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Effect of Plant Age and Altitude on the Essential Oil Composition of *Cinnamomum cullilawan* from Maluku, Indonesia

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Abstract
Cinnamomum cullilawan Blume from Maluku is a potential source of essential oil for pharmaceutical, cosmetic, food, and natural-product-based industries. This study evaluated the effects of plant age and elevation on the yield and chemical composition of *C. cullilawan* essential oil. Bark samples were collected from four different locations ($n = 4$), representing plant ages of 8, 10, 15, and 20 years and different elevation gradients. Essential oils were extracted by steam distillation and analyzed using gas chromatography–mass spectrometry (GC–MS). Statistical analyses included linear regression, Analysis of Variance (ANOVA), partial t-test, and Principal Component Analysis (PCA). The essential oil yield ranged from 0.84% to 1.83%, with the highest yield obtained from 20-year-old plants (1.83%). ANOVA showed that plant age and elevation had a significant simultaneous effect on essential oil yield ($p = 0.04$), with significant partial effects of plant age ($p = 0.026$) and elevation ($p = 0.034$). GC–MS analysis revealed that eugenol and linalool were the dominant compounds. The highest eugenol content was found in 8-year-old plants (92.35%), whereas samples from higher elevation showed the highest linalool content (24.45%) and the lowest safrole content (0.76%). Statistical analysis indicated that eugenol ($p = 0.03$), safrole ($p = 0.038$), linalool ($p = 0.047$), and terpineol ($p = 0.038$) were significantly influenced by plant age and elevation, while other minor compounds showed no significant effect ($p > 0.05$). PCA showed that the first two principal components accounted for 83.14% of the total variation. These findings indicate that ontogenetic and ecological factors influence essential oil yield and chemical composition and may contribute to shifts in the relative dominance of phenylpropanoid and terpenoid compounds, providing a scientific basis for optimizing cultivation and standardizing *C. cullilawan* essential oil quality.

Keywords
C. cullilawan, Essential Oil, Plant Age, Elevation, Eugenol, GC–MS

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1. INTRODUCTION

Indonesia, as a tropical country, possesses abundant natural resources, including essential oils (EOs), which are widely utilized in the pharmaceutical, cosmetic, food, and healthcare industries due to their biological properties and antimicrobial activities. Essential oil-producing plants such as clove, ylang-ylang, and patchouli are known to contain bioactive compounds with important applications across various industrial sectors (Guzmán and Lucia, 2021). In addition, EOs have been widely reported as alternative antimicrobial agents due to their broad-spectrum activity and relatively environmentally friendly properties (Lima et al., 2019; Chukwuma et al., 2023; Saleh et al., 2023).

Species within the genus *Cinnamomum* are known to contain diverse bioactive compounds with broad biological activities, including antimicrobial, antioxidant, anti-inflammatory, antidiabetic, anticancer, and neuroprotective effects, supporting their potential as sources of herbal and pharmaceutical raw materials (Sharifi-Rad et al., 2021). Essential oils from several *Cinnamomum* species, such as camphor oil and *Cinnamomum cassia*, have also been reported to have broad applications in both traditional and modern medicine, as well as significant antioxidant and antibacterial activities for the food and healthcare industries (Lee et al., 2022; Liang et al., 2022). Furthermore, *Cinnamomum cassia* essential oil in nanoemulsion formulations has demonstrated promising antioxidant, antibacterial, and anticancer activities (Alam et al., 2023), while *Cinnamomum*-derived compounds have been reported to inhibit bacterial and fungal infections associated with biofilm formation (Didehdar et al., 2022).

Cinnamon leaf oil is also known to exhibit antioxidant, antidiabetic, anticholinesterase, and antiglaucoma activities, indicating that its secondary metabolite composition plays an important role in determining its biological properties (Mutlu et al., 2023). The effectiveness of essential oils in various industrial applications is strongly influenced by their chemical composition, as major active compounds such as linalool, eugenol, and eucalyptol are known to contribute to biological activities, including antibacterial effects (Hurria et al., 2026; Putri et al., 2025). Nevertheless, most studies on the genus *Cinnamomum* have primarily focused on major commercial species, whereas endemic or underexplored species remain relatively understudied, leaving their chemical and biological potential insufficiently understood.

One potential essential oil-producing plant from eastern Indonesia is *C. cullilawan*, a forest species whose bark yields an essential oil of significant economic value. Unlike several other *Cinnamomum* species, which are generally dominated by cinnamaldehyde or camphor, *C. cullilawan* has been reported to possess a distinctive chemical profile characterized by the dominance of phenylpropanoid compounds and certain monoterpenes, potentially resulting in distinct bioactivity characteristics. However, essential oil quality, both in terms of yield and chemical composition, is influenced by various physiological and ecological factors.

Plant age is one of the major physiological factors that plays an important role in the biosynthesis of secondary metabolites, thereby causing variations in essential oil yield and chemical composition (Xia et al., 2022; Farias et al., 2023; Eiasu and Araya, 2022). In woody species, including the genus *Cinnamomum*, essential oil yield and composition are also influenced by tree age and the plant parts used (Rostiana et al., 2020). This is supported by studies on *Cinnamomum camphora*, which showed that different plant tissues exhibit different antimicrobial activities, indicating variations in the distribution of secondary metabolites among plant parts (Poudel et al., 2021).

In addition to physiological factors, environmental factors such as climate, soil conditions, harvesting time, extraction methods, and geographical location also contribute to variations in EO composition (Ngo et al., 2020; Angane et al., 2022; El-Hack et al., 2022). Geographical location, particularly altitude, has been shown to affect the chemical composition of essential oils by altering microclimatic conditions that influence plant metabolism (Demirbolat et al., 2024). The influence of environmental factors on essential oil yield and chemical profiles has also been reported in *Cinnamomum camphora*, where geographical variation exhibited clear compositional gradients in major compounds (Zhang et al., 2023). Moreover, variations in secondary metabolism among different varieties of *Cinnamomum longepaniculatum* have been associated with differences in light exposure, indicating that environmental factors play an important role in shaping plant metabolite profiles (Zhao et al., 2022). These findings suggest that the interaction between physiological and ecological factors plays a crucial role in determining essential oil quality and potential chemotype variation.

Studies on the variation in essential oil composition within the genus *Cinnamomum* are still generally limited to the effects of single factors, such as plant age or growing location, in specific species, for example, *Cinnamomum burmannii* and *Cinnamomum camphora*. Several studies have reported that environmental variation in these species can alter the dominance of major compounds such as cinnamaldehyde, eugenol, and linalool, reflecting metabolic responses to ecological conditions. Previous studies have shown that plant age and environmental conditions can significantly affect essential oil yield and chemical composition; however, studies integrating these two factors simultaneously remain very limited. Particularly in *C. cullilawan*, available studies are still limited to general chemical characterization and have not examined how the interaction between plant age and environmental factors shapes chemotype variation and essential oil quality. In addition, data on *C. cullilawan* growing in Maluku, its natural habitat, remain very limited.

Therefore, this study aimed to investigate the effects of plant age and altitude on the yield and chemical composition of essential oils from *C. cullilawan* in Maluku, Indonesia. Specifically, this study aimed to (1) determine the variation in EO yield at different plant ages, (2) analyze the chemical composition of EOs using GC–MS, and (3) evaluate the effects of plant age and altitude on EO quality. This study offers novelty through a comprehensive analysis of the simultaneous effects of plant age and altitude on the essential oil composition of *C. cullilawan*, which has not been systematically reported to date. Furthermore, this study identifies patterns of chemical composition variation indicating a relative shift between phenylpropanoid and terpenoid compounds, reflecting possible changes in secondary metabolite biosynthetic pathways in response to interactions among physiological and environmental factors, thereby providing a new scientific basis for the cultivation, development, and quality standardization of the essential oil of this species.

2. EXPERIMENTAL SECTION

2.1 Sample Preparation

Bark samples of *C. cullilawan* were collected from four locations in West Seram Regency, Indonesia: Tounussa, Makububuy, Tanopol, and Tansi. The collection was conducted with permission from the relevant authorities (Figures 1 and 2). At each location, samples were collected from a single representative mature tree, yielding 4 biological samples per site.

Each sampling location was represented by one individual tree. Trees were selected based on the availability of naturally growing *C. cullilawan* populations in the targeted age classes and elevation ranges. Therefore, the sampling design should be considered exploratory. The observed variation may reflect both environmental conditions and individual tree characteristics.

This study employed an observational and exploratory sampling approach in which plant age and growing altitude were observed under naturally occurring field conditions rather than experimentally manipulated as factorial treatments. Therefore,

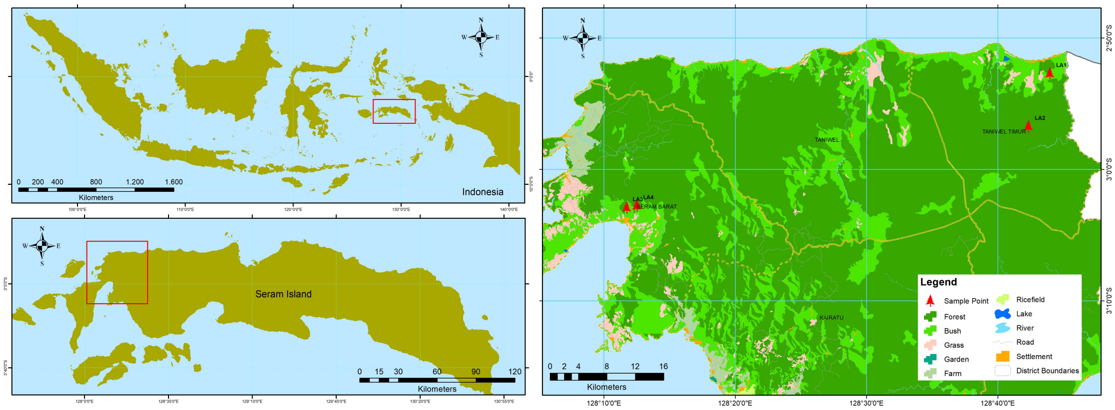

Figure 1. Sampling Locations Mapped Using ArcGIS 10.8 (Esri) with Data from Indonesia's Geospatial Information Agency (BIG)

the study design aimed to identify ecological and ontogenetic associations with essential oil yield and composition rather than establish causal effects. Approximately ±7 kg of fresh bark was collected from each tree. The geographical coordinates and altitude of each location were recorded using a Global Positioning System (GPS). Plant age was determined from landowner-provided information, verified using stem morphological characteristics and plant growth estimates, and subsequently classified into age categories. The plant material was identified and authenticated by Efraim Samson at the Botany Laboratory, Faculty of Science and Technology, Pattimura University, and deposited under voucher specimen number 73. The collected bark samples were sun-dried for approximately ±5 days until a constant weight was achieved. The dried samples from each tree were then cut into small pieces and homogenized before distillation.

Each homogenized sample was distilled in three technical replicates. This approach improved the accuracy and reproducibility of essential oil yield measurements. The obtained essential oils were analyzed using GC–MS.

2.2 Environmental Characteristics of the Sampling Sites

The environmental characteristics of the sampling sites were described using secondary climatological data from regional meteorological sources and relevant literature for the West Seram Regency, Maluku. In general, the study area has a tropical climate, with average temperatures of 25–30°C, relative humidity of 70–90%, and annual rainfall exceeding 2000 mm. Lowland sites are generally characterized by higher temperatures and relatively stable humidity, whereas higher-altitude sites exhibit lower temperatures and greater microclimatic variation. The soils in the study area are predominantly tropical forest soils with moderate to high organic matter content. This environmental information was used as supporting data for the ecological interpretation of variations in essential oil yield and chemical composition among sampling sites.

2.3 Essential Oil Isolation

A total of 2.5 kg of dried sample was weighed and prepared for steam distillation. The samples, cut into approximately 1 × 1 cm pieces, were placed on a sieve inside the distillation vessel at the Department of Industry and Trade of Maluku. The steam distillation procedure was adapted from previous studies on *Cinnamomum culilawan*, which reported successful isolation of essential oil using conventional steam distillation for 6 h (Sohilait and Kainama, 2016). Steam distillation was carried out for approximately 6 h.

Each sample was distilled in three technical replicates to obtain more accurate essential oil yield values. The distillate obtained was separated into oil and water phases. The oil fraction was subsequently dried with excess anhydrous sodium sulfate (Na_2SO_4) to remove residual moisture after distillation, following the procedure described by Sohilait and Kainama (2016), then filtered to obtain a water-free essential oil. The drying process was continued until the oil appeared clear, with no visible water phase separation observed prior to further analysis.

The selected distillation duration was also consistent with previous reports on the extraction of *C. culilawan* bark essential oil, which employed steam distillation for 6 h (Sohilait and Kainama, 2016) and water distillation for 5 h (Kapelle et al., 2016), ensuring adequate recovery of volatile constituents. The oil yield was calculated on a dry weight basis. The color characteristics of the oil were observed visually and compared with standard color references.

2.4 Analysis of Essential Oil Chemical Composition

The chemical composition of essential oils was analyzed using a Shimadzu Corporation GC–MS instrument (QP2010) equipped with an Rtx-5MS capillary column (60 m × 0.25 mm i.d.) and helium as the carrier gas. The operating conditions were as follows: initial column temperature of 50°C, inlet pressure of 100 kPa, column flow rate of 0.85 mL/min, split ratio of 20:1, injector temperature of 280°C, MS interface

Figure 2. Plant Samples of *C. cullilawan* were Collected from L4 (Tansi Village) (a) and L3 (Tanopol Village) (b)

temperature of 280°C, ion source temperature of 200°C, and pyrolysis temperature of 400°C. The selected split ratio was suitable for the analysis of essential oils and allowed efficient separation of volatile constituents while minimizing column overloading.

Compound identification was performed tentatively by first comparing the obtained mass spectra with the Wiley Registry of Mass Spectral Data database. This approach followed previous analyses of *C. culilawan* essential oils reported by Sohilait and Kainama (2016). Only compounds with a similarity index (SI, a numerical measure of how closely the observed spectrum matches a reference spectrum) value of ≥95% were accepted. Next, retention time (RT, the time a compound takes to travel through the chromatography column) was used to help verify peak consistency in repeated analyses and to compare chromatographic profiles with relevant literature reports. The identified compounds were further evaluated against previously reported constituents of *C. culilawan* bark essential oil (Sohilait and Kainama, 2016; Kapelle et al., 2016). However, retention index (RI) data, a standardized value used to identify compounds based on their elution order, were not available in this study; thus, compound identification should be considered tentative. Finally, the relative composition of each compound was calculated using peak-area normalization (the process of determining the proportion of each compound based on the area under its peak in the chromatogram).

2.5 Data Analysis

Essential oil yield data were presented as mean ± standard deviation from three technical replicates. Statistical analyses were conducted to evaluate the associations between plant age and growing altitude under natural field conditions, and between variations in essential oil yield and the major and minor chemical compositions of *C. cullilawan* essential oil. Due to the limited number of biological observations, statistical analyses were intended to identify preliminary patterns and associations. The relationships between the independent variables (plant age and growing altitude) and the dependent variables (essential oil yield and chemical compound concentrations) were analyzed using linear regression to identify patterns of association. Regression results were reported as regression coefficients (β), coefficients of determination (R^2), and significance values (p-value). Associations between plant age and growing altitude, and between essential oil yield and the content of major compounds (eugenol, safrole, linalool, and terpineol), were explored using analysis of variance (ANOVA) at a significance level of 5% ($\alpha = 0.05$). Because plant age and altitude were observed under naturally occurring conditions rather than experimentally assigned treatments, ANOVA results were interpreted as exploratory and descriptive rather than causal. Partial t-tests were performed to explore the statistical associations between individual variables and observed variations in essential oil characteristics.

