THE POTENTIAL OF CARDAMOM LEAF IN THE AGROFORESTRY SYSTEM: ESSENTIAL OIL YIELD AND 1.8-CINEOL CONTENT

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THE POTENTIAL OF CARDAMOM LEAF IN THE AGROFORESTRY SYSTEM: ESSENTIAL OIL YIELD AND 1.8-CINEOL CONTENT. Cardamom (*Amomum cardamomum*), the 'Queen of Spices', is a native Indonesian spice and a type of potential biopharmaceutical currently prospective because of its high selling value, especially for its fruit, with various benefits and wide use. So far, cardamom essential oil comes from the use of its fruit, but production is limited. Therefore, its leaves have the potential to be developed as a source of essential oil since they are more abundant and available all year. In cardamom farming, low light intensity due to shading effects in agroforestry and low nutrients could stimulate the production of specific secondary metabolites. This study aimed to analyze the cardamom leaf essential oil (CLEO) yield and 1.8-cineol content of CLEO grown in agroforestry systems. The CLEO was obtained by steam-water distillation, while the 1.8-cineol content was analyzed by gas chromatography–mass spectrometry (GC-MS). The experimental design employed was a randomized block design with three cropping patterns, namely *Falcataria moluccana* + cardamom (FC), *F. moluccana* + cardamom + arrowroot (FCA), and Monoculture cardamom (MC) as treatment levels and three doses of bokashi manure as blocks. The results showed that the highest CLEO yield was generated in the FC agroforestry pattern of 3.16%, and the highest 1.8-cineol content in CLEO was generated in the FCA pattern of 47.23%. The lowest CLEO yield and 1.8-cineol content were found in the monoculture pattern of 2.02% and 43.16%, respectively. Compared to monoculture practices, agroforestry practices have the potential to increase the CLEO yield and 1.8-cineol content, which will be prospective in forest management to support forestry multi-business and social forestry programs.

Keywords: *Falcataria moluccana*, *Amomum cardamomum*, eucalyptol; medicinal plant; secondary metabolites

*POTENSI DAUN KAPULAGA DALAM SISTEM AGROFORESTRI: RENDEMEN MINYAK ATSIRI DAN KANDUNGAN 1,8-SINEOL. Kapulaga (*Amomum cardamomum*), sang 'Ratu rempah', merupakan rempah asli Indonesia, salah satu jenis biofarmasi potensial yang prospektif saat ini karena nilai jualnya yang tinggi, terutama buahnya, dengan beragam manfaat dan kegunaannya yang luas. Selama ini minyak atsiri kapulaga berasal dari pemanfaatan buahnya, namun produksinya terbatas. Oleh sebab itu, daun kapulaga berpotensi dikembangkan sebagai sumber minyak atsiri karena produksinya lebih banyak dari pada buah dan tersedia sepanjang tahun. Pada praktik budidaya kapulaga, rendahnya intensitas cahaya akibat efek naungan pada agroforestri dan rendahnya unsur hara dapat memacu produksi metabolit sekunder spesifik. Penelitian ini bertujuan untuk menganalisis rendemen minyak atsiri daun kapulaga (MADK) dan kandungan 1,8-sineol pada MADK yang ditanam pada sistem agroforestri. MADK diperoleh dengan distilasi uap-air, sedangkan kandungan 1,8-sineol dianalisis dengan kromatografi gas-spektrometri massa (GC-MS). Rancangan percobaan yang digunakan adalah Rancangan Acak Kelompok dengan tiga pola tanam sebagai perlakuan, yaitu *Falcataria moluccana* + kapulaga (FK), *F. moluccana* + kapulaga + garut (FKG), dan Monokultur kapulaga*

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(MK) serta tiga dosis pupuk bokashi sebagai blok. Hasil penelitian menunjukkan bahwa rendemen MADK tertinggi dihasilkan pada pola agroforestri FK sebesar 3,16%, dan kandungan 1,8-sineol tertinggi pada MADK dihasilkan pada pola agroforestri FKG sebesar 47,23%. Rendemen MADK dan kandungan 1,8-sineol terendah ditemukan pada pola monokultur masing-masing sebesar 2,02% dan 43,16%. Dibandingkan dengan praktik monokultur, praktik agroforestri berpotensi meningkatkan rendemen MADK dan kandungan 1,8-sineolnya yang prospektif dalam pengelolaan hutan lestari untuk mendukung program perhutanan sosial dan multi usaha kehutanan.

