative analysis across different samples. For systematic evaluation of the different patchouli plant sources, a relative rank value was proposed using a specific formula (Eq. 1). This ranking system was designed to provide a quantitative basis for comparing the quality and productivity of patchouli plants from different regions, taking into account both the yield and quality parameters of the extracted oil.

$$Rr = (Y \times PA)/Y_{Pmax} \quad (1)$$

where: Rr is the relative rank (1 is the highest rank and 5 is the lowest rank); Y and PA are yield (%) and patchouli alcohol (PA) concentration (%) of an individual sample, respectively; and Y_{Pmax} is a maximum value of Y x PA.

Gas chromatography-mass spectrometry (GC-MS) detection

A Thermo Scientific TSQ 9000 GC-MS/MS System was used to look at the compounds of sesquiterpene hydrocarbons (SQHC) in PEO.

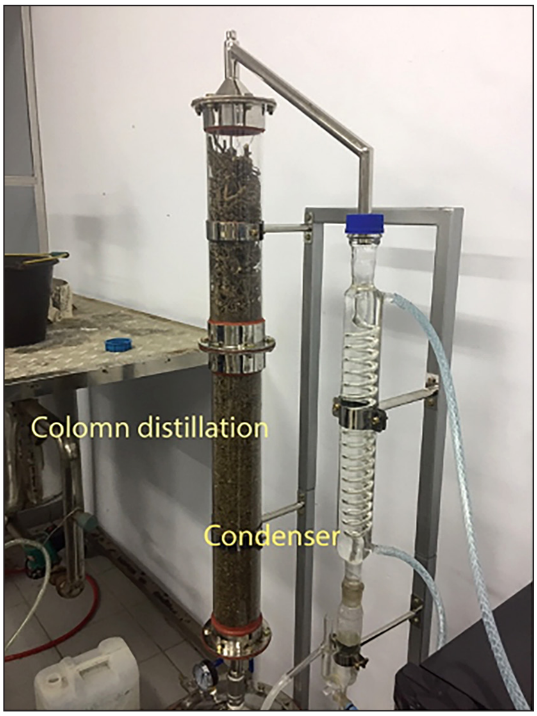

Figure 2. Photograph of the experimental setup

Compound separation was achieved using a specialized capillary column measuring 30 m in length, with a 0.25 mm internal diameter and a 0.25 mm film coating thickness. The analysis followed a precise temperature program, with the oven temperature gradually increasing from 70 °C to 220 °C at a controlled rate of 4 °C per minute. Helium served as the carrier gas, maintained at a constant flow rate of 1 ml/min. Both injector and detector temperatures were set at 250 °C throughout the analysis. Upon reaching the final temperature of 220 °C, these conditions were maintained for an additional 10 minutes to ensure complete separation of compounds. The transfer line temperature was consistently maintained at 250 °C. Mass spectrometry analysis was performed under electron impact conditions with an acceleration energy of 70 eV. The concentration of these constituents was subsequently calculated using a formula (Eq. 2) designed to account for peak areas and response factors.

$$\textit{SQHC constituent}\ (\%) = pA/TpA \times 100 \qquad (2)$$

where: pA is the SQHC constituent peak area; TpA is the total peak area.

Table 1. Process condition of the PEO extraction

No.	Parameter	Condition
1.	Boiler temperature (°C)	100
2.	Boiler pressure (atm)	1
3.	Steam loading (L/m^2-min)	7
4.	Cooling water flow rate (L/min)	3
5.	Cooling water inlet temperature (°C)	30
6.	Cooling water outlet temperature (°C)	40
7.	Condenser temperature (°C)	90
8.	Process duration (h)	4

Soil sampling and analysis

Soil samples were systematically collected from all five patchouli cultivation regions: Sabang, Aceh Besar, Aceh Jaya, Aceh Selatan, and Gayo Lues. The sampling focused on the productive layer at a depth of 20 cm, with three replicate samples randomly collected from each plantation area to ensure representative results. Following collection, the soil samples underwent a standardized preparation process in the laboratory. They were first air-dried under controlled conditions and then carefully ground using a mortar to achieve uniform particle size. The processed samples were passed through a 2 mm screen for consistency and stored in sealed plastic bags to preserve their integrity. Soil composition analysis employed the Bouyoucos hydrometer method to determine the relative percentages of sand, silt, and clay. Basic soil properties were assessed using standardized procedures: pH and electrical conductivity (EC) measurements were conducted using a glass electrode with a 1:2.5 soil:water ratio. Organic carbon (OC) content was quantified using the Walkey-Black method [Anonymous, 2019]. Nutrient analysis included several key measurements. Total available nitrogen was determined using the Kjeldahl method, while available phosphorus was assessed using Bray No. 2 extract methods [Bray and Kurtz, 1954] and quantified via UV-spectrophotometry using a Shimadzu UV-1800 at a 693 nm wavelength. For exchangeable potassium analysis, following Thomas's [1982] procedure, soil samples were treated with 1 N ammonium acetate solution (pH 7) and shaken for 24 hours. The resulting extracts were analyzed using a Shimadzu AA-700 atomic absorption spectrophotometer. This comprehensive soil analysis protocol provided detailed information about the physical and chemical properties of soils from each cultivation region, enabling correlation analysis between soil characteristics and patchouli oil yield and composition. It is important to note that this study was conducted during a single growing season. The variability in soil parameters observed across regions likely results from several environmental factors, including topographical differences affecting soil formation, varying rainfall patterns influencing soil pH and nutrient availability, and differences in organic matter input and decomposition rates due to regional temperature and humidity variations.

RESULTS AND DISCUSSION

Characteristics of the regions and physicochemical properties of the soil

The five study regions in Aceh province – Sabang, Aceh Besar, Aceh Jaya, Aceh Selatan, and Gayo Lues – exhibit distinct geographical and environmental characteristics, as detailed in Table 2. These regions are strategically distributed across the province: Aceh Jaya and Aceh Selatan occupy the western region, Aceh Besar lies in the east, Sabang is situated on an island, and Gayo Lues is positioned in the highlands. The topographical features vary significantly among these regions. Sabang, Aceh Besar, and Aceh Jaya share a relatively gentle land slope of 3%, while Aceh Selatan and Gayo Lues present steeper gradients of 6% and 8%, respectively. Elevation ranges markedly across the regions, from 221 meters in Sabang to 1500 meters in the highland region of Gayo Lues.

The climate data across the five regions in Aceh province reveals distinct patterns in topography, temperature, humidity, and rainfall. The regions show varying land slopes, with Sabang, Aceh Besar, and Aceh Jaya sharing a gentle 3% gradient, while Aceh Selatan and Gayo Lues feature steeper terrains of 6% and 8%, respectively. This topographical variation is further emphasized by significant differences in altitude, ranging from coastal levels in Sabang (221 m) to highland elevations in Gayo Lues (1500 m), with intermediate elevations in Aceh Besar (400 m), Aceh Jaya (698 m), and Aceh Selatan (804 m).

Temperature patterns demonstrate a clear correlation with altitude. The lowland regions of Sabang and Aceh Besar maintain the highest temperatures at 28 °C, while Aceh Jaya and Aceh Selatan show slightly cooler conditions at 27 °C. Gayo Lues, with its highland location, records the lowest temperature at 25 °C. Humidity levels follow an increasing trend from coastal to highland regions, starting at 78% in Sabang and progressively rising through Aceh Besar (81%), Aceh Jaya, and Aceh Selatan (both 84%), reaching their highest level in Gayo Lues (86%).

Rainfall distribution shows an intriguing pattern across the regions. The western regions (Aceh Jaya, Aceh Selatan) and the highland region (Gayo Lues) receive the highest annual rainfall at 2,300 mm. In contrast, the coastal regions experience slightly lower precipitation, with Sabang receiving 2,030 mm and Aceh Besar recording the lowest at 1,918 mm annually. These

Table 2. Region characteristics and physico-chemical properties of soil samples

Criteria	Regions				
	Sabang	Aceh Besar	Aceh Jaya	Aceh Selatan	Gayo Lues
Land slope (%)	3%	3%	3%	6%	8%
Altitude (m)	221	400	698	804	1500
Temperature (°C)	28	28	27	27	25
Humidity (%)	78	81	84	84	86
Rain fall (mm)	2,030	1,918	2,300	2,300	2,300
Parameter					
Soil texture	Silty loam	Silty loam	Silty loam	Silty loam	Clay
Bulk density (kg/L)	1.28	1.15	1.19	1.16	1.11
pH	5.2–5.9	5.90–5.97	4.5–4.9	4.8–5.0	5.4–5.5
EC (dS/m)	0.053 ±0.005	0.193 ±0.054	0.063 ±0.012	0.027 ±0.005	0.25 ±0.050
OC (%)	0.95 ±0.06	3.91 ±0.18	1.68 ±0.05	1.27 ±0.23	3.46 ±0.06
Available N (kg/ha)	47.4 ±9.13	121 ±9.13	80 ±9.6	50.4 ±2.09	168.89 ±2.09
Available P (kg/ha)	0.53 ±0.43	6.68 ±0.48	0.21 ±0.01	0.16 ±0.04	1.40 ±0.45
Exchangable K (meq/100 g)	0.68 ±0.05	1.47 ±0.07	0.18 ±0.15	0.07 ±0.01	1.18 ±0.07

variations in rainfall patterns, combined with the differences in temperature and humidity, create distinct microclimates that could significantly influence patchouli cultivation.

The analysis of soil samples from the five regions revealed marked differences in both physical and chemical characteristics. While four regions exhibited silty loam soil texture, Gayo Lues distinctively featured clay soil composition. The analysis of chemical properties demonstrated significant regional variations in pH, EC, OC, and nutrient availability. Soil acidity levels varied considerably, with Aceh Jaya (4.5–4.9) and Aceh Selatan (4.8–5.0) showing the most acidic conditions. Other regions maintained pH levels between 5.2–5.9 and 5.90–5.97, aligning more closely with the optimal pH range of 5–7 required for patchouli cultivation [Anonymous, 2014]. EC measurements showed substantial variation, peaking in Gayo Lues (0.25 ± 0.050 dS/m) and reaching their lowest in Aceh Selatan (0.027 ± 0.005 dS/m). OC content, crucial for patchouli growth with an optimal range of 2–3% [Anonymous, 2006], was notably high in Aceh Besar (3.91 ± 0.18%) and Gayo Lues (3.46 ± 0.06%). Other regions showed lower OC levels, ranging from 0.95 ± 0.06% to 1.68 ± 0.05%. Nutrient availability also exhibited significant regional variations. Gayo Lues demonstrated the highest available nitrogen content (168.89 ± 2.09 kg/ha), while Aceh Besar led in available phosphorus (6.68 ± 0.48 kg/ha). Conversely, Sabang showed the lowest nitrogen levels (47.4 ± 9.13 kg/ha), and Aceh Selatan had minimal phosphorus content (0.16 ± 0.04 kg/ha). Exchangeable potassium levels varied substantially across regions, with optimal patchouli growth requiring 0.6–1 meq/100 g [Anonymous, 2006]. Aceh Besar recorded the highest exchangeable potassium (1.473 ± 0.07 meq/100 g), while Aceh Selatan showed the lowest levels (0.07 ± 0.01 meq/100 g), falling significantly below the recommended range for optimal patchouli cultivation.

Yield and PA concentration

The PEO yields and the PA concentrations for the different regions are presented in Table 3. The data reveals significant variations in PEO characteristics across the five studied regions, which are examined through four key parameters: oil color, yield percentage, PA concentration, and relative rank.

The color of PEO shows two distinct variations: light deep brown, observed in Sabang and Aceh Besar, and light yellow, found in Aceh Jaya, Aceh Selatan, and Gayo Lues. Oil yield percentages demonstrate notable differences among regions. Sabang stands out with the highest yield at 4.50 ± 0.05%, significantly higher than other regions. Aceh Besar shows the lowest yield at 2.20 ± 0.10%, while the remaining regions display intermediate values: Aceh Jaya (2.60 ± 0.30%), Gayo Lues (2.60 ± 0.05%), and Aceh Selatan (2.90 ± 0.80%). PA concentration, a crucial quality indicator, varies considerably across regions. Gayo Lues exhibits the highest concentration at 42.76 ± 1.00%, followed by Aceh Besar (37.53 ± 0.27%) and Aceh Selatan (36.77 ± 2.13%). Lower concentrations are found in Aceh Jaya (30.87 ± 0.61%) and Sabang (28.87 ± 5.02%). The relative rank, which appears to be a composite quality indicator, provides an overall assessment of the PEO quality from each region. Sabang achieves the highest rank of 117 (ranked 1st), followed by Gayo Lues at 111 (2nd), Aceh Selatan at 107 (3rd), Aceh Besar at 83 (4th), and Aceh Jaya at 80 (5th). This ranking system suggests that while Sabang produces the highest oil yield and Gayo Lues shows the highest PA concentration, other factors contribute to the overall quality assessment of the essential oil from each region. The ranking (*Rr*) was based on oil yield and PA concentration, as these are primary indicators of essential oil productivity and quality. Water resources were not included due to the generally adequate rainfall across all regions studied, as evidenced by consistent precipitation data collected during the study period.

Table 3. The yield and PA concentration of the PEO from the different regions, as well as their relative ranks

Regions	PEO color	PEO yield (%)	Pacthouli alcohol concentration (%)	Relative rank
Sabang	Light deep brown	4.50 ±0.05	28.87 ± 5.02	117 (1)
Aceh Besar	Light deep brown	2.20 ±0.10	37.53 ± 0.27	83 (4)
Aceh Jaya	Light yellow	2.60 ±0.30	30.87 ± 0.61	80 (5)
Aceh Selatan	Light yellow	2.90 ±0.80	36.77 ± 2.13	107 (3)
Gayo Lues	Light yellow	2.60 ±0.05	42.76 ± 1.00	111 (2)

Identification of components in the PEO from the different regions

GC-MS serves as a powerful analytical tool for investigating volatile compounds in essential oils, as initially documented by Lamparsky and Fingerprints [1987]. The technique relies on two key principles: compound separation based on retention times and peak identification through mass spectral comparison with reference standards. The representative ion chromatogram displayed in Figure 3 reveals the chemical composition of the analyzed PEO. The chromatographic separation had resolution, and the five main peaks could be easily distinguished and identified by their unique mass spectral patterns. Through comparison with the MS library database, these peaks were definitively identified as β-patchoulene (Peak 1), caryophyllene (Peak 2), α-guaiene (Peak 3), aciphyllene (Peak 4), and PA (Peak 5). Each peak demonstrates distinct separation from neighboring compounds, enabling accurate quantification of individual components. The chromatogram exhibits well-defined peak shapes and minimal baseline noise, indicating optimal analytical conditions. The profile of the compounds found matches what Buré and Sellier [2004] found when they did a GC and GC-MS analysis of Indonesian PEO. The successful separation and identification of these major compounds provide crucial information about the oil's composition and quality. The presence of these specific compounds, particularly PA as a key marker compound, confirms the authenticity of the PEO samples. This analytical approach not only enables qualitative identification of the oil's components but also provides quantitative data about their relative abundances, making it an invaluable tool for quality assessment and standardization of PEO.

Patchouli cultivation in Aceh Province is concentrated in five main regions: Gayo Lues, Aceh Jaya, Aceh Selatan, Aceh Besar, and Sabang. Chemical analysis of PEO from these diverse

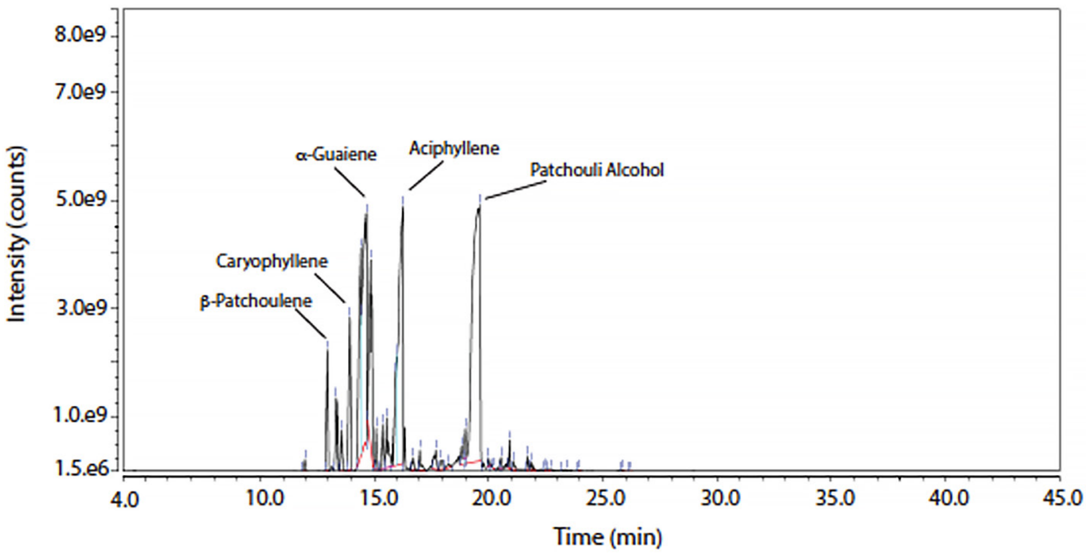

Figure 3. A typical GCMS ion chromatogram of this study

Table 4. Composition of PEO in the different regions

Compound (%)	Regions					Range(1)
	Sabang	Aceh Besar	Aceh Jaya	Aceh Selatan	Gayo Lues	
β-patchoulene	2.48 ±0.30	1.70 ±0.48	2.70 ±0.58	3.70 ±0.50	2.70 ±0.50	0.03–12
Caryophyllene	4.03 ±0.50	2.79 ±0.48	4.44 ±0.01	4.24 ±0.01	2.80 ±0.01	0.75–6.8
α-guaiene	10.84 ±0.50	13.71 ±2.09	12.11 ±1.09	13.00 ±2.22	20.91 ±1.02	2.90–23
Aciphyllene	14.61 ±0.23	12.61 ±0.21	13.61 ±0.21	16.61 ±0.21	15.61 ±0.23	0.70–4.2
PA	28.87 ±5.02	37.53 ±0.27	30.87 ±0.61	36.77 ±2.13	42.76 ±1.00	11–72
Total	60.83	68.34	63.73	74.32	84.78	

cultivation areas, as presented in Table 4, reveals significant variations in their chemical compositions. These findings align with previous research by Hu et al. [2006] and Silva et al. [2004], who demonstrated that geographic location and cultivation conditions significantly influence the volatile oil composition of patchouli plants. Analysis shows that PEO is particularly rich in SQHC, with PA being the predominant compound (see Table 2). As a tricyclic sesquiterpene hydrocarbon, PA holds considerable importance in the perfumery and cosmetic industries, as documented by Swamy and Sinniah [2015] and Bauer et al. [1997]. The variation in PA content across different regions suggests that environmental and geographical factors play crucial roles in determining the chemical profile and quality of PEO, ultimately affecting its commercial value and industrial applications.

The study of SQHC in PEO shows that aciphyllene (guai-4,11-diene) is the second most common compound, after PA. Its levels range from 12.61% ± 0.21% in Aceh Besar to 16.61% ± 0.21% in Aceh Selatan. This finding aligns with van Beek and Joulain's [2018] research, which established aciphyllene as a consistent component of PEO. The study identified β-patchoulene as another significant compound, with concentrations varying from 1.70% ± 0.48% (Aceh Besar) to 3.70% ± 0.50% (Aceh Selatan). These values fall within the broader range of 0.03% to 12% reported by van Beek and Joulain [2018)] According to Ohloff [2012], β-patchoulene formation occurs through PA dehydration and subsequent Wagner-Meerwein rearrangements during the steam distillation process. Caryophyllene, while consistently present, showed relatively modest concentrations ranging from 2.79% ± 0.48% to 4.44% ± 0.01% across the regions. In particular, α-guaiene became the third most important SQHC component, with concentrations ranging from 10.84% ± 0.50% in Sabang to 20.91% ± 1.02% in Gayo Lues, showing big differences between regions. The total SQHC content showed marked differences across regions. Sabang recorded 60.83%, while Aceh Besar showed 68.34%, followed by Aceh Jaya at 63.73%. Higher concentrations were found in Aceh Selatan (74.32%) and Gayo Lues, which demonstrated the highest total SQHC content at 84.78%. These findings hold particular significance for commercial cultivation, especially considering PA's role as the standard marker compound in PEO quality assessment. The consistently higher SQHC content, especially the higher PA concentration in Gayo Lues samples, suggests that this area is perfect for growing a lot of patchouli in Aceh Province. Additionally, the full chemical profile analysis supports this conclusion, showing that geographical and environmental factors in Gayo Lues help patchouli plants make more SQHC.

The superior chemical composition of Gayo Lues samples, despite lower oil yield, suggests potential for yield optimization through targeted agronomic interventions. These could include optimized irrigation systems, soil amendment strategies specific to the region's clay soil characteristics, and cultivation techniques adapted to highland conditions. These findings align with global research on environmental influences on essential oil production, particularly regarding the effects of altitude and soil conditions on oil composition and quality. Furthermore, the results provide valuable comparative data for similar studies in other patchouli-producing regions worldwide.

CONCLUSIONS

The comprehensive analysis of PEO from five distinct regions in Aceh Province reveals significant variations in chemical composition, yield, and quality across different geographical locations. The study demonstrates that environmental and geographical factors substantially influence the oil's characteristics, particularly its SQHC content. Among the regions studied, Gayo Lues emerges as the most promising location for large-scale patchouli cultivation, demonstrating the highest total SQHC content (84.78%) and superior PA concentration. The oil yield from Sabang was the highest (4.50%), but the chemical makeup of Gayo Lues was the best, with the right amounts of PA, aciphyllene, α-guaiene, β-patchoulene, and caryophyllene. The variation in chemical profiles across regions aligns with previous research findings, confirming the significant impact of environmental conditions on essential oil composition. These results provide valuable insights for optimizing patchouli cultivation in Aceh Province, suggesting that the highland conditions of Gayo Lues offer ideal parameters for producing high-quality PEO. This understanding can guide future cultivation strategies and help maintain consistent oil quality for commercial applications in the perfumery and cosmetic industries.

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