Principal Component Analysis (PCA) was conducted to evaluate multivariate patterns among ontogenetic factors (plant age), ecological factors (growing altitude), essential oil yield, and major chemical components. All data were standardized using z-scores before analysis to eliminate differences in variable scales. PCA results were interpreted using eigenvalues, cumulative explained variance, score plots, and loading plots. Minor compounds detected only at specific locations (eucalyptol, cymene, cavibetol, α-copaene, α-cadinol, l-limonene, and trans-caryophyllene) were also analyzed using ANOVA to assess their distributions in relation to plant age and growing altitude. Given the observational design, limited sample size (n = 4), and absence of controlled factorial treatments, statistical analyses were interpreted as exploratory and hypothesis-generating. The aim was to identify preliminary biological and ecological patterns rather than draw definitive statistical inferences. All analyses were conducted at the 95% confidence level.

3. RESULTS AND DISCUSSION

3.1 Essential Oil Yield and General Characteristics

The isolation of essential oil (EO) from *C. cullilawan* using the steam distillation method yielded 0.84% to 1.83% across the four sampling locations (Table 1), accompanied by visually observable differences in oil color. This variation in yield is associated with differences in the chemical composition of the essential oils, particularly the balance between terpene-derived and phenylpropanoid compounds (Sadono et al., 2019). The distillation process facilitates rapid diffusion of volatile compounds through disrupted cell walls, enabling the efficient release of essential oils.

Figure 3 shows the relationship between plant age, plantation altitude, and essential oil yield. The observed pattern indicates an increasing yield with plant age, with 20-year-old plants (L4) producing the highest yield (1.83%) and 8-year-old plants (L3) producing the lowest (0.84%). This pattern suggests that plant physiological maturity may enhance the capacity for essential oil accumulation.

The ANOVA test showed that plant age and altitude together affected essential oil yield ($p = 0.04$). This means that yield changes may result from both factors working together. Separate t-tests also showed that altitude ($p = 0.034$) and plant age ($p = 0.026$) each affected yield. The smaller p-value for plant age suggests that plant age is more closely linked to changes in oil yield than altitude.

Statistical analysis showed that as plants age, their essential oil yield rises. The link between oil yield and altitude was less consistent across locations. Principal Component Analysis (PCA) confirmed this, indicating that older plants and certain terpenoid compounds, such as terpineol, cymene, *l*-limonene, and trans-caryophyllene, are associated with higher oil yield. The distinct position of sample L4 in the PCA results indicates that older plants produce more oil and a broader range of these compounds. This supports the idea that older plants have a more stable and efficient system for making secondary metabolites (Li et al., 2020). Besides age, factors such as altitude can also impact oil yield by altering temperature, humidity, and stress, thereby indirectly affecting oil production.

3.2 Variation of Major Chemical Compounds

The GC–MS chromatogram (Figure 4) revealed distinct peaks for the major constituents of the essential oil, and their composition and relative abundance are summarized in Table 2. Specifically, the essential oil of *C. cullilawan* consisted mainly of eugenol and linalool. However, their proportions varied considerably across locations, a variation likely linked to geographical and environmental factors that affect biosynthesis and chemical profiles (Demirbolat et al., 2024).

Furthermore, samples collected from lowland areas exhibited higher eugenol content, particularly at L1 (82.374%) and L3 (92.351%) (Table 2). In contrast, the sample obtained from the higher-elevation site (L2; 444 m above sea level) showed the highest linalool content (24.446%) and the lowest safrole content (0.76%) (Table 2). Together, these results indicate a shift in the dominance of major compounds, likely influenced by environmental gradients, and suggest changes in the orientation of secondary metabolism between the phenylpropanoid and terpenoid pathways.

Statistical analysis showed that eugenol content was associated with the combination of plant age and altitude (ANOVA, $p = 0.03$). Partial t-test results indicated that both altitude ($p = 0.05$) and plant age ($p = 0.046$) were associated with differences in eugenol accumulation. These findings suggest that eugenol dominance in lowland locations may be associated with habitat conditions and plant developmental stages.

Linalool content showed significant associations with both altitude and plant age (ANOVA, $p = 0.047$; altitude, $p = 0.030$; plant age, $p = 0.049$). These results suggest a link between linalool biosynthesis and ecological variation, particularly elevation. Principal Component Analysis (PCA) revealed that the second principal component (PC2) was strongly associated with altitude, linalool, and α-copaene. The L2 position, which had the highest score on PC2, supports that higher elevation correlates with linalool biosynthesis. In contrast, L1 and L3 clustered in the PCA region associated with eugenol, indicating that lowland environments favor dominance of the phenylpropanoid pathway.

These differences were likely influenced by environmental gradients, temperature, light intensity, rainfall, and soil nutrient availability. Higher elevations generally have lower temperatures, which may alter plant metabolic activity and essential oil biosynthetic pathways (Sadono et al., 2019). In addition, water limitation and variation in soil nutrients also affect secondary metabolite production (Virga et al., 2020; Chrysargyris et al., 2016). Climate variability also plays an important role in modifying plant secondary metabolite profiles (Dobhal et al., 2024).

To place these findings within the context of the genus *Cinnamomum*, comparisons were made with several other previously reported species. Table 3 shows that most *Cinnamomum* species exhibit distinct chemical profiles that depend on plant organ, geographical factors, and genetic factors. For example, *Cinnamomum zeylanicum* bark is dominated by (*E*)-cinnamaldehyde in the range of 46–78% (Abd D. Amran et al., 2023; Mutlu et al., 2023; Živković et al., 2025), while the leaves are also dominated by (*E*)-cinnamaldehyde (73%) together with benzyl benzoate and cinnamyl acetate (Mutlu et al., 2023). In *Cinnamomum malabatrum*, linalool (38%) is the major component with caryophyllene content of 12%, accompanied by minor amounts of eugenol and cinnamaldehyde (Kuttithodi et al., 2023; Surendran et al., 2025). Meanwhile, *Cinnamomum camphora* shows more diverse chemotypes dominated by 1,8-cineole, linalool, camphor, nerolidol, and selina-6-en-4-ol (Bottoni et al., 2021; Zhao et al., 2022; Zhang et al., 2023; Min et al., 2025).

When specifically compared based on eugenol content (Ta-

Table 1. General Characteristics of the Sampling Locations and Essential Oil (EO) Isolation Yields

Code	Location	Position	Elevation (masl)	Plant age (years)	Average Temperature (°C)	Air Humidity (%)	Annual Rainfall (mm/year)	Soil pH	Yield (%)	EO color
L1	Tounusa Village	2°52'41.4"S	74	10	27.0–28.5	78–83	2000–2500	6.0–6.8	1.64 ± 0.11	Yellow
L2	Makububuy Village	2°56'42.6"S	444	15	24.5–26.0	82–86	2500–3000	5.5–6.2	1.13 ± 0.13	Brownish-yellow
L3	Tanopol Village	3°02'53.8"S	167	8	26.5–27.8	79–84	2200–2600	5.8–6.5	0.84 ± 0.12	Blackish red
L4	Tansi Village	3°04'48.8"S	323	20	25.0–26.5	81–85	2400–2800	5.5–6.3	1.83 ± 0.08	Yellow clear

Note. Elevation data were calculated from geographic coordinates for each village. Environmental parameters were derived from regional profiles using available datasets. Temperature ranges were calculated via Braak's adiabatic lapse rate formula based on each village's elevation. Humidity and annual rainfall were gathered from local meteorological station records (BMKG, 2023), reflecting Seram Island's tropical wet climate (Af/Am). Soil pH ranges were identified from documented distributions of Red-Yellow Podzolic and Cambisol soils in Maluku.

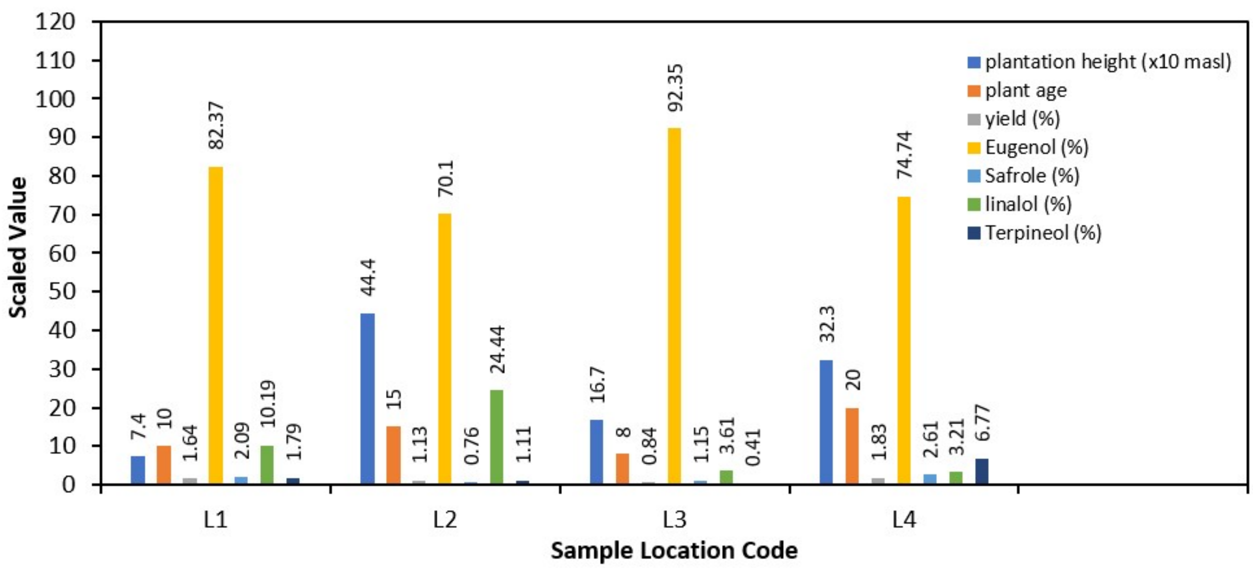

Figure 3. Bar Chart Showing the Relationship Between Plant Age, Plantation Height, and Essential Oil Yield of *C. Cullilawan* Across Sampling Locations

ble 4), *C. cullilawan* showed a relatively high eugenol range (70–92.35%), placing it in the upper range compared with several other species. *Cinnamomum verum* has been reported to contain approximately 52-90% eugenol in leaves (Weeratunge et al., 2024; Prathibhani et al., 2021, 2024; Xavier et al., 2022), even reaching 93.6% in some locations in Brazil (Xavier et al., 2022). *Cinnamomum tamala* showed a very broad range (35.1–94.3%) (Rana et al., 2009), whereas *Cinnamomum zeylanicum* in India showed eugenol content of 60–89.8%, influenced by seasonal variation (Joshi, 2019). In contrast, *Cinnamomum malabatrum* contained only 8.75% eugenol, with linalool as the dominant compound (Kuttithodi et al., 2023). These comparisons indicate that *C. cullilawan* from Maluku has a distinctive chemical characteristic, with a tendency toward a phenylpropanoid-dominant chemotype, particularly in younger plants growing in lowland areas, distinguishing it from several other *Cinnamomum* species that are more monoterpenoid- and sesquiterpenoid-dominated.

3.3 Association of Plant Age with Eugenol and Minor Compounds

Plant age clearly influenced eugenol accumulation in *C. cullilawan* essential oil. Younger plants (8–10 years) had higher eugenol concentrations. Eight-year-old plants (L3) showed the highest relative abundance at 92.351%, while plants aged 15–20 years showed lower levels, ranging from 70–74%. This suggests that early growth is more favorable for eugenol, a major defensive metabolite produced via the phenylpropanoid pathway.

Figure 3 shows the relation between plant age, altitude, and the distribution of eugenol and other major compounds.

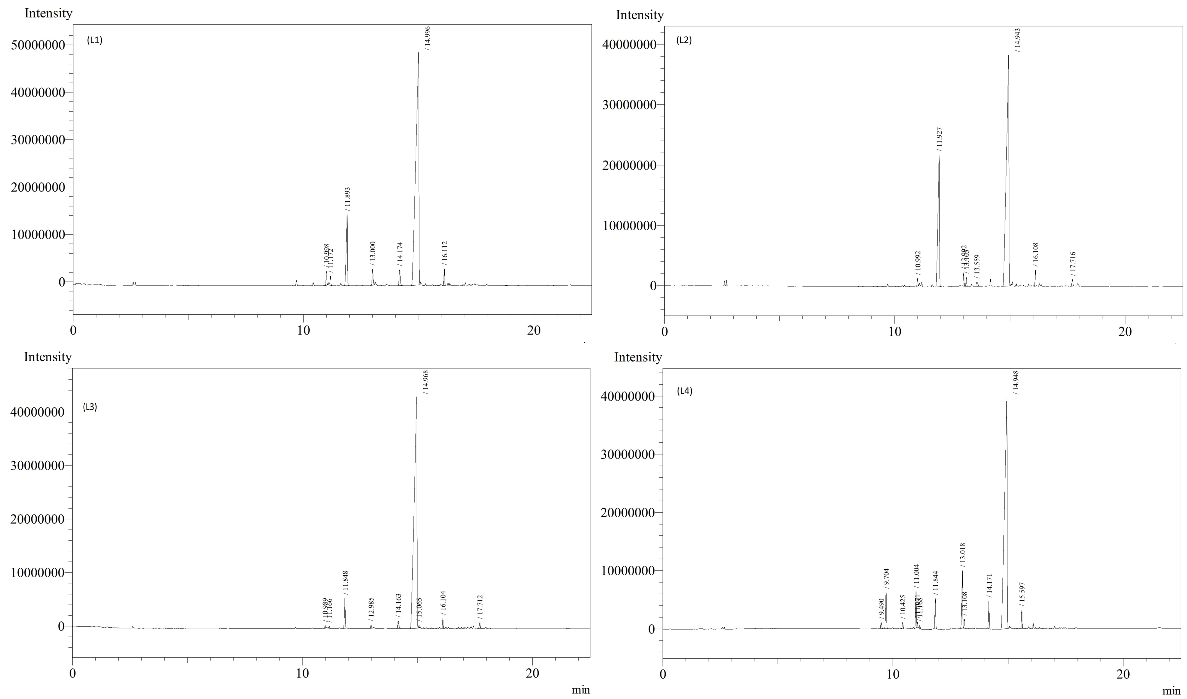

Figure 4. Representative GC–MS Chromatograms of *Cinnamomum cullilawan* Bark Essential Oil from Four Locations: L1 (Tounusa), L2 (Makububuy), L3 (Tanopol), and L4 (Tansi)

Table 2. Major Essential Oil (EO) Components Identified in *C. cullilawan*

Compound Name	Rt (minute)	SI	Concentration (%)			
			Tounusa Village	Makububuy Village	Tanopol Village	Tansi Village
cymene	5.578	95	1.20 ± 0.22	0.67 ± 0.20	–	–
l-limonene	5.683	95	–	–	–	3.53 ± 0.21
Eucalyptol	5.781	97	0.89 ± 0.17	–	–	–
Terpineol	8.565	96	1.79 ± 0.11	1.11 ± 0.36	0.41 ± 0.29	6.77 ± 0.31
Safrole	10.128	95	2.09 ± 0.26	0.76 ± 0.27	1.15 ± 0.11	2.61 ± 0.21
Linalool	7.167	98	10.19 ± 0.26	24.44 ± 0.227	3.61 ± 0.15	3.21 ± 0.21
Eugenol	10.944	97	82.37 ± 0.22	70.10 ± 0.22	92.35 ± 0.09	74.74 ± 0.20
Cavibetol	12.618	95	1.44 ± 0.18	0.80 ± 0.12	0.95 ± 0.12	–
α-copaene	11.142	96	–	1.34 ± 0.11	–	–
α-cadinol	13.869	97	–	–	0.82 ± 0.11	–
trans-caryophyllene	11.679	95	–	–	–	1.68 ± 0.12

Younger plants accumulate more eugenol, while older plants show more safrole and terpineol. This change suggests that secondary metabolism shifts as plants develop.

Statistical analysis showed measurable variation in composition among samples. Safrole variation was linked to both plant age and altitude (ANOVA, $p = 0.038$), with partial links to altitude ($p = 0.026$) and age ($p = 0.027$). Increased safrole in older plants may reflect changes in secondary metabolites as plants mature. Terpineol showed similar associations with both variables (ANOVA, $p = 0.038$) and partial associations with altitude ($p = 0.049$) and age ($p = 0.025$). Mature plants diversify secondary metabolites, including more terpenoid compounds.

This pattern indicates an ontogenetic metabolic shift, namel y a change in the biosynthetic priority of secondary metabolites during plant physiological development. Principal Component Analysis (PCA) further supported this pattern, where eugenol showed a strong loading on the negative side of PC1 and clustered samples L1 and L3, while sample L4 was positioned on the positive side of PC1 together with safrole and terpineol. This separation indicates a shift in secondary metabolic orientation from phenylpropanoid dominance in the juvenile phase toward more complex metabolite diversification in the mature

Table 3. Comparison of the Major Essential Oil Compounds Among Selected Species of the Genus *Cinnamomum*

Species & Plant Part	Dominant Compounds	References
Cinnamomum zeylanicum (bark)	(E)-cinnamaldehyde (~46–78%)	Abd D. Amran et al. (2023); Mutlu et al. (2023); Živković et al. (2025)
Cinnamomum zeylanicum (leaf)	(E)-cinnamaldehyde (73%), benzyl benzoate, cinnamyl acetate	Mutlu et al. (2023)
Cinnamomum malabatrum (leaf)	Linalool (38%), caryophyllene (12%), benzyl benzoate, eugenol, cinnamaldehyde	Kuttithodi et al. (2023); Surendran et al. (2025)
Cinnamomum camphora (leaf, various chemotypes)	1,8-cineole, linalool, camphor, nerolidol, selina-6-en-4-ol	Bottoni et al. (2021); Zhao et al. (2022); Zhang et al. (2023); Min et al. (2025)

Table 4. Comparison of Eugenol Content Ranges Among Selected Species of the Genus *Cinnamomum*

Species & Plant Part	Eugenol Content (%) (Range)	Brief Description	References
Cinnamomum verum (leaf)	52–90%	Major chemotype (eugenol-dominant chemotype)	Weeratunge et al. (2024); Prathibhani et al. (2021, 2024); Xavier et al. (2022)
Cinnamomum verum (leaf, Brazil)	60–93.6%	Variation among geographical locations	Xavier et al. (2022)
Cinnamomum zeylanicum (leaf, India)	60–89.8%	Seasonal variation affects eugenol content	Joshi (2019)
Cinnamomum malabatrum (leaf)	8.75%	Linalool as the dominant compound	Kuttithodi et al. (2023)

phase.

The high concentration of eugenol in younger plants is likely associated with active defense mechanisms during the early growth stage. Eugenol is known to possess antimicrobial and anti-herbivory activities that protect plants against biotic pressures, such as pathogen infection and herbivore attack (Al-Khayri et al., 2023; Divekar et al., 2022). The production of eugenol at this stage is presumed to be part of a metabolic resource-allocation strategy for defense, before the plant redirects part of its biosynthetic capacity toward diversifying other secondary metabolites during the maturation phase (Elshafie et al., 2023; Selwal et al., 2023).

3.4 Minor Compounds and Statistical Significance

In addition to eugenol and linalool, several minor compounds also showed location-specific distribution patterns, including safrole, terpineol, eucalyptol, cymene, cavibetol, α-copaene, α-cadinol, *l*-limonene, and trans-caryophyllene. Safrole, linalool, and terpineol exhibited clearer variations associated with plant age and altitude, whereas the other minor compounds showed more location-specific distributions.

This distribution was clear: eucalyptol was detected only in L1, α-copaene in L2, α-cadinol in L3, and *l*-limonene and trans-caryophyllene in L4, illustrating a strong link between specific secondary metabolites and certain habitat conditions. Furthermore, statistical analysis showed that several minor compounds, such as eucalyptol, were not significantly affected by plant age or altitude (ANOVA, $p = 0.677$); similar results appeared for cymene, cavibetol, α-copaene, α-cadinol, *l*-limonene, and trans-caryophyllene ($p > 0.05$). Thus, the distribution of these compounds is likely tied to microhabitat factors or local genetic variation rather than age or elevation.

Nevertheless, Principal Component Analysis (PCA) showed that minor compounds still contributed to sample differentiation, where α-copaene contributed to the separation of L2 on PC2, while *l*-limonene and trans-caryophyllene contributed to the separation of L4 on PC1. This indicates that although their concentrations were relatively low, minor compounds still play a role in shaping the specific chemical characteristics of each location.

The presence of safrole warrants special attention due to its toxicological implications and regulatory concerns. Safrole is a phenylpropanoid compound belonging to the alkenylbenzene group that possesses antimicrobial, insecticidal, and cytotoxic activities, but it is also known to be hepatotoxic, genotoxic, and potentially carcinogenic. Safrole has been classified as possibly carcinogenic to humans (Group 2B) by the International Agency for Research on Cancer and has been shown to be a genotoxic carcinogen in animal studies (Kemprai et al., 2019; Eisenreich et al., 2021; Götz et al., 2022).

Biochemically, safrole metabolism can generate reactive intermediates such as 1′-hydroxysafrole, which can bind to DNA and cellular proteins, thereby potentially triggering mutations, liver damage, and tumor formation upon long-term exposure. In plants, safrole accumulation is presumed to function as a chemical defense mechanism against herbivores and pathogens. In this study, the lower safrole content in high-altitude plants indicates the potential to produce essential oils with safer chemical profiles for industrial applications, particularly in the pharmaceutical, cosmetic, and flavoring sectors. In contrast, the increased safrole content in older plants suggests that plant age is an important factor in raw material selection, not only for optimizing essential oil quality but also for ensuring product safety and compliance with international regulations.

3.5 Ecological Interpretation

The variation in essential oil yield and composition observed in *C. cullilawan* suggests an adaptive response. This response is due to differences in environmental conditions and plant developmental stages. The results indicated that plant age and altitude were associated with changes in the chemical profile of the essential oil. This reflects how ontogenetic factors interact with the ecological conditions of the growing habitat.

Principal Component Analysis (PCA) results further clarified this ecological pattern. The samples showed clear separation in multivariate space. The first two components (PC1 and PC2) explained 83.14% of the total variation. This indicates that most chemical variation is associated with plant age and altitude. PC1 was mainly linked to the ontogenetic gradient. It showed increased oil yield and accumulation of terpenoids, including terpineol, cymene, *l*-limonene, and trans-caryophyllene. PC2 was more related to the ecological gradient. It was characterized by elevated levels of linalool and α-copaene.

The PCA score plot showed a consistent ecological pattern in sample distribution. Sample L4 (20 years old) occupied a distinct position, being associated with higher oil yield and a more complex chemical profile, indicating that physiological maturity may lead to greater diversity of secondary metabolites. Sample L2 (at 444 m above sea level) was linked to linalool and α-copaene, suggesting a relationship between elevation and changes in secondary metabolic pathways. In contrast, samples L1 and L3 clustered in a region dominated by eugenol, reflecting the characteristics of younger plants found in lowland habitats.

These differences are likely related to microclimatic conditions among locations. Lowland areas, which generally have higher temperatures and relatively stable humidity, appear to favor phenylpropanoid pathway activity, as reflected by the high eugenol content in L1 and L3. In contrast, cooler highland conditions with greater variation in light intensity and humidity may influence the regulation of secondary metabolism and enhance the biosynthesis of terpenoid compounds such as linalool, as observed in L2.

Beyond temperature and elevation, rainfall, water availability, and soil characteristics can influence essential oil production by altering plant physiology and nutrient availability. Seasonal changes, such as shifts between rainy and dry periods, affect proportions of major volatile compounds in aromatic plants, as observed in *Eugenia patrisii* (da Cruz et al., 2022). Water deficit or drought stress can increase essential oil content and alter its composition, as seen in *Cymbopogon flexuosus* and *Satureja hortensis* (Mahmoud et al., 2023; Rasouli et al., 2023). Combined effects of salinity and water availability shape essential oil yield and profile in *Mentha spicata* and *Origanum* spp. by altering physiological traits, including chlorophyll content, proline levels, and antioxidant activity (Stefanakis et al., 2024).

Soil conditions with low nutrient availability may also trigger increased secondary metabolite synthesis as an adaptive response to environmental stress, leading to higher levels of phytotoxic monoterpenes as an ecological competitive mechanism. Physiologically, changes in environmental conditions can affect photosynthetic activity, hormonal balance, proline accumulation, and plant antioxidant systems, which ultimately correlate with changes in essential oil biosynthesis. In some cases, moderate environmental stress conditions may even enhance secondary metabolite accumulation as part of an adaptive defense mechanism (Mwithiga et al., 2024; Kintamani et al., 2023).

Overall, these results show that *C. cullilawan*'s chemical plasticity is shaped by interactions between plant development and habitat ecology. Together, these factors control essential oil yield and compound distribution, which in turn affect oil quality and industrial potential. However, due to a lack of biological replication at each elevation, our ecological findings and interpretations of local variation are tentative. These ecological patterns should be viewed as preliminary until larger, more replicated sampling across elevation gradients is completed.

3.6 Biosynthetic Mechanisms and Regulation of Secondary Metabolites

The variation in the chemical composition of essential oils in *C. cullilawan* suggests that differences in major compounds may be associated not only with environmental factors and plant age, but also with the regulation of secondary metabolite biosynthetic pathways. Specifically, eugenol and safrole, both in the phenylpropanoid group, are synthesized via the phenylpropanoid pathway, which uses phenylalanine as the main precursor. In contrast, linalool is a monoterpene formed via the terpenoid pathway, particularly through the methylerythritol phosphate (MEP) pathway. Thus, the phenylpropanoid pathway is instrumental in the formation of aromatic C6–C3 compounds such as eugenol and safrole, which function ecologically in plant defense and environmental interactions (Lv et al., 2024; Ninkuu et al., 2025).

The dominance of one of these compound groups indicates a shift in carbon allocation within plant secondary metabolism in response to ontogenetic and ecological factors. The high eugenol content in younger plants (8–10 years), particularly in samples L3 (92.351%) and L1 (82.374%), indicates that the phenylpropanoid pathway is more dominant during the early growth phase. At this stage, plants tend to allocate their metabolic resources toward the synthesis of defensive compounds in response to biotic pressures such as herbivory and pathogen infection. Eugenol is known to possess antimicrobial and anti-herbivory activities; therefore, its accumulation during early growth can be regarded as part of the plant's chemical defense strategy (Al-Khayri et al., 2023; Divekar et al., 2022). The activity of key enzymes such as Phenylalanine ammonialyase (PAL) and eugenol synthase is presumed to be higher at this stage, thereby supporting elevated eugenol accumulation (Ninkuu et al., 2025).

In contrast, the high linalool content in sample L2 (24.446%) indicates increased activity of the terpenoid pathway, which may result from specific environmental conditions at higher elevations. For example, lower temperatures, reduced light intensity, and changes in humidity can influence the expression of genes that regulate monoterpene biosynthesis. Specifically, these factors may affect the activity of linalool synthase, which catalyzes the conversion of geranyl diphosphate (GPP) into linalool. Ecological conditions such as temperature variations and environmental stress are documented to modulate terpenoid biosynthetic pathways and alter plant essential oil profiles (Dobhal et al., 2024; Demirbolat et al., 2024). Thus, ecological variation could plausibly drive shifts in the balance of secondary metabolism from the phenylpropanoid pathway toward the terpenoid pathway.

The Principal Component Analysis (PCA) results further support this interpretation by showing clear separation between eugenol-rich and linalool-rich samples. Samples L1 and L3 clustered in the region associated with eugenol, whereas L2 clustered in the region associated with linalool and α-copaene. This pattern indicates metabolic differentiation reflecting differences in biosynthetic pathway regulation in response to the combined effects of plant age and habitat conditions.

In addition, the increased safrole content in older plants, particularly in L4, indicates further transformation within the phenylpropanoid pathway. Safrole is a phenylpropanoid derivative formed through structural modification of phenolic compounds via methylation processes. The increase in safrole, together with elevated terpineol, cymene, *l*-limonene, and trans-caryophyllene, indicates that plant physiological maturity is associated with more complex secondary metabolite diversification. Similar patterns have been reported across various aromatic plant species, in which increasing plant age correlates with the diversification of essential oil components, driven by changes in metabolic regulation during plant development (Li et al., 2020; Farias et al., 2023).

Overall, the variation in the chemical composition of *C. cullilawan* essential oil reflects a dynamic interaction between phenylpropanoid and terpenoid biosynthetic pathways, influenced by ontogenetic and ecological factors. During the juvenile phase, the phenylpropanoid pathway is more dominant to support defense functions, whereas in older stages or under specific environmental conditions, metabolic diversification occurs toward increased production of terpenoids and other phenylpropanoid derivatives. These findings demonstrate the high metabolic plasticity of *C. cullilawan* and provide a scientific basis for optimizing cultivation and standardizing essential oil quality for industrial applications.

4. CONCLUSION

This study demonstrated that plant age and growing altitude were associated with variations in the yield and chemical composition of *C. cullilawan* essential oil in Maluku. Variations in eugenol, linalool, safrole, and terpineol contents suggest metabolic plasticity and indicate a phenylpropanoid-dominant chemotype. These findings provide insight into the regulation of secondary metabolites in tropical essential oil-producing species and offer a scientific basis for optimizing cultivation practices, site selection, and harvest age for industrial applications. Further studies using larger sample sizes and molecular approaches are needed to clarify the biosynthetic mechanisms underlying chemotype variation.

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REFERENCES

Abd D. Amran, A., K. Khalid Al-Derawi, and S. Sadiq Al-Saadi (2023). Phytochemical Constituents of Bark Essential Oils of *Cinnamomum zeylanicum* Blume and Effects on Liver Tissue of Rats. *University of Thi-Qar Journal of Science*, **10**(2); 165–170

Al-Khayri, J. M., R. Rashmi, V. Toppo, P. B. Chole, A. Banadka, W. N. Sudheer, P. Nagella, W. F. Shehata, M. Q. Al-Mssallem, F. M. Alessa, M. I. Almaghasla, and A. A. Rezk (2023). Plant Secondary Metabolites: The Weapons for Biotic Stress Management. *Metabolites*, **13**(6); 716

Alam, A., M. Ansari, M. Alqarni, M. Salkini, and M. Raish (2023). Antioxidant, Antibacterial, and Anticancer Activity of Ultrasonic Nanoemulsion of *Cinnamomum cassia* L. Essential Oil. *Plants*, **12**(4); 834

Angane, M., S. Swift, K. Huang, C. A. Butts, and S. Y. Quek (2022). Essential Oils and Their Major Components: An Updated Review on Antimicrobial Activities, Mechanism of

Action and Their Potential Application in the Food Industry. *Foods*, **11**(3); 464

Bottoni, M., F. Milani, M. Mozzo, D. Kolloffel, A. Papini, F. Fratini, F. Maggi, and L. Santagostini (2021). Sub-Tissue Localization of Phytochemicals in *Cinnamomum camphora* (L.) J. Presl. Growing in Northern Italy. *Plants*, **10**(5); 1008

Chrysargyris, A., C. Panayiotou, and N. Tzortzakis (2016). Nitrogen and Phosphorus Levels Affected Plant Growth, Essential Oil Composition and Antioxidant Status of Lavender Plant (*Lavandula angustifolia* Mill.). *Industrial Crops and Products*, **83**; 577–586

Chukwuma, I. F., N. O. Uchendu, R. O. Asomadu, W. F. C. Ezeorba, and T. P. C. Ezeorba (2023). African and Holy Basil: A Review of Ethnobotany, Phytochemistry, and Toxicity of Their Essential Oil. *Arabian Journal of Chemistry*, **16**(7); 104870

da Cruz, E. N. S., L. S. Peixoto, J. S. da Costa, R. H. V. Mourão, W. M. O. do Nascimento, J. G. S. Maia, W. N. Setzer, J. K. da Silva, and P. L. B. Figueiredo (2022). Seasonal Variability of a Caryophyllane Chemotype Essential Oil of *Eugenia patrisii* Vahl Occurring in the Brazilian Amazon. *Molecules*, **27**(8); 2417

Demirbolat, I., U. Karık, and I. Iscan (2024). Effect of Cultivation and Geographical Location on Chemical Composition and Enantiomeric Distribution in Linalool-Rich *Origanum dubium* Boiss. Essential Oils. *Journal of Essential Oil Research*; 1–7

Didehdar, M., Z. Chegini, S. P. Tabaeian, S. Razavi, and A. Shariati (2022). *Cinnamomum*: The New Therapeutic Agents for Inhibition of Bacterial and Fungal Biofilm-Associated Infection. *Frontiers in Cellular and Infection Microbiology*, **12**; 930624

Divekar, P. A., S. Narayana, B. A. Divekar, R. Kumar, B. G. Gadratagi, A. Ray, A. K. Singh, V. Rani, V. Singh, A. Kumar, R. P. Singh, R. S. Meena, and T. K. Behera (2022). Plant Secondary Metabolites as Defense Tools Against Herbivores for Sustainable Crop Protection. *International Journal of Molecular Sciences*, **23**(5); 2690

Dobhal, P., V. K. Purohit, S. Chandra, S. Rawat, P. Prasad, U. Bhandari, V. L. Trivedi, and M. C. Nautiyal (2024). Climate-Induced Changes in Essential Oil Production and Terpene Composition in Alpine Aromatic Plants. *Plant Stress*, **12**; 100445

Eiasu, B. K. and H. T. Araya (2022). Effect of Leaf Age on Essential Oil Yield and Composition in Rose-Scented Geranium. *HortScience*, **57**(12); 1524–1528

Eisenreich, A., M. Götz, B. Sachse, B. Monien, K. Herrmann, and B. Schäfer (2021). Alkenylbenzenes in Foods: Aspects Impeding the Evaluation of Adverse Health Effects. *Foods*, **10**(9); 2139

El-Hack, M. E. A., M. T. El-Saadony, A. M. Saad, H. M. Salem, N. M. Ashry, M. M. A. Ghanima, M. Shukry, A. A. Swelum, A. E. Taha, A. M. El-Tahan, S. F. AbuQamar, and K. A. El-Tarabily (2022). Essential Oils and Their Nanoemulsions as Green Alternatives to Antibiotics in Poultry Nutrition. *Poultry Science*, **101**(2); 101584

Elshafie, H. S., I. Camele, and A. A. Mohamed (2023). A Comprehensive Review on the Biological, Agricultural and Pharmaceutical Properties of Secondary Metabolites Based on Plant Origin. *International Journal of Molecular Sciences*, **24**(4); 3266

Farias, J. P., A. L. N. Barros, A. R. de Araújo-Nobre, E. P. C. Sobrinho-Júnior, M. M. M. Alves, F. A. A. Carvalho, K. A. F. Rodrigues, I. M. de Andrade, F. A. Silva-Filho, and D. C. Moreira (2023). Influence of Plant Age on Chemical Composition, Antimicrobial Activity and Cytotoxicity of *Varronia curassavica* Essential Oil. *Agriculture*, **13**(2); 373

Götz, M., B. Sachse, B. Schäfer, and A. Eisenreich (2022). Myristicin and Elemicin: Potentially Toxic Alkenylbenzenes in Food. *Foods*, **11**(13); 1988

Guzmán, E. and A. Lucia (2021). Essential Oils and Their Individual Components in Cosmetic Products. *Cosmetics*, **8**(4); 114

Hurria, A. Alfian, and R. Mahmudah (2026). Phytochemical Properties, *In Silico* and *In Vitro* Analysis of the Antibacterial Activity of *Cinnamomum sulavesianum* Bark from Sulawesi. *Science and Technology Indonesia*, **11**(1); 121–136

Joshi, R. K. (2019). Chemical Disparity in the Oil from Leaves of *Cinnamomum zeylanicum* Blume. *Flavour and Fragrance Journal*, **34**(6); 443–449

Kapelle, I. B. D., T. T. Irawadi, M. S. Rusli, D. Mangunwidjaja, and Z. A. Mas'ud (2016). Modification of Synthesis Process of Lawang's Bark (*Cinnamomum cullilawan* Blume) as a Cancer Drug Precursor. *Journal of Forest Products Research*, **34**(3); 217–229

Kemprai, P., B. Mahanta, D. Sut, R. Barman, D. Banik, M. Lal, S. Saikia, and S. Haldar (2019). Review on Safrole: Identity Shift of the 'Candy Shop' Aroma to a Carcinogen and Deforester. *Flavour and Fragrance Journal*, **35**(1); 5–23

Kintamani, E., I. Batubara, C. Kusmana, T. Tiryana, E. Mirmanto, and S. F. Asoka (2023). Essential Oil Compounds of Andaliman (*Zanthoxylum acanthopodium* DC.) Fruit Varieties and Their Utilization as Skin Anti-Aging Using Molecular Docking. *Life*, **13**(3); 754

Kuttithodi, A. M., A. Narayanankutty, N. U. Visakh, J. T. Job, B. Pathrose, O. J. Olatunji, A. Alfarhan, and V. Ramesh (2023). Chemical Composition of the *Cinnamomum malabatrum* Leaf Essential Oil and Analysis of Its Antioxidant, Enzyme Inhibitory and Antibacterial Activities. *Antibiotics*, **12**(5); 940

Lee, S., D. Kim, S. Park, and H. Park (2022). Phytochemistry and Applications of *Cinnamomum camphora* Essential Oils. *Molecules*, **27**(9); 2695

Li, Y., D. Kong, Y. Fu, M. R. Sussman, and H. Wu (2020). The Effect of Developmental and Environmental Factors on Secondary Metabolites in Medicinal Plants. *Plant Physiology and Biochemistry*, **148**; 80–89

Liang, D., B. Feng, N. Li, L. Su, Z. Wang, F. Kong, and Y. Bi (2022). Preparation, Characterization, and Biological Activity of *Cinnamomum cassia* Essential Oil Nano-Emulsion.

Ultrasonics Sonochemistry, **86**; 106009

Lima, M. C., C. P. de Sousa, C. Fernandez-Prada, J. Harel, J. D. Dubreuil, and E. L. de Souza (2019). Fruit Phenolic Compounds as Potential Antimicrobials. *Microbial Pathogenesis*, **130**; 259–270

Lv, M., L. Zhang, Y. Wang, Y. Yang, X. Zhou, L. Wang, X. Yu, and S. Li (2024). Floral Volatile Benzenoids/Phenylpropanoids: Biosynthetic Pathway, Regulation and Ecological Value. *Horticulture Research*, **11**; 220

Mahmoud, N., M. A. H. Abdou, S. Salaheldin, W. S. Soliman, and A. M. Abbas (2023). The Impact of Irrigation Intervals and NPK/Yeast on the Vegetative Growth Characteristics and Essential Oil Content of Lemongrass. *Horticulturae*, **9**(3); 365

Min, Z., B. Zheng, and D. Yan (2025). Distinction and Pharmacological Activity of Monoterpenes and Sesquiterpenes in Different Chemotypes of *Cinnamomum camphora* (L.) Presl. *Applied Sciences*, **15**(16); 8922

Mutlu, M., Z. Bingol, E. Uc, E. Köksal, A. Goren, S. Alwasel, and I. Gulcin (2023). Comprehensive Metabolite Profiling of Cinnamon (*Cinnamomum zeylanicum*) Leaf Oil Using LC-HR/MS, GC/MS, and GC-FID: Determination of Antiglaucoma, Antioxidant, Anticholinergic, and Antidiabetic Profiles. *Life*, **13**(1); 136

Mwithiga, G., S. Maina, P. W. Muturi, and J. Gitari (2024). Lemongrass (*Cymbopogon flexuosus*) Growth Rate, Essential Oil Yield and Composition as Influenced by Different Soil Conditioners Under Two Watering Regimes. *Heliyon*, **10**(4); e25540

Ngo, T. C. Q., T. H. Tran, and X. T. Le (2020). Influencing Parameters on *Eucalyptus globulus* Essential Oil Extraction. In *IOP Conference Series: Materials Science and Engineering*, volume 991. page 012126

Ninkuu, V., O. O. Aluko, J. Yan, H. Zeng, G. Liu, J. Zhao, H. Li, S. Chen, and F. D. Dakora (2025). Phenylpropanoids Metabolism: Recent Insight into Stress Tolerance and Plant Development Cues. *Frontiers in Plant Science*, **16**; 1571825

Poudel, D. K., A. Rokaya, P. K. Ojha, S. Timsina, R. Satyal, N. S. Dosoky, P. Satyal, and W. N. Setzer (2021). The Chemical Profiling of Essential Oils from Different Tissues of *Cinnamomum camphora* L. and Their Antimicrobial Activities. *Molecules*, **26**(17); 5132

Prathibhani, M. R., R. Azad, S. Ranaweera, L. Jayasekara, R. A. A. K. Ranawaka, G. Senanayake, S. Abeynayake, and S. Geekiyanage (2024). Variation in Plant Morphology and Leaf Essential Oil Composition of a Representative *Cinnamomum verum* Collection from Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, **52**(1); 3–16

Prathibhani, M. R., R. A. A. K. Ranawaka, A. R. Samantha, and S. Geekiyanage (2021). Protogynous Dichogamy, Leaf Morphology and Leaf Essential Oil Composition of Selected *Cinnamomum* Species in Sri Lanka. *Tropical Agricultural Research and Extension*, **24**(3); 185–197

Putri, A. N., A. K. Soesantyo, and E. D. Iftitah (2025). Effect of Edible Coating Material Composition Based on Chitosan-Gelatin-$CaCl_2$ and Cinnamon (*Cinnamomum verum*) Essential Oil on the Protection of Cocoa Beans (*Theobroma cacao* L.) During Storage. *Science and Technology Indonesia*, **10**(2); 528–537

Rana, V. S., C. B. Devi, M. Verdeguer, and M. A. Blázquez (2009). Variation of Terpenoid Constituents in Natural Population of *Cinnamomum tamala* (L.) Leaves. *Journal of Essential Oil Research*, **21**(6); 531–534

Rasouli, F., T. Amini, S. Skrovankova, M. Asadi, M. B. Hassanpouraghdam, S. Ercisli, M. Buckova, M. Mrazkova, and J. Mlcek (2023). Influence of Drought Stress and Mycorrhizal (*Funneliformis mosseae*) Symbiosis on Growth Parameters, Chlorophyll Fluorescence, Antioxidant Activity, and Essential Oil Composition of Summer Savory (*Satureja hortensis* L.) Plants. *Frontiers in Plant Science*, **14**; 1151467

Rostiana, O., E. Suryani, S. Purwiyanti, R. Heriyanto, and T. Arlianti (2020). Yield and Essential Oil Quality of Indonesian Cinnamon at Different Harvest Ages. In *IOP Conference Series: Earth and Environmental Science*, volume 418. page 012025

Sadono, R., D. Soeprijadi, and P. Y. A. P. Wirabuana (2019). Land Suitability for *Eucalyptus* Plantation Development. *Journal of Natural Resources and Environmental Management*, **10**(1); 43–51

Saleh, Z. M., A. Z. Azeiz, A. B. M. Mehany, and Z. A. S. El-Swaify (2023). Anticancer and Antimicrobial Activity of *Jatropha* Leaves Extracts. *Egyptian Journal of Botany*, **63**(2); 621–634

Selwal, N., F. Rahayu, A. Herwati, E. Latifah, Supriyono, C. Suhara, I. B. K. Suastika, W. M. Mahayu, and A. K. Wani (2023). Enhancing Secondary Metabolite Production in Plants. *Journal of Agriculture and Food Research*, **14**; 100702

Sharifi-Rad, J., A. Dey, N. Koirala, S. Shaheen, N. Omari, B. Salehi, T. Goloshvili, N. C. C. Silva, A. Bouyahya, and S. Vitalini (2021). *Cinnamomum* Species: Bridging Phytochemistry Knowledge, Pharmacological Properties and Toxicological Safety for Health Benefits. *Frontiers in Pharmacology*, **12**; 600139

Sohilait, H. J. and H. Kainama (2016). GC/MS Analysis of Bark Essential Oil from *Cinnamomum culilawan*. *American Journal of Applied Chemistry*, **4**(4); 157–160

Stefanakis, M. K., A. E. Giannakoula, G. Ouzounidou, C. Papaioannou, V. Lianopoulou, and E. Philotheou-Panou (2024). The Effect of Salinity and Drought on the Essential Oil Yield and Quality of Various Plant Species of the Lamiaceae Family (*Mentha spicata* L., *Origanum dictamnus* L., *Origanum onites* L.). *Horticulturae*, **10**(3); 265

Surendran, A., K. B. Rameshkumar, E. S. Santhoshkumar, R. Ananthakrishnan, and R. Murugan (2025). Analysis of Chemical Composition and Biological Efficiency of Leaf Essential Oils Isolated from Seven Species of *Cinnamomum* of the Western Ghats, India. *Biomass Conversion and Biorefinery*, **15**(5); 8041–8072

Virga, G., L. Sabatino, M. Licata, T. Tuttolomondo, C. Leto, and S. La Bella (2020). Irrigation Effects on Growth and

Essential Oil of Oregano. *Plants*, **9**(11); 1618

Weeratunge, H. D., G. A. S. Premakumara, E. D. de Silva, and W. W. P. Rodrigo (2024). Comparative Study on Chemical Characteristics of Essential Oils and Genetic Characteristics of True Cinnamon (*Cinnamomum zeylanicum* Blume) and Three Wild Cinnamon Species of Sri Lanka. *Journal of Essential Oil Research*, **36**(3); 234–246

Xavier, J. K. A., T. G. C. Baia, O. V. Alegria, P. L. B. Figueiredo, A. R. Carneiro, E. C. O. Moreira, J. G. S. Maia, W. N. Setzer, and J. K. R. da Silva (2022). Essential Oil Chemotypes and Genetic Variability of *Cinnamomum verum* Leaf Samples Commercialized and Cultivated in the Amazon. *Molecules*, **27**(21); 7337

Xia, X., C. Chen, L. Yang, Y. Wang, A. Duan, and D. Wang (2022). Analysis of Metabolites in Young and Mature Leaves. *PeerJ*, **10**; e12844

Zhang, T., Y. Zheng, C. Fu, H. Yang, X. Liu, F. Qiu, X. Wang, and Z. Wang (2023). Chemical Variation and Environmental Influence on Essential Oil of *Cinnamomum camphora*. *Molecules*, **28**(3); 973

Zhao, X., Y. Yan, W. Zhou, R. Feng, Y. Shuai, L. Yang, M. Liu, X. He, and Q. Wei (2022). Transcriptome and Metabolome Reveal the Accumulation of Secondary Metabolites in Different Varieties of *Cinnamomum longepaniculatum*. *BMC Plant Biology*, **22**; 363

Živković, M., I. Stanisavljević, N. Gajović, S. Pavlović, B. S. Marković, I. P. Jovanović, S. Cupara, V. Tadić, A. Žugić, M. T. Milenković, and A. Barjaktarević (2025). Comprehensive Phytochemical Analysis and Evaluation of Antioxidant, Antimicrobial, Cytotoxic, and Immunomodulatory Activities of Commercial Cinnamon Bark Essential Oil (*Cinnamomum zeylanicum* L.). *Plants*, **14**(14); 1996