Kata kunci: Falcataria moluccana, Amomum cardamomum, *ekaliptol, tumbuhan obat, metabolit sekunder*

I. INTRODUCTION

Indonesia, 'a mega-biodiversity country', possesses the second-largest biodiversity, the second-highest number of indigenous medicinal plants, and the third-largest tropical forest area in the world (Yoganingrum, 2020; MOEFRI, 2022). Indonesia's tropical forests have great potential as a home for medicinal plants and food providers. However, Indonesia's tropical forest management encounters several challenges due to the high community need for forest resources, including their basic needs for food. More than 50% of villages are located on the edge and within forest areas (BPS, 2020). Currently, there are 19,410 villages located around forests. A total of 3.02% of villages are categorized as highly vulnerable to climate change, with a population of about 48.8 million people depending on the forest's resources (MOEFRI, 2022). Climate change also significantly influences crop production, leading to exacerbating the food crisis challenge.

The conversion of forests to agricultural land is the main cause of deforestation (FAO, 2021; FAO, 2022). Forest damage and land degradation directly impact the people living in these villages. Agroforestry becomes a land management system that can potentially reduce deforestation and soil degradation while ensuring food security and overcoming food crisis problems (Tomar et al., 2021). Furthermore, it provides environmental services and has good prospects for supporting sustainable food production (Rosso, Cantamessa, Chiarabaglio & Coaloa, 2021; Octavia et al., 2022; Bishaw, Soolanayakanahally, Karki & Hagan, 2022). Smart agroforestry (SAF) is a set of silviculture and agriculture knowledge and practices to improve environmental parameters, including soil and water conservation, biodiversity enhancement, climate change mitigation, and adaptation, as well as increase profits and resilience for farmers (Octavia et al., 2022). Climate SAF systems and practices provide a range of vital goods and services for human welfare, particularly for people living below the poverty line (Ntawuruhunga et al., 2023). Currently, agroforestry is encouraged to be developed in the Social Forestry (SF) program, particularly in tropical countries, as a solution to address several problems that cannot be solved just by forestry science (Gunawan et al., 2022). It can also significantly improve farmers' livelihoods due to better access to food, fodder, and fuelwood for livelihood capital (Jewel et al., 2022). SF schemes have been set as one of the priority activities that support the Poverty Alleviation Priority Program in Indonesia (Suharjito, Rahayu, Kartika, Arsyad & Meilantina, 2023). Agroforestry for rehabilitation activities is also encouraged by Indonesia's Forestry and Other Land Use (FOLU) Net Sink 2030 for mitigating and controlling climate change (MOEFRI, 2022).

Agroforestry systems have the potential to stimulate the production of secondary metabolites or bioactive compounds when the stress of water or soil nutrients occurs, as well as the stress of light intensity due to shading effects and a lack of soil fertility or other important resources needed by plants. Secondary metabolites are beneficial to assess the quality of therapeutic ingredients, which are used nowadays as important natural-derived drugs such as immune suppressants, antioxidants, antibiotics, anticancer drugs, and anti-diabetics. In addition, plants can produce a variety of secondary metabolites to manage the negative effects of stress (Jan, Asaf, Numan, Lubna & Kim, 2021; Pant, Pandey & Dall'Acqua, 2021). This potential serves the short-term benefit of compensating for the long-term benefit of planting trees in agroforestry sites. Leaves, branches, and twigs can be a potential source of secondary metabolites (Verma, Kumar & Saresh, 2021).

Regarding the high dependence of farmers on tropical forest services (Njurumana et al., 2020), optimizing forest land use and increasing its productivity are urgently needed to gain ecological and economic benefits for the community and to avoid pressure on the forest by diversifying species, including multipurpose tree species of legume groups, medicinal plants, and food crops. One of the fast-grown legume tree species with the multipurpose potential is 'sengon' (*Falcataria moluccana*), while the group of spice/medicinal plants and food crops that have the potential to be developed include cardamom (*Amomum cardamomum*) and arrowroot (*Maranta arundinacea*). *F. moluccana* is one of plantation forest commodities in Indonesia and is one of the most popular tree species as shade plants used by farmers. As a legume group, sengon provides nitrogen (N) that maintains soil fertility, can grow on marginal land and is easily cultivated and marketed (Hani & Octavia, 2020).

Cardamom fruit has a high economic value, while the production of the leaf is higher than that of the fruit in a cardamom clump. Therefore, the potential of other parts of the cardamom species, including the leaf, is an important one to study in its cultivation through agroforestry systems. Pruning leaves, an integral aspect of tending and leaf litterfall, yields enhanced value when processed into essential oil within agroforestry practices. Thus, this potential will be able to enhance farmers' livelihoods and augment the community's income, as well as expand the benefits to those residing in the SF area.

The content of 1.8-cineol in cardamom leaf has an interesting potential to be developed as a component of medicinal raw materials in the current COVID-19 pandemic era. The previous study revealed that among the seven *Zingiberaceae* species, *Elettaria cardamomum* leaf generated the highest yield of essential oil, which was 2.43%. This species also generated the best antibacterial activity, which found 1.8-cineol as the main compound responsible for antibacterial activity (Batubara, Wahyuni & Susanta, 2016). The antimicrobial (antifungal, antibacterial, anti-pathogenic) and immune-modulatory effects of cardamom essential oil have also been reported in several studies (Heimesaat et al., 2021).

The 1.8-cineol is classified as a monoterpenoid compound a secondary metabolite, which is extensively used in healthcare products and cuisine (Jan, Asaf, Numan, Lubna & Kim, 2021). The 1.8-cineol compound has fresh characteristics with a pungent aroma and sharp taste and has bioactivity with various benefits. Some studies found that the 1.8-cineol content with antiviral, anti-inflammatory, antioxidant, and antimicrobial activity can increase protection against influenza virus attacks (Bahrami, Yaghmaei & Yousofvand, 2023) as well as have the potential to be an alternative treatment to relieve symptoms of COVID-19 (Tshibangu et al., 2020).

In recent decades, demand for herbal medicines, including essential oil from the medicinal plant, has increased due to their lower side effects compared to conventional medicine. Cardamom is currently prospective because of its high selling value, with a variety of benefits and wide use, as well as being high needs, specifically in the pharmaceutical field (Nair, 2020). The long rotation period of trees becomes the main constraint on the spread of agroforestry. These benefits of secondary metabolites from leaves can be harvested many times during their growing period. Therefore, finding and analyzing the important secondary metabolites in leaves produced by plants in agroforestry systems is important in this research. This study aims to analyze the potential yield and 1.8-cineol content of cardamom leaf essential oil (CLEO) in agroforestry systems.

II. MATERIALS AND METHODS

A. Study Site

The research was conducted in October 2021 - September 2022 at the Cikabayan Forest, Bogor Agricultural University (IPB University), West Java, Indonesia. The study site was at an altitude of 150-200 meters above sea level with coordinate of latitude 6°32'48" S and longitude 106°42'58" E.

B. Tools and Materials

Planting materials used were cardamom seedlings (having at least 4-5 leaves and a height of 70-90 cm), arrowroot tubers (cultivar Creol), three-year-old sengon stands (which previously existing with a planting space of 1.5 m × 1.5 m), and manure (bokashi) fertilizer. Bokashi, 'fermented organic matter' containing microbial groups having the ability to create beneficial bioactive substances and enzymes as well as to execute many kinds of useful functions, including the breakdown of hazardous chemicals and waste. It also stands for Organic Material Rich Biological Sources and can be produced by the community themselves by utilizing the forest resources from the surrounding area (Kote, Lailogo, Purmanto & Hewe, 2021). The mixed planting of cardamom and arrowroot under the sengon stands (in an agroforestry pattern) was carried out on a 3 m × 3 m plot. Likewise, the monoculture plot in the opened area also uses the same size of plot, with a planting space of 1 m × 1 m and consisting of 16 seedlings or tubers in each plot (Figure 1). Cardamom seedlings used were local cardamom of red cultivars from Pamijahan sub-district, Bogor Regency, while the arrowroot tubers used were selected genotype and phenotype of West Java accessions from the germplasm collection in Dawuan experimental garden of National Research and Innovation Agency (BRIN) at Subang, West Java. The tools used were a GPS, lux meter, thermohygrometer, distillation unit, and gas chromatography-mass spectrometry (GC-MS).

C. Methods

1. Leaf sample preparation

Cardamom leaves were harvested from a ten-month-old cardamom plant and formed as a composite from cardamom plant in each treatment for the tested samples. Furthermore, the leaves were distilled by steam-water distillation method to generate essential oil.

2. Yield of cardamom leaf essential oil measurement

Steam-water distillation was applied to the samples of cardamom leaves, and the test method was based on SNI 01-3180-1992. Cardamom leaves were weighed before being put into the distillation kettle and measured for the water content. A total of 3 kg of leaves were distilled for each treatment. Heating was carried out at a temperature of 100 °C. The distillation time was calculated from the first drop for

FC **FCA** **MC**

Note: FC = *Falcataria moluccana* +cardamom, FCA=*F.moluccana* + cardamom + arrowroot, MC=monoculture cardamom

Figure 1. Planting patterns (cardamom and arrowroot) in agroforestry and monoculture plots

4-5 hours until no more oil drops were added. Subsequently, oil was collected in a measuring cup, and 2% of the oil volume was added with Na_2SO_4, then filtered using filter paper until pure CLEO was obtained. The essential oil yield of cardamom leaves was determined based on their dry weight. Oil yield was measured using

$$\text{Oil yield (\%)} = \frac{\text{Volume of oil produced (ml)}}{\text{Dry weight of processed material (g)}} \times 100\% \quad ..(1)$$

the following formula:

3. Analysis of 1.8-cineol content

For further analysis, the 1.8-cineol content of the CLEO were determined using the steam-water distillation method. Each treatment consisted of three replications. The 1.8-cineol content was determined by the GC-MS method concerning the method performed by Batubara, Wahyuni and Susanta (2016) with some adjustments. The CLEO was further analyzed by GC-MS (Shimadzu-QP-2010 Ultra, column: Rtx-5MS, 30m x 250 µm ID x 0.25 µm film thickness) and the temperature was programmed from 60 °C to 270 °C (for 28 minutes) at a rate of 10 °C per minute. The injection port temperature was 270 °C, meanwhile, the detector temperature was 250 °C. The inlet pressure was 8.23 psi, and the injection mode was split (200:1). Helium was employed as the carrier gas, with a flow rate of 0.83 mL per minute. The mass spectrometer conditions were set as follows: MS source temperature at 25 °C, MS quadrupole temperature at 150 °C, interface temperature at 270 °C, and ionization voltage at 70 eV. Cineol and other compounds were identified by comparing the mass spectra of cineol and other compounds with spectra from NIST library data in the literature.

4. Experimental design

The experimental design employed was the randomized block design, with three planting patterns by species combination as the treatment in agroforestry models as follows: A1: *F. moluccana* + cardamom (FC), A2: *F. moluccana* + cardamom + arrowroot (FCA), A3: Monoculture cardamom (MC), and doses of manure fertilizer as replication (block), which consisted of 3 levels (B1 = 0, B2 = 250, and B3 = 500 g for each plant), on a plot area of 1500 m^2.

D. Data analysis

The CLEO yield and 1.8-cineol content data were analyzed with analysis of variance (ANOVA) at a confidence level of 95% using SAS 9.4 software. Duncan's Multiple Range Test (DMRT) was used for further analysis when the variance (F-test) showed a significant effect. Origin 85 software was employed ..(2) for analyzing and graphing chromatograph data of 1.8-cineol content. The 1.8-cineol content in leaves per plant was obtained as follows: ..(3)

1.8-cineol content in leaves per plant = 1.8-cineol in each g leaves × the leaf dried weight per plant

1.8-cineol in per g leaves = CLEO yield × 1.8-cineol content in the essential oil

III. RESULTS AND DISCUSSION

A. Results

1. Environmental condition of the planting site

In this research, cardamom grew up well at an altitude of 150-200 meters above sea level, where the average air temperature was 28.7 °C and air humidity was 79.5%. The shade intensity of 3-4- year- old *F. moluccana* amounts to an average of 65%, ranging from 45 – 73%, as shown in Figure 2. The soil texture was clay, with a clay content range of 54-60%, a cation exchange capacity (CEC) value in medium category of 16.1– 18.4 cmol(+)/kg, a N total before planting of 0.27 (medium category), and a N total after 10 months of planting of 0.34. The C-organic content was high (3.1%), equivalent to soil organic matter (SOM) of 5.2%.

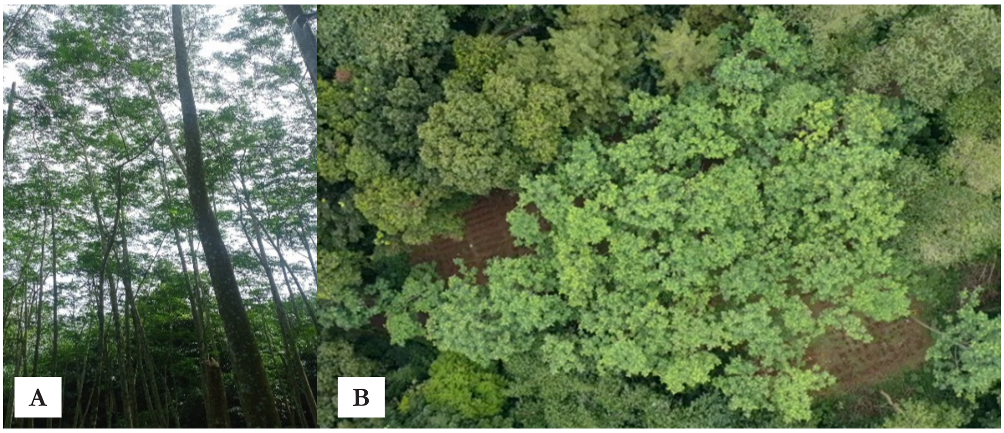


Figure 2. Canopy shade of sengon, viewed from under (A) and above (B) canopy

Table 1. The CLEO yield, 1.8-cineol content, and cineol quantity of CLEO in different planting patterns and doses of manure fertilizer

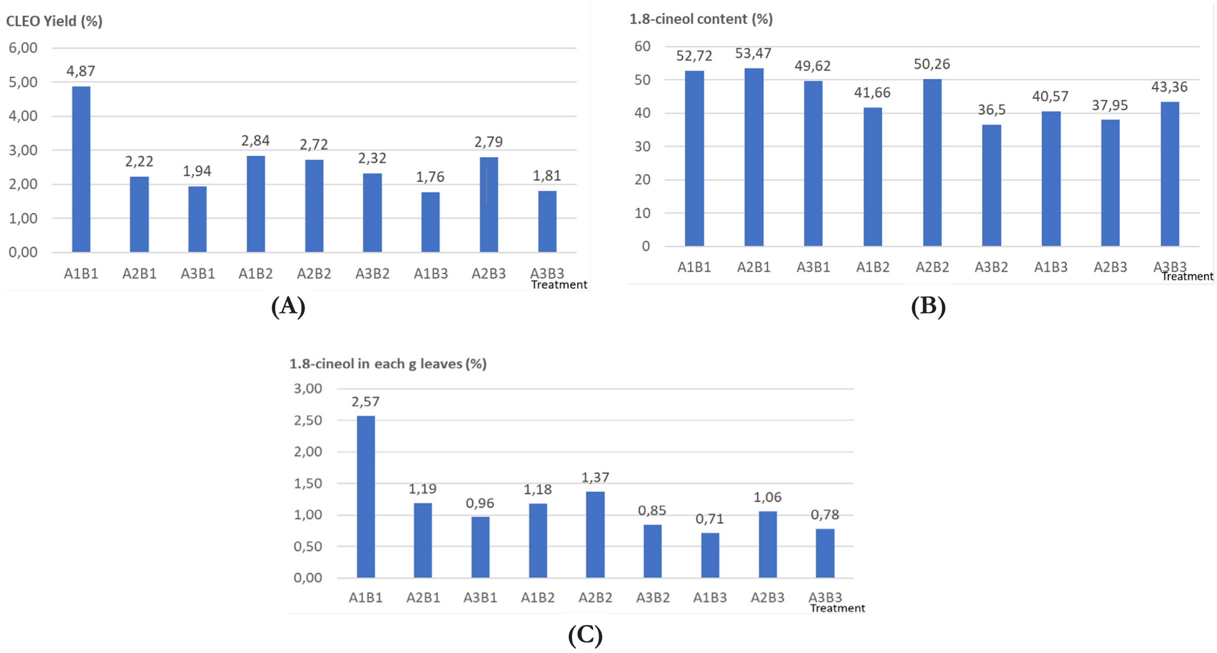
Treatments	Yield of CLEO (%, g essential oil in g dried leaves)	1.8-Cineol content (%, cineol in CLEO)	1.8-Cineol in each g leaves (%)	Fresh leaves weight per plant (g)	1.8-Cineol in leaves per plant (g)
Planting pattern					
A1 (FC)	**3.16**	44.98	**1.49**	**1249.60**	**17.78**
A2 (FCA)	2.58	**47.23**	1.21	1135.69	13.64
A3 (MC)	2.02	43.16	0.86	1211.87	10.60
Dose of manure					
B1 (0 g/plant)	**3.01**	**51.94a**	**1.57**	1212.34	**18.41**
B2 (250 g/plant)	2.63	42.81ab	1.13	1146.16	13.08
B3 (500 g/plant)	2.12	40.63b	0.85	**1238.66**	10.52

Note: Mean values followed by different letters within a column indicate that the treatment has a significantly different effect ($P < 0.05$). The mean value in bold is the highest value among the treatments. FC = *F. moluccana* + cardamom; FCA = *F. moluccana* + cardamom + arrowroot; MC = monoculture cardamom; CLEO = cardamom leaf essential oil.

2. Yield and 1.8 cineol content of cardamom leaf essential oil in an agroforestry system

Table 1 shows how the type of agroforestry planting and the amount of manure fertilizer changed the yield of CLEO, the amount of 1.8-cineol present, and the content of 1.8-cineol. Table 1 shows that agroforestry planting models generated a higher yield, 1.8-cineol content, and cineol quantity of CLEO (FC and FCA). Meanwhile, the lowest value of the three variables was gained from the monoculture planting pattern (MC). The highest yield, cineol content, and cineol quantity of CLEO were generated by the block of 0 g of manure fertilizer application (without applied manure fertilizer). The lowest value of the three variables was obtained in the block of 500 g of manure fertilizer application.

The fresh weight of leaves per plant shown in Table 2 is the real plant production, not the sample weight for the analysis of 1.8-cineol content. Likewise, the 1.8-cineol content did not have a positive correlation with leaf fresh weight. The 1.8-cineol content is correlated to the abundance of cineol compounds among the other bioactive compounds in CLEO. In Table 2, it can be seen that the highest fresh weight of leaves is found in the dose of 500 g of treatment (1238.66), but in contrast, they have the lowest 1.8-cineol content in each g leaf weight of 0.85%and also the lowest 1.8-cineol



Note: A1 = *F. moluccana*+cardamom; A2 = *F. moluccana*+cardamom+arrowroot; A3 = monoculture cardamom;
B1 = 0 g manure; B2= 250 g ; B3= 500 g

Figure 3. Yield of CLEO (A), 1.8-cineol content in CLEO (B), and 1.8-cineol in each g leaf (C) for each treatment

Table 2. Production of essential oil and 1.8-cineol from the pruned leaves in each treatment

Treatments	Yield (%, g essential oil in g dried leaves)	1.8-cineol in each g leaves (%)	Amounts of 1.8-cineol in leaves per ha (kg)	Amounts of CLEO per clump (ml)	Amounts of CLEO per ha (liter)	Income estimation per ha (IDR)
FC	3.16	1.49	37.25	7.89	78.9	316.000.000
FCA	2.58	1.21	30.25	6.45	64.5	258.000.000
MC	2.02	0.86	21.50	5.05	50.5	202.000.000

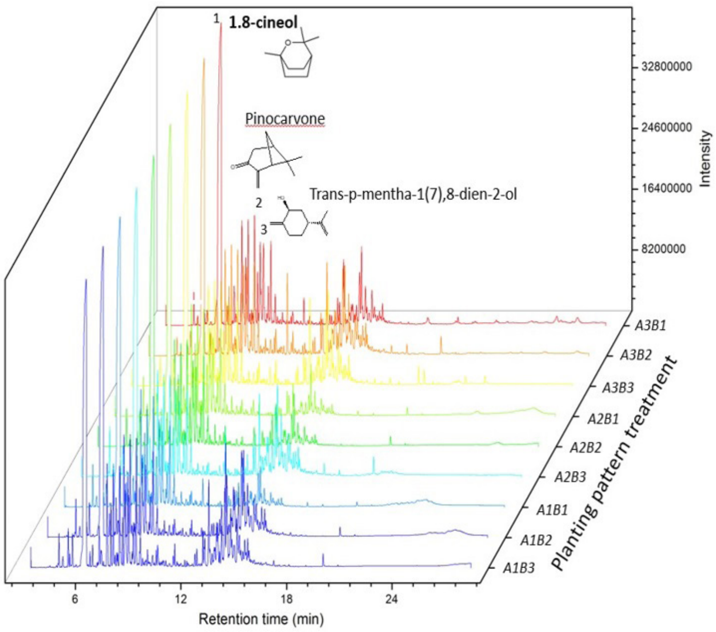
Note: 1 USD equal to IDR 14,500

content in CLEO of 40.63%. The effect of planting patterns at various doses of manure fertilizer on the CLEO yield and 1.8-cineol content is shown in Figure 3.

Figure 3 demonstrated that the FC agroforestry planting model with no manure fertilizer (A1B1) and FCA with no manure fertilizer (A2B1) produced the highest CLEO yield and 1.8-cineol content, respectively. Whereas, the lowest CLEO yield was attained in the FC planting pattern with 500 g of manure fertilizer (A1B3), which was 1.76%, even though it was not significantly different from that in monoculture (A3B3), which was 1.81%. Likewise, the lowest 1.8-cineol content in CLEO was obtained in the monoculture plot with 250 g of manure fertilizer (A3B2), which was 36.5%. The 1.8-cineol quantity referred to the 1.8-cineol content in each g of cardamom leaf weight in each treatment. The highest 1.8-cineol in each g of leaves was generated by the A1B1 treatment, amounting to 2.57%; meanwhile, the lowest value was generated in A1B3, amounting to 0.71 %; even though it was insignificantly different from that in monoculture (A3B3) amounting to 0.78%. Table 2 presents the production of essential oil and 1.8-cineol quantity from the pruned leaves of cardamom per hectare in planting spacing of 1 m × 1 m, with a number of 10,000 cardamom clumps per hectare when 1000 g of leaves were pruned per clump (the average leaf moisture content was 75%), resulting in dry leaf weight amounting to 250 g as distilled material.

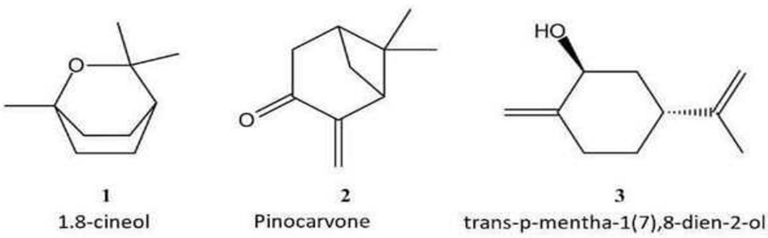
The chromatogram of CLEO in each treatment showed that 1.8-cineol was the one major compound found in CLEO at a retention time range of 6.133-6.147 minutes (Figure. 4). The other compounds in the second and third ranks of the area percentage and their chemical structure are shown in Figure 5.

Based on the GC-MS results, two other main bioactive compounds were found in addition to 1.8-cineol. Origin 85 software was used to draw their structures. In addition to the three compounds above, several other compounds were also found, among others lemnalol, santalol, alpha-pinene, linalool, carvone, gamma-terpinene, cyclohexen, trans-pinocarveol, (1R)-(-)-myrtenal, beta-santalol, (-)-trans-isopiperitenol, cis-p-mentha-1(7),8-diene-2-ol and (1R,2R,4S,6S,7S,8S)-8-Isopropyl-1-methyl-3-methylene for various benefits.



Note: A1 = *F. moluccana*+cardamom; A2 = *F. moluccana*+cardamom+arrowroot; A3 = monoculture cardamom; B1 = 0 g manure; B2= 250 g ; B3= 500 g

Figure 4. Chromatogram of *Amomum cardamomum* leaves essential oil in each treatment



Source: Primary data

Figure 5. Structure of three major compounds found in cardamom leaf essential oils

B. Discussion

1. Environmental condition of the planting site

The environmental conditions in cardamom planting plots are under the plant growth requirements. Cardamom is a plant species that requires shade throughout its life in fertile and loose soilat an altitude of 0-500 m above sea level with rainfall of 2500-4500 mm/year (Hani & Octavia, 2020). The total N content of the soil increased by 29% at 10 months after planting (MAP) in agroforestry plots (FC and FCA models). This is assumed because the litter of fallen leaves rapidly decomposes to become a nutrient source for plants.

Interplanting annual and perennial legumes can increase soil fertility by enhancing plant-available N and potassium (K) and plant yield, as well as farming profitability, so that the planting pattern can sustain the above-ground biomass cover (Tibasiima et al., 2023). The phosphorus (P) released from leaf litter was affected by the vegetation type, which was related to the favored soil microbial populations at tree roots during decomposition (Correa, Carvalhais, Utida, Oliveira & Scotti, 2016). Gunawan, Wijayanto and Budi (2019) reported that eucalyptus-based vegetable agroforestry planting patterns in some age classes improved the soil chemical fertility status for CEC, available P, and available K into high categories. Another study showed that complex agroforestry and natural forest land had similar physical soil quality (Briliawan, Wijayanto & Wasis, 2022; Purnama, Wijayanto & Wasis, 2022). Furthermore, multi-strata agroforestry can be a solution for improving soil quality on degraded lands. Multistrata agroforestry is an agroforestry planting system with a combination of plant species with a variety of canopy heights (high, medium, and low canopy), such as F. moluccana (high canopy) with cardamom (medium canopy) and grass (low canopy). Iskandar et al. (2022) also stated that revegetation served as a driver of physical and chemical soil property changes.

The SOM in the demonstration plot area was still high, reaching 5% under ten MAP. Despite there was a small decrease, the occurrence was lower in agroforestry plots compared to monoculture. This was caused by the positive influence of leaf litter, twigs, and root activity of *F. moluccana* trees which provided soil nutrients. The plants' combination found in agroforestry practices increases the chances of maintaining soil fertility resulting from litter decomposition to maintain soil organic C content, enhancing food security, land productivity, and biodiversity (Mulia & Phuong, 2021).

Another study revealed that soil organic C in *Acacia* stand plantations was subjected to changes that tended to decrease by increasing the age of the stand due to an increase in the ability of trees to absorb carbon. Furthermore, the youngest stand shows the highest soil organic C (Lee, Ong, King, Chubo & Su, 2015). The SOM is a crucial soil component that can accumulate as a component of a closed nutrient cycle with minimal nutrient losses, particularly in natural forests (Widyati et al., 2022). The agroforestry model produces more litter layers due to the presence of litterfall (twigs and leaves) on the soil surface, which can increase soil infiltration, minimize runoff, and maintain the availability of organic matter needed by plants. Besides that, this condition reduces the need for fertilizer and pesticide use in agroforestry systems, amounting to half of the fertilizer and pesticide requirements for monoculture farming (Nuddin, Arsyad, Putera, Nuringsi & Teshome, 2019). Reducing the use of fertilizers and pesticides is profitable for farmers, specifically those with limited start-up capital.

In agroforestry plots, earthworms are more commonly found, and this is an indicator of soil fertility. Hani and Suhaendah (2019) revealed that the number of soil macrofauna that become organic decomposers in agroforestry is higher than that in non-productive land. Therefore, land management with an agroforestry pattern has a positive impact on community livelihood and forest sustainability. According to Kainama, Matinahoru and Latumahina (2021), agroforestry provides opportunities for communities to increase their participation in forest management and obtain benefits from forests to increase social, economic, and ecological sustainability through social forestry programs. These above-mentioned conditions may provide promising benefits and are prospective for being applied in the social forestry area.

2. The potential yield and 1.8 cineol content of cardamom leaf essential oil (CLEO) in an agroforestry system

In this research, 1.8-cineol (in the commercial trade called 'eucalyptol') is the one major compound found in CLEO at a retention time range of 6.133-6.147 minutes, which was about 37-53% of the abundance of 1.8-cineol content. In line with another study on another species of cardamom, 1.8-cineol is also the major compound found in *Elettaria cardamomum* essential oil at a retention time of 8.781 minutes, about 83% in abundance. This compound serves as an antibacterial against *Streptococcus mutans* and for biofilm degradation (Batubara, Wahyuni & Susanta, 2016).

Another interesting finding from this study is that CLEO yield, 1.8-cineol content in CLEO and 1.8-cineol in each g of leaves, were higher in cardamom leaves at agroforestry plots (FC and FCA) than in monoculture planting patterns (MC). The highest value is also found in plant treatments without bokashi manure biofertilizer. This shows that the lack of light intensity under the sengon stands and fewer nutrients stimulate the production of CLEO and 1.8-cineol content. Light quality can impact the synthesis of secondary metabolites and bioactive compounds in plants (Jan, Asaf, Numan, Lubna & Kim, 2021; Pant, Pandey & Dall'Acqua, 2021). This was also confirmed in another study performed by Juliarti, Wijayanto, Mansur & Trikoesoemaningtyas (2022) on the other species that yield (2.84%) and 1.8-cineol content (50.70%) in cajuput leaf essential oil produced under agroforestry model is higher than that under the monoculture plot. The dosage of fertilizer had no significant effect on cajuput leaf essential oil yield and 1.8-cineol content. However, in this research, the dosage of fertilizer significantly affected the 1.8-cineol content of CLEO. Ramezani, Rezaei and Sotoudehnia (2019) also stated that nutrient effect on the chemical composition of EO varied among plant species, environmental conditions, and EO components.

The availability of nutrients had a significant effect on the 1.8 cineol content but not on the weight of fresh cardamom leaves. The highest weight of fresh leaves was found at agroforestry FC and application of bokashi 500 g. It was similarly discovered in another study that revealed the interaction of cropping pattern treatment and biofertilizer application did not significantly affect malapari growth, but the combination of the application of mycorrhiza biofertilizer and organic manure produced the highest growth after planting (Hani, Dendang & Pieter, 2021).

Another study on *Mahonia* ('well-known traditional Chinese' medicine) used for the treatment of several diseases also showed a higher yield of alkaloids under 50% of sunlight followed by 30% of sunlight rather than under 10% of sunlight and 100% of sunlight (Li, Kong, Liang & Wu, 2018). The opposite situation was also reported in traditional medicine *Flourensia cernua*, that used to treat various diseases, and indicated a higher content of total phenolic compounds under partial shade rather than under fully irradiated situations (Pant, Pandey & Dall'Acqua, 2021).

Subsequently, another study revealed that DNA methylation is probably responsible for changes in the content of the major secondary metabolites in a novel kind of tea cultivar 'Yujinxiang' in China recently, which is assumed to be related to the increased leaf chlorophyll level under the shading effects (Xu et al., 2020). The N, P, and K fertilizer applications affected essential oil biosynthesis in medicinal plants. They influence the levels of enzymes, which are very important for the biosynthesis of terpenoids (Verma & Shukla, 2015). Their effect on the chemical composition of EO varies among plant species, environmental conditions, and EO components (Ramezani, Rezaei & Sotoudehnia, 2019). For example, in *Ocimum basilicum* foliar, spraying of N increased the concentration of epicadinol and linalool but decreased 1.8-cineol, eugenol, and geraniol (Nurzyn´ska-Wierdak, Bogucka-Kocka, Sowa & Szymczak, 2012). Furthermore, eugenol, linalool, 1.8-cineol, and germacrene-D concentrations were not influenced by phosphorus application in sweet basil, while in *Chamomilla recutita*, α-bisabolol content increased with elevated phosphorus application (Rioba, Itulya, Saidi, Dudai & Bernstein, 2015). The other study showed that fertilization of 200 kg P ha^{-1} on *Vitex negundo* generated the highest essential oil yield and biomass, the highest number of volatile components, and the highest content of bioactive ingredients. Therefore, NPK fertilization treatment resulted in positive effects on the essential oil yield, biomass, and bioactive compounds of cultivated *V. negundo* (Peng & Ng, 2022). The primary and secondary metabolite content in plants is the main factor that determines their nutrition and health as well as promotes the value of the plant (Saleh, Selim, Jaouni & Abdelgawad, 2018).

Several factors can affect the composition of essential oil (EO) content, among them growth conditions, soil type, altitude, climate, cultivation and agricultural methods, including fertilization, plant part extraction, developmental stage, and harvesting time. Several factors determine the yield and chemical variability of EO for each plant species, including physiological and geographic variations, environmental conditions, genetic factors, and the amount of plant material (Figueiredo, Barroso, Pedro & Scheffer, 2008). The synthesