

RESEARCH ARTICLE



Descriptive GC-MS Profiling of Volatile Compounds in Cendana (*Santalum album* L.) Wood from Three Gunungkidul, Indonesia Sites: Silvicultural Implications for Site Matching

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ABSTRACT

Santalum album L. (sandalwood) is one of the world's most valuable aromatic tree species, with oil quality largely determined by α - and β -santalol content. Despite extensive studies in India and Australia, little is known about how ecological variation in Java shapes the chemical composition of *S. album* wood. This research objective is to identify volatile compounds in the outerwood of *S. album* from Nglanggeran, Wanagama, and Petir, Gunungkidul, as a preliminary study with implications for *S. album* silviculture. Samples were obtained from three mature trees per site, extracted with n-hexane, and analyzed using Gas Chromatography-Mass Spectrometry. Fourteen volatile compounds were detected across sites, comprising aliphatic hydrocarbons (undecane, pentadecane, dodecane, trimethyl isomers, hexadecane) and sesquiterpene alcohols (α - and β -santalol). The results show that the *S. album* compound profile differs across the 3 research sites. In this research, α -santalol ($21.18 \pm 12.87\%$) and β -santalol ($6.54 \pm 4.19\%$) were detected only in samples from Petir and Nglanggeran. The dominant compounds in the samples from Nglanggeran and Wanagama are alkane groups. The results stipulate that Petir has the prospective to produce good sandalwood oil. This preliminary study also shows the use of applying a phytochemistry profile to specify area-specific chemical expression in sandalwood. While the present results are based on a limited set of detectable compounds, they provide an initial foundation for identifying promising production areas, and more extensive, replicated research will be vital to boost and validate these initial findings.

Introduction

Cendana (*Santalum album* L.) has high economic value with some functions [1,2]. Some environmental degradations made sandalwood in a dangerous condition [3,4]. The financial benefit is a result of a major compound with aromatic and medicinal effects. The volatile compounds of the object can be detected by chemical analytical instruments [1,5,6]. That method can be used for habitat handling for projecting the Sandalwood yield and protection [7]. Kucharska et al. [8] compared several commercial *S. album* oils and found considerable variation in santalol content, with many samples failing to meet ISO 3518:2002 (now ISO 5318:2025) [9]. Gas Chromatography-Mass Spectrometry (GC-MS) is highly sensitive to both major and trace volatile components, making it suitable for verifying the geographical origin and processing quality of *S. album* oil. Advanced techniques such as GC \times GC-TOF MS have further enhanced the resolution of the volatilome, revealing greater chemical complexity in sandalwood samples [10].

In Indonesia, *S. album* has high ecological, economic, and cultural significance, particularly in Timor and Sumba, where it has been traditionally managed for centuries [4,11]. *S. album* has existed in Petir, Nglanggeran, and Wanagama since the 1960s [12,13]. But, the existence of these plants is still not good, given

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the lack of suitable habitat and other environmental conditions [13,14]. *S. album* wood is best grown at 15-20 years of age; product quality is affected by external factors and cultivation methods [15,16].

Oil production and its quality can be increased by a new conservation approach. This approach (in vitro and environmental management) also guards the population sample [17]. The financial value of *S. album* is primarily determined by the content of α - and β -santalol. These compounds vary in plants depending on some factors such as site conditions, tree age, and genetics [18,19]. Research in India has documented the variation of santalol content. This study reveals there are interactions between physiological processes and environmental stress [18]. Environmental stressors (drought, nutrient limitation, and host-plant interactions) affected the secondary metabolites, including santalol, as sesquiterpenes [20,21]. Stress conditions are one of the environmental factors can stimulate the biosynthesis santalol by affect its transcription factors, that is AREB SaAREB6s [21,22].

The mechanisms of environmental stress stimulation are important for implementing site-based silvicultural techniques. It can be used to higher oil quality, also support commercial goals and environmental sustainability. The findings of this research provide opportunities to include environmental inputs for optimizing yield, particularly in regions where natural production is suboptimal. Those strategies are underutilized in Indonesia at this time. This strategy gives a potential way for long-term management. Ariyanti and Asbur [23] emphasize, the interaction between internal and external factors can determine the growth of *S. album* and its oil production. They underline the need to assess environmental suitability across Indonesia's varied environmental gradients.

Studies on outerwood chemistry of *S. album* have a little attention. Most of the research in India and Australia focused on the heartwood of *S. album* [24–26]. In Indonesia, research that focused on environmental factors affecting *S. album* was also limited. In this research, areas of Nglanggeran, Wanagama, and Petir show different environmental conditions, especially in altitude, soil type, and water supply. Nglanggeran is an area with volcanic soil, high rainfall. Wanagama is a managed forest with fertile and deeper soil. Petir is in a low altitude with limestone karst soil and drought/dry soil. This environmental distinction may affect the secondary metabolite biosynthesis, such as santalolin *S. album* sample. This research, as a preliminary study, can be used as early information for future study.

Some previous research on sandalwood has been conducted in the Gunungkidul and Gunung Sewu areas. Those studies generally focused on growth performance, provenance testing, and genetic/morphological variation. For instance, the research topic of Setiawan et al. [27] is about the *S. album* seedlings, focusing on survival and growth without plant chemistry. Arifriana et al. [28] conducted descriptive analyses of the morphological variation of *S. album* in the Petir area without linking them to phytochemistry [28]. Ratnaningrum et al. [29] focused the research on propagation techniques such as grafting. Putri et al. [30] studied the genetic diversity of *S. album* in Imogiri. These studies did not examine the environmental factors affecting essential oil composition. The information on how different environmental conditions in Gunungkidul affect the chemistry of *S. album*, especially on volatile compounds, such as α - and β -santalol concentrations. This research aims to reveal comparative chemical analysis of *S. album* outerwood from three distinct environmental sites in Gunungkidul. The findings of this research offer preliminary silvicultural insights to be used as early information to optimize oil yield and quality of *S. album* oil.

The objectives of research are: 1) identify the outerwood compound profile of *S. album* from the Nglanggeran, Wanagama, and Petir Gunungkidul areas of Indonesia, 2) analyse the profile of *S. album* as a preliminary study for *S. album* silviculture implications, and 3) compare the presence and concentration of santalol among the sites with different environmental conditions, to provide preliminary information for a site-based silvicultural overview.

Materials and Methods

Study Locations and Site Characteristics

The study was conducted in three ecologically distinct sites of Gunungkidul, Yogyakarta. Figure 1 represents both cultivated and naturally regenerating populations of *S. album*. These sites were chosen to capture a gradient of soil fertility, hydrological regime, and climatic conditions. Nglanggeran (northern zone, volcanic regosols) represents high-rainfall uplands; Wanagama (central zone, fertile latosols) reflects managed lowland forest; and Petir (southern zone, karstic limestone) represents nutrient-poor, drought-prone terrain. Key environmental characteristics are summarized in Table 1. Such edaphoclimatic contrasts provide an

opportunity to assess how site conditions shape sandalwood wood chemistry, since previous studies have shown that even under uniform environments, variation in α - and β -santalol can arise from microenvironmental stress and tree physiological responses [31].

Table 1. The environmental data show different ecological conditions at 3 sites. A combination of latitude, rainfall, and soil type accounts for the main differences among the 3 sites. The highest latitude and rainfall are on Nglanggeran, which can supply water better than the Petir sites. This condition can cause water/drought stress in plants in Petir, one of the factors that can trigger the biosynthesis of secondary compounds (including santalol).

Site	Coordinates (Lat–Long)	Geopark Zone	Substrate / Soil Type	Elevation (m asl)	Annual Rainfall (mm)	Main References
Nglanggeran	7° 50' 28" S 110° 32' 29" E	Northern	Volcanic andesite, shallow regosols	641	2,100	[32–34]
Wanagama	7° 53' 0.5" S 110° 32' 48.7" E	Middle	Latosols/Mediterranean, fertile soils	180	1,900	[33–35]
Petir	8° 04' 49.841" S 110° 44' 02.451" E	Southern	Karstic limestone, shallow nutrient-poor soils	170	1,800	[32–34]

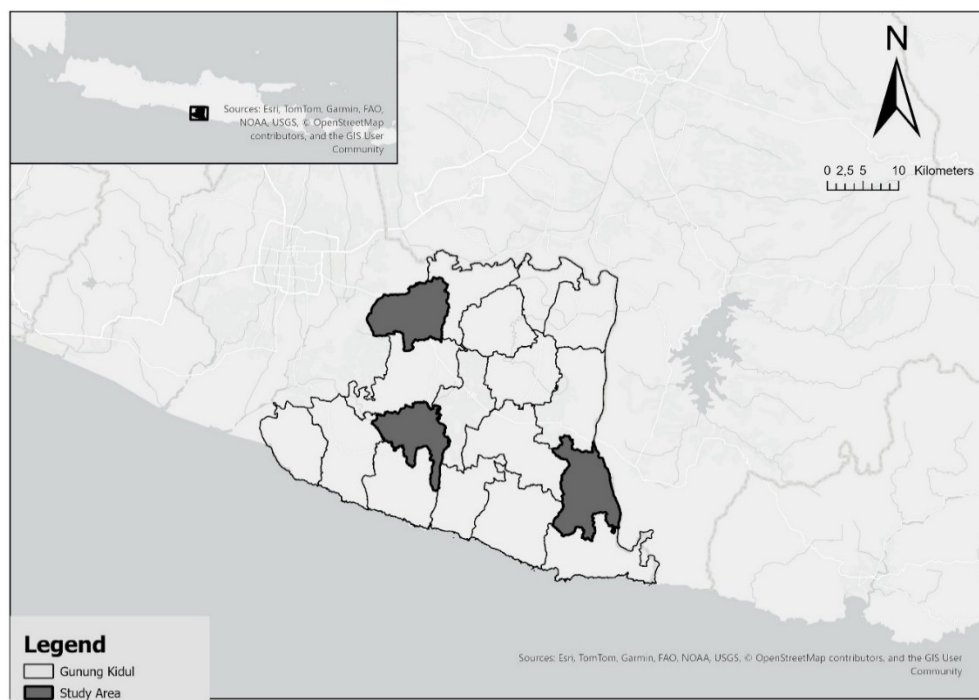


Figure 1. Study sites in Gunungkidul, Yogyakarta, Indonesia. The research has been conducted at three sites with different conditions: Nglanggeran (Volcanic soil), Wanagama (Forest soil), and Petir (Karst soil). In this research, santalol has been detected in the Petir sample.

Sampling and Experimental Design

Three mature *S. album* trees were purposively selected from each site ($n = 9$) to capture ecological contrasts while controlling for tree size and condition. Trees had stem circumferences ≥ 20 cm and were estimated to be 30–40 years old. Tree age was determined using a non-destructive diameter–age estimation approach. Published growth studies on *S. album* report mean annual diameter increments of about 0.5–1.0 cm year⁻¹

across different ecological settings, and this range provides a reasonable basis for estimating age without resorting to destructive ring analysis [36–38]. Samples were taken at ~30 cm above the soil surface using a manual drill to get the outerwood layer (3–5 cm depth). Information about circumference, estimated age, and site conditions was documented. Because the sample size ($n = 3$ trees per site) was limited, results are preliminary and must be interpreted cautiously, as representativity is limited. This method serves as initial comparative data but is limited by the number of samples and the robustness of the statistics. This is a beginning study, intended to generate provisional comparative data rather than quantitative analysis.

Extraction and GC-MS Analysis

Choosing *S. album* trees were drilled using a hand-operated wood drill at approximately 30 cm above the soil surface. The resulting drilling powder was then manually sorted, and the finer particles were collected for use as analytical samples. Outerwood powders (~2 g per sample) were open-dried at 40 °C and extracted in 20 mL n-hexane for 24 h at room temperature with intermittent restlessness. Extracts were neat by Whatman No. 1 filter paper, condensed using a rotary evaporator at 40 °C, then stored at –20 °C until analysis. This procedure follows proven methods for terpenoid extraction from sandalwood outerwood tissues [39]. Wood samples from three trees per site yielded nine single-injection chromatograms. GC-MS was selected as the analytical platform because it has proven effective in characterizing tissue-specific chemical profiles of *S. album* [40], and this approach is consistent with established methods for profiling volatile constituents in sandalwood oils, including quantification of key sesquiterpenes such as α -santalol and β -santalol [9].

Data Processing and Compound Identification

Extracts were analyzed using an Agilent 7890 GC coupled to a 5975 MS detector, with an HP-5MS column (30 m \times 0.25 mm \times 0.25 μ m). The oven was programmed to 60 °C (2 min) at 5 °C/min, then to 280 °C, held for 10 min. Injection volume was 1 μ L in splitless mode, with helium as carrier gas (1.0 mL/min) and ionization energy of 70 eV, scanning m/z 40–500. Peaks were identified by comparison with the NIST spectral library and published retention indices of sandalwood sesquiterpenes [18].

Metabolite Annotation and Confidence Criteria

Metabolites in *S. album* wood volatiles were annotated using GC-MS library matching (NIST 2020). Secondary metabolite identification was classified based on the Similarity Index (SI). Candidate compounds with SI $\geq 90\%$ were considered to have high confidence, SI 80%–89% were considered to have medium confidence, and SI 70–79% or major peaks with significant area percentages were categorized as tentative and require caution in interpretation. In this research, candidate compounds were initially selected based on a similarity index (SI) $\geq 80\%$, while also considering compounds with relatively high % area, even if SI was slightly below the threshold. To enhance confidence in annotation, selected candidates were further verified by manual inspection of fragmentation patterns and peak shapes against the library summary.

Data Analysis

Evaluation was descriptive due to limited duplication ($n = 3$ per site). The restricted replication reflects environmental restriction in the area: few *S. album* individuals with stem circumference ≥ 20 cm were present, as most trees at the sampling sites represent natural regeneration rather than cultivated plants. Thus, this preliminary dataset is intended to provide comparative ecological overviews and guide hypotheses for broad-scale research rather than to produce statistically generalizable results. Relative peak areas of main compounds were averaged, with standard deviations calculated to signify variation. Data visualizations were created using Microsoft Excel. Inferential statistics were not used, consistent with preliminary environmental phytochemistry research [20]. Although restricted, the technique provides comparative site insights and preliminary suggestions for silvicultural design.

Principal component analysis (PCA) was performed to consider whether the GC-MS compound profiles of *S. album* differed across sampling areas. PCA was performed using a data matrix built from the relative peak areas (% area) of all identified compounds. The dataset was mean-centered and scaled prior to analysis, and PCA was used with standard multivariate tools (R or Python). Score and loading plots were inspected to impose sample clustering and identify the compounds contributing to the dispersion. This analysis provides an objective multivariate confirmation of chemical differentiation among areas.

Site Matching Relevance

The results of this research can be used to give information about the relation of site-matching planning for environmental conditions with compound profiles. Compounds profile of the outerwood *S. album*. in this

result can give information to the silviculture consideration. For examples to select the ideal cultivation areas and provenance trials. This information also can be used for viewing the enrichment planting to increase santalol content in *S. album*. This includes identifying sites with environmental conditions to increase santalol content in *S. album*. Result of this research also add the knowledge of variability in santalol content due to internal and external factors. Zhang et al. [40] and Bisht et al. [41], emphasizes the need for strategic provenance selection and adaptive silviculture of *S. album*. This point of view can improve silvicultural design, including provenance trials, nursery stock distribution, and adaptive management practices tailored to each site prospective.

Results

The Profile of Volatile Compounds Detected in the Three Gunungkidul Sites Sampling

There are 14 compounds found at all three sites (Nglanggeran, Wanagama, Petir). In Nglanggeran detected 7 compounds dominated by the alkane group. In Wanagama 8 kinds of compounds. Undecane do not found in Wanagama. In Petir 11 kinds of compounds were detected. This is the largest amounts of compounds. The compounds are diverse in type and abundance. The most abundant compounds are Santalol, cis- α with 21.18% which is found in Petir. The total compounds are 27.72% in Petir.

Table 2 shows that each site has different dominant compounds. For example, the alkane group, including Undecane, Pentadecane, Eicosane, 2-methyl-, Dodecane, 2,6,11-trimethyl-, dominates at Nglanggeran, whereas Pentadecane, Hexadecane, 2,6,11,15-tetramethyl-, Eicosane, 2-methyl-, Dodecane, Dodecane, 2,7,10-trimethyl-, and Hexadecane dominate at Wanagama. Wanagama, on the other hand, has detected santalol, a compound from the Petir site, as the dominant compound. This suggests that biosynthesis of santalol in Petir may be faster than in the other two (Nglanggeran and Wanagama), or that the ecological conditions in Nglanggeran and Wanagama do not support it as strongly as in Petir.

Table 2. The average of secondary metabolites detected in *S. album* wood from 3 study sites. The total compounds detected were 14. This table presents a compositional variation between sites. Santalol was only detected in the Petir sample. This data can be used to consider more intensive and specific follow-up studies.

No	Compound names	Nglanggeran (%Area \pm SD)	Wanagama (%Area \pm SD)	Petir (%Area \pm SD)
1	Undecane	6.38 \pm 0.83	–	3.64 \pm 1.44
2	Pentadecane	7.44 \pm 0.14	7.52 \pm 0.20	3.88 \pm 1.09
3	Heptadecane, 2,6,10,15-tetramethyl-	4.70 \pm 2.80	5.39	7.30
4	Hexadecane, 2,6,11,15-tetramethyl-	7.89	8.35 \pm 0.51	3.79 \pm 1.38
5	Tetradecane, 2,6,10-trimethyl-	3.86 \pm 2.72	–	4.75
6	Eicosane, 2-methyl-	7.03 \pm 1.43	8.11	–
7	Dodecane, 2,6,11-trimethyl-	8.03 \pm 0.24	8.03 \pm 0.47	3.34 \pm 2.59
8	Dodecane	–	6.14 \pm 0.25	–
9	Dodecane, 2,7,10-trimethyl-	–	6.13	–
10	Hexadecane	–	8.45 \pm 0.47	9.81 \pm 5.07
11	Santalol, cis- α	–	–	21.18 \pm 12.87
12	Santalol, trans- β	–	–	6.54 \pm 4.19
13	Santalol, E-cis, epi- β	–	–	0.72
14	Decane, 2,4,6-trimethyl-	–	–	4.02

A representative GC-MS chromatogram of *S. album* wood was generated to depict the qualitative profile of volatile compounds present in the sample. The chromatogram resolves the major peaks, including sesquiterpene alcohols such as cis- and trans-santalol, as well as branched hydrocarbons like heptadecane and 2,6,10,15-tetramethyl-, thereby providing visual confirmation of the compounds quantified in the % area analysis. The retention times and relative abundances detected confirm the identification and characterization of the principal chemical constituents, which are coherent with earlier reports on the chemistry of *S. album* essential oil. This image serves as a basic reference for subsequent quantitative and multivariate analyses, including PCA. The chromatogram in Figure 2 complements the tabulated data and

enables a comprehensive interpretation of the chemical profile, and the average area percentage for compounds is shown in Figure 3.

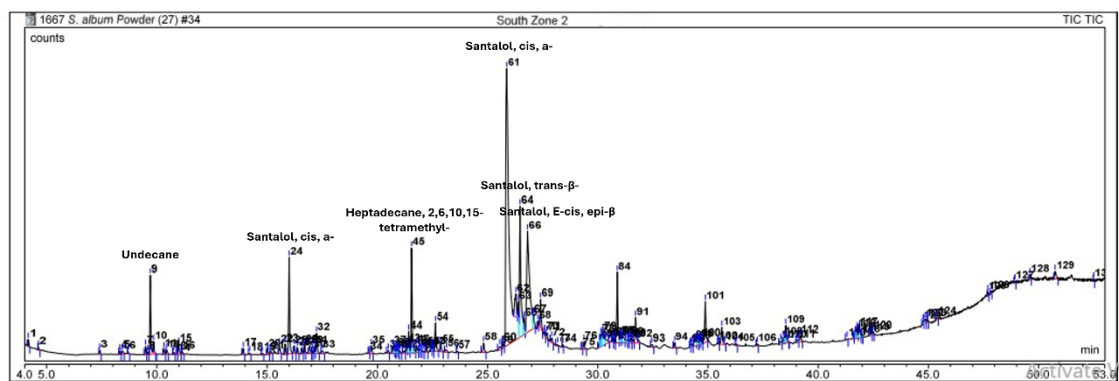


Figure 2. Chromatogram view of *S. album* outerwood from Petir. This picture exhibits the separation of the main volatile compounds detected in the outerwood of *S. album* based on retention time and signal intensity. Some dominant peaks indicate sesquiterpene alcohols, which are santalol isomers, as well as branched aliphatic hydrocarbons that contribute to the sample's chemical composition. This chromatogram's view supports compound identification and serves as the basis for quantitative data interpretation and next analysis.

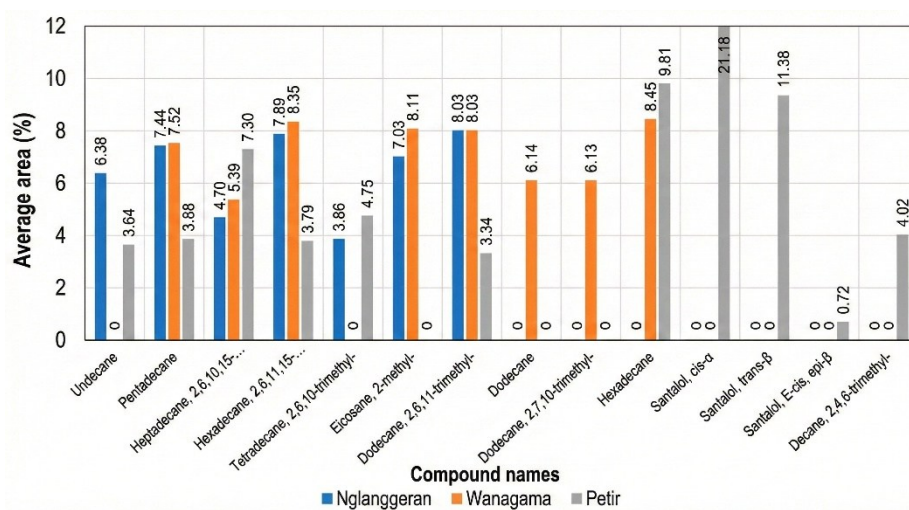


Figure 3. Average area percentage for each compound from Nglanggeran, Wanagama, and Petir. Axis X displays all compounds listed, and the percentage of average area is displayed by axis Y. Various santalol isomers are found in high percentages at Petir and are higher than those of the other compounds at all three sites.

Spatial Differences in the Chemical Composition of *Santalum album* Across the Three Sites

The result shows the variation in chemical composition in *S. album* samples from Nglanggeran, Wanagama, and Petir varies. We noticed there is a diverse chemical profile of *S. album* outerwood as shown in Table 1. From Table 1, we can see that Santalol, cis- α , Santalol, trans- β , Santalol, E-cis, epi- β can be found in Petir sites sample and these compounds cannot be found in the Nglanggeran and Wanagama samples. Both Wanagama and Nglanggeran are dominated by alkane groups such as Dodecane, 2,6,11-trimethyl-, Hexadecane, 2,6,11,15-tetramethyl-, and Pentadecane. The presence of santalol (27.72%) in Petir shows that these sites indicate suitability for *S. album* for the synthesis of these compounds. The karst and low water in Petir may act as drought stress, stimulating santalol biosynthesis. This drought/water stress cannot be found in Wanagama or Nglanggeran, which have more fertile soil than the Petir soil. This fact can be used for future intensive study to ensure that Petir is the most potential site for *S. album* plantation.

Principal Component Analysis (PCA) to GC-MS Area Percentage Data

The result of Principal Component Analysis (PCA) (Figure 4) in this research shows the clustering of the three sites volatile compound composition. It shows that the volatile compounds composition from three sites is distinct from one to another. It means each of the sites has a specific composition of volatile compounds. This distinct composition may be related to environmental conditions, especially soil type, altitude, and rainfall as shown in Table 2.

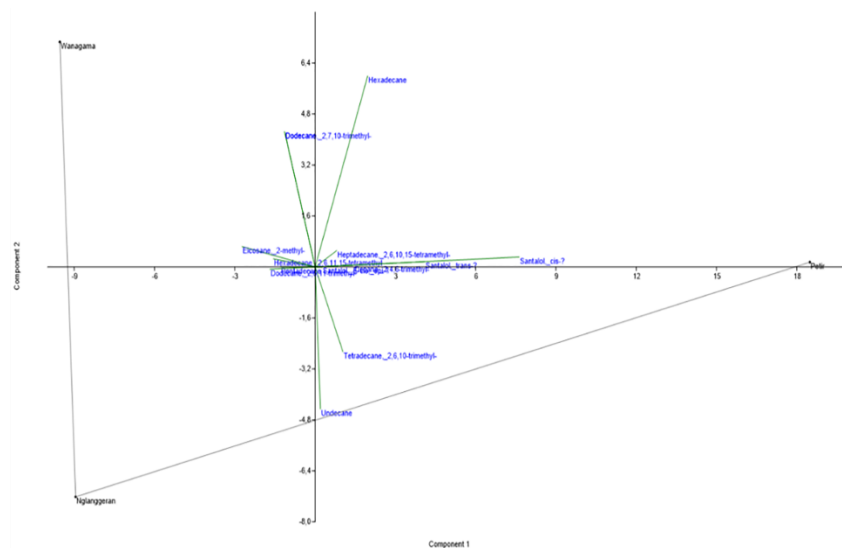


Figure 4. Petir samples clustered specifically on the positive side of PC1, indicating a specific chemical profile compared to the other locations. Wanagama samples clustered on the negative side of PC1, forming a separate cluster that displays a distinct dominant compound. Nglanggeran samples occupied the lower negative region of PC2, indicating another distinct chemical pattern. The PCA confirmed that each location displays a specific compound composition, distinguishing it from the others.

Discussion

In this research, santalol is detected in the highest percentage (a total of 27.72%) than other compounds (below 10%). Santalol (and its isomers) is a key compound of *S. album* oil [36]. In this research, the compound was only detected in samples from Petir sites. Other compounds, such as alkanes of undecane, pentadecane, and hexadecane, were identified as the main components at Nglanggeran and Wanagama. The trends reported here are tentative and restricted to the trees sampled. It needs more complete research to adequately support this finding [42].

Spatial Variation in Volatile Profiles

Data from compound profiling of the Petir site sample showed that the sesquiterpenes, especially cis- α -santalol ($21.18 \pm 12.87\%$) and trans- β -santalol ($6.54 \pm 4.19\%$). These compounds are known to contribute significantly to the aroma and quality of sandalwood oil [43,44]. Their presence in Petir samples but their absence in Nglanggeran and Wanagama suggest that environmental or genetic factors may enhance sesquiterpene biosynthesis at this site. This finding is in line with previous studies showing that sesquiterpene production in *S. album* can be influenced by habitat-specific microclimatic conditions, soil type, and tree maturity [31,41].

Data of Compound Profiling

Data of compound profiling from the Nglanggeran site showed higher abundance and greater consistency of saturated alkanes, such as undecane ($6.38 \pm 0.81\%$) and pentadecane ($7.44 \pm 0.14\%$). Although they do not contribute significantly to aroma, these compounds are often considered indicators of wood maturation and metabolic stability [45]. Current studies have noted that alkane-dominance of chemical profiles usually happens under less stressful or more metabolically uniform conditions, where sesquiterpene biosynthesis is least or retarded [18,45]. The steady presence of alkanes across the Nglanggeran replicates may reflect stable

site conditions and limited induction of secondary metabolic pathways. This is distinct from the sesquiterpene-rich chemical profile of the Petir sample.

The chemical profiling facts from samples of the Wanagama area showed a middle profile, with considerable levels of Hexadecane ($8.45 \pm 0.33\%$) and 2,6,11-trimethyl-Dodecane ($8.03 \pm 0.47\%$). These findings indicate the adequate accumulation of sesquiterpenes and hydrocarbons [46]. Volatile compounds in samples from Wanagama are spreading evenly. This condition may relate to the Wanagama area as a managed forest. This condition may decrease environmental stress and stimulate the metabolic equity [47]. This fact is caused by good soil and water conditions, which stimulate growth rather than activate the secondary metabolite synthesis [48]. The compounds in the *S. album* sample from Wanagama may be shaped by local ecological conditions in the Wanagama area. This condition was not environmental stress and did not initiate specific chemical compounds synthesis in the sample from this area [21,22]. From these results, we have information that the Wanagama area may produce *S. album* with low specific volatile compound composition [17,38].

Implications for Essential Oil Quality and Resource Management

Santalum album also has a prominent bioactive profile in the fragrance industry. Some research has reported the antimicrobial potential of compounds derived from *S. album*, particularly from its leaves. Swandiyasa et al. [49] prove that the leaf extract of *S. album* exhibited inhibition to *Candida albicans*, emphasizing the pharmacological properties related to this plant beyond its essential oil production. These findings advise that wood and leaf parts may be fully utilized in the development of therapeutic and functional products. In the fragrance industry, *S. album* has good potential because of its industrial and pharmacological potential, such as antioxidant, antimicrobial, and anti-inflammatory activities, making it valuable for broader bio-based implementations [26,28].

Comparative Interpretation and Broader Relevance

The result of this research supports the fact that chemistry includes secondary metabolites in medicinal and aromatic plants related to environmental conditions [41,49,50]. Based on some recent literature, the quality of *S. album* oil is modulated by climate and soil acidity. Our findings in this research show the importance of chemistry profile review, including volatile compounds to utilize the natural resources [1,4]. In general, Indonesia has a variation in ecological landscapes. Ecological variation and chemistry are important to develop methods to manage natural resources, including strong silviculture development. This research has connected the chemistry aspect with the ecology aspect to utilize the area in Gunungkidul for *S. album*.

This research emphasized the integration of chemical analysis with ecology/environmental science [51]. Sample from Petir shows a profitable chemical compound. For the continuity of these findings, a study about harvest monitoring and the efforts of replantation is needed [23]. Nglanggeran and Wanagama have more potential for genetic diversity and serve variability of *S. album*, although both are still potent to produce *S. album* with santalol [52,53].

Silviculture Implication

The santalol was detected in *S. album* from Petir samples, but not in Wanagama or Nglanggeran samples. This may be related to dry stressors regulating biosynthesis of secondary metabolism. Petir is a karst zone with shallow soils, low nutrient availability, and often drought. These conditions cause activation of stress-responsive transcription factors (e.g., SaAREB6) and increase terpenoid production [21]. The same pattern has been found in fragrant plants, where drought and nutrient restriction shift carbon allocation from growth to secondary metabolites [54]. Soil in Wanagama is rich with nutrients, and volcanic soil in Nglanggeran may promote growth but lower the stimulus for santalol accumulation. Genetic distinction among local varieties in the Gunung Sewu Geopark may further explain differences in oil quality by sites [55].

Paudel et al. [38] showed that distinctions in soil conditions, altitude, and rainfall importantly affect the growth achievement and secondary metabolism of *S. album* in Nepal. This is reinforcing the role of ecological heterogeneity in forming sandalwood oil grade [38]. Based on a silvicultural perspective, this implies that *S. album* cultivation in marginal karst sites, although riskier for growth and survival, can produce good-grade oil. Mesic sites remain acceptable for seedling production and conservation. Thus, integrating site edaphic conditions, genetic variation, and host management offers a path to optimizing sandalwood oil production and grade in Indonesia.

In the Nglanggeran, *S. album* can grow and collect basic volatile compounds. This may not be optimal for high-value oil production. Some intervention (e.g., thinning or pruning to decrease light stress) is needed to activate the biochemical pathways leading to santalol biosynthesis in this condition. The Wanagama area can

be used as a developmental or juvenile cultivation area for *S. album*, where early growth and the formation of hydrocarbon precursors happen. At a mature stage, transplantation or a shift in management to a drier site, such as Petir, may be good for commercial oil production. Petir is suitable for mature-stage cultivation or essential oil yield. Natural stress conditions produce high santalol content. It makes sense for in situ wild harvesting or conservation-based agroforestry representation. However, reforestation and guided regeneration need careful consideration, given shallow soil depths and limited water-saving capacity.

Nglanggeran, located on volcanic soil at a relatively high altitude (~641 m above sea level), with rainfall exceeding 2,100 mm per year. This condition can provide a suitable condition for plant growth, but with fewer stress cues that would promote secondary metabolite accumulation. The regosol soils in this area exhibit the specific described in the next research [55,56], including feeble horizon growth, rough texture, and low nutrient retention capacity. Although these soil conditions may appear fringier than fertile soils, they are not stressful enough to elicit the strong physiological responses required for increased metabolite production. These may cause sandalwood trees in Nglanggeran to allocate carbon to early growth processes, such as biomass production and canopy development, rather than to secondary metabolites such as santalol. This environmental context helps explain why santalol has not been detected in *S. album* samples from Nglanggeran, unlike in *S. album*, which grows in more stressful conditions, such as Petir.

Wanagama, at mid-altitude (~180 m asl), with fertile soils and rainfall of 1,900 mm. These conditions can support steady growth while restricting the stimulus for santalol production. Wanagama is a managed educational forest with moderate elevation and relatively good soil fertility. Soil of Wanagama is characterized by porosity, organic carbon, and nutrients yaitu P, K, and Cation Exchange Capacity (CEC) [36]. Chemical analysis in the sample from Wanagama is dominated by methylated alkanes, including Dodecane, Pentadecane, and Hexadecane. This result shows that environmental stability and fertility in Wanagama possibly *S. album* tree produce complex hydrocarbons and restricted sesquiterpenes.

The Petir area has shallow karst soils, poor nutrients, and low altitude and rainfall. These conditions can cause edaphic and drought stress. This stress will induce the activation of terpenoid biosynthesis. In Nepal, site-specific variations in soil nutrients, latitude, and rainfall influence the growth performance and metabolic traits of *S. album* [57]. Soils developed on carbonate materials typically exhibit shallow profiles, consisting of low organic matter [57,58]. These stressful conditions, including periodic drought and high sun disclosure, appear to promote the accumulation of sesquiterpenes, particularly cis- α -santalol (9.25 \pm 6.24%), along with trans- β -santalol and epi- β -santalol. The Petir area shows high potential for essential oil grade due to its sesquiterpene content, particularly the santalol isomer [43,44].

The Petir area is a cultivation site for *S. album*, with striking morphological variations in leaves and flowers [18]. This area is located in the southeastern part of the Gunungkidul karst landscape, characterized by shallow soils rich in calcium carbonate, derived from weathered limestone. According to Siradz [27], soils in the Gunungkidul karst area generally exhibit a neutral to acidic pH (6.2–8.0), high base saturation (35–93%), and a cation exchange capacity (CEC) of 30–60 cmol (+)/kg. Despite adequate macronutrient availability, these soil characteristics suggest that *S. album* in Petir may experience periodic environmental stress (especially drought), which can stimulate sesquiterpene (e.g, santalol) biosynthesis [21].

The environmental differences among Nglanggeran, Wanagama, and Petir provide a distinguishing basic context for the distinction in secondary metabolite production in *S. album*. While Nglanggeran and Wanagama represent relatively mesic environments with deeper, more fertile soils, only Petir showed detectable santalol in this research. This may be related to edaphic stress in karst ecosystems, where shallow soils with low water-holding capacity induce drought stress, thereby increasing terpenoid biosynthesis as part of the plant's adaptive response [37,59]. Similar findings in sandalwood plantations in Nepal indicate that altitude, soil depth, and rainfall variability significantly influence growth and secondary metabolite expression [38]. Furthermore, studies in other aromatic plants have shown that nutrient limitation and seasonal drought on calcareous substrates can enhance the mevalonate pathway, leading to higher sesquiterpene accumulation [60]. Thus, the karstic Petir site may act as a natural silvicultural niche where environmental constraints stimulate santalol biosynthesis, even though tree growth is slower compared to more fertile soils in Wanagama and Nglanggeran. There are similarities in the karst ecological conditions in some areas (Table 3).

Table 3. Comparative ecological characteristics of karst ecosystems in some sites relevant to secondary metabolite production in plants. All the karst sites there are drought/dry, which can trigger the synthesis of santalol. This condition supports the cultivation of *S. album*.

Location	Substrate / Soil Type	Soil Depth (cm)	Drainage	Nutrient Status	Annual Rainfall (mm)	Seasonality / Dry Stress	References
Petir (Gunungkidul, Indonesia)	Calcareous/shal low karst soil	10–40	Rapid	Low (N, P, K)	1,800–2,200	Extended dry season	[60,61]
Gunung Sewu Karst (Indonesia)	Karstic limestone	10–50	Rapid	Low	1,500–2,200	Seasonal drought	[60,61]
Yunnan Karst (China)	Calcareous rocky soil	10–35	Rapid	Low	800–1,200	Pronounced dry season	[62,63]
Mediterranean Karst (Spain / Italy)	Limestone/dolomite	10–40	Rapid	Low	400–1,000	Long summer drought	[64]

Table 3 emphasizes comparative ecological parameters of karst ecosystems worldwide, including Mount Sewu (Petir) in Java, the South China Karst, the Mediterranean Karst, and the Deccan Plateau in India. Although geographically distinct, these regions share standard ecological features that define marginal karst landscapes. Soils are typically shallow, often less than 50 cm, and consist of skeletal or regozolic substrates that limit rooting depth and restrict water and nutrient storage [61]. Karst soils are deficient in essential nutrients, especially nitrogen and phosphorus, which restrict plant growth while stimulating exchange in regard to secondary metabolite production [54]. Although these karst areas may have moderate to high rainfall per year, ranging from 1,800 to 2,200 mm, their fast drainage, combined with a long dry season, results in recurrent drought stress. This condition further forms plant adaptation strategies [22]. In response to these environmental pressures, many fragrant and therapeutic plants allocate carbon resources to the production of terpenoids, phenolics, and essential oils. In *S. album*, drought stress has been proven to activate transcription factors such as SaAREB6, which directly enhance the biosynthesis of santalol, the principal fragrant component of *S. album* oil [21].

Integrated Site-Matching Consideration

The purpose of the Site-Matching Considerations is to align environmental characteristics with the detected chemical profiles and silvicultural needs of *S. album* in the sampling area. By considering soil type, microclimate, and dominant volatile compounds, preliminary site-specific considerations can be developed to inform future research, optimize growth potential, and support conservation objectives. Arunkumar et al. [63], given that *S. album* is listed as Vulnerable by the IUCN, strategic silvicultural planning is essential for sustainable use and conservation. This approach ensures that management strategies are environmentally grounded and chemically informed. These observations are preliminary and not yet generalizable beyond the sampled sites. Table 4 summarizes the observed relationships between site characteristics, dominant volatile compounds, and corresponding preliminary silvicultural considerations for each location.

Table 4. Presents dominant volatile compounds and silviculture recommendations for *S. album* in Gunungkidul, Indonesia. The dominance of Santalol in Petir can serve as initial information for the development of *S. album* silviculture in this karst area.

Site	Ecological Condition	GC-MS Volatile Profile	Silviculture Recommendation
Nglanggeran	Latosol, moderate fertility, acidic	Hydrocarbons (Undecane, Eicosane)	Nursery, early-stage growth
Wanagama	Luvisol, balanced pH, managed forest	Methylated alkanes	middle growth, evaluation of oil precursors
Petir	Karst, shallow soil, xeric, alkaline	Santalol-rich sesquiterpenes	Oil creation, seed orchard, conservation

Based on Table 4, nutrient-poor, dry soil conditions in Petir stimulate high sesquiterpenoid production, particularly santalol. In contrast, Wanagama and Nglanggeran have more balanced soil and moisture levels, resulting in simpler volatile profiles with lower santalol content. These environmental differences are essential for understanding the chemical variation in *S. album*. These variations directly influence the appropriate silvicultural practices for each location. Therefore, site-specific management strategies are crucial for optimizing growth and essential oil quality. Based on these findings, tailored silvicultural recommendations are proposed for each location.

Petir is a marginal karst landscape. It has good potential to produce high-grade essential oils. Thin, nutrient-poor soils and long droughts create intense environmental stress, which has been proclaimed to stimulate increased accumulation of secondary metabolites in various essential oil-producing tree species. This area is suitable for development as both a vital oil production area and a natural seed orchard, as environmental stress can increase the expression of desirable genetic traits. Petir can play a double role, as a natural conservation site and a source of sandalwood with high santalol content. These implications support a site-matching approach in silviculture to optimize growth quality rather than simply quantity.

Wanagama has relatively more fertile soil and more moderate ecological conditions. This condition can support the early growth phase of *S. album* L. This location is suitable for use as an early planting area to reinforce seedling growth before being transferred to a harsher area to stimulate the accumulation of secondary metabolites. This practice aligns with the principles of assisted silviculture, in which the initial stage focuses on ensuring plant survival, while subsequent stages are intended to improve metabolite quality. Wanagama, as an initial area, is relevant to ex situ conservation strategies, as it provides a stable environment conducive to seedling survival. This area occupies a basic position in the silvicultural management chain based on growth stages.

Area Nglanggeran is dominated by volcanic soil. Based on its soil characteristics, the Nglanggeran area is suitable for early-stage cultivation, such as seedlings. This land is not good enough to induce santalol biosynthesis in *S. album*. Nglanggeran's soil is suitable for a nursery to produce seedlings. These seedlings can be distributed to other locations. Nglanggeran supports the quantitative aspects of silviculture, particularly the availability of good-quality seedlings, which are a prerequisite for optimal productivity in other areas.

Conclusions

Based on profiling data, this research identified 14 compounds. Santalol, which is a major chemical constituent of *Santalum album* (sandalwood) oil, was found with a total santalol of 27.72% in samples obtained from Petir. This site has karst limestone conditions that may induce drought and nutrient stress. This condition fits the paradigm of ecological stress, in which increased edaphic harshness up-regulates biosynthesis of important secondary compounds. Although the number of known compounds is low, the presence of santalol at this site can be used as a chemical distinction between Petir and the other two sites. It suggests the potential for *Santalum. album* cultivation in Petir, but more elaborate and repeated studies over a much larger sample size and broader chemical coverage are required to substantiate these site-specific findings or qualify them.

Author Contributions

JA: Conceptualization, Methodology, Investigation, Writing-Review & Editing; **SY:** Supervision, Writing-Review & Editing; **SC:** Methodology, Writing-Review & Editing; **SDM:** Data curation; Methodology; Formal Analysis

AI Writing Statement

During the preparation of this work, the authors used GRAMMARLY in order to make grammar corrections. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of Interest

There are no conflicts to declare

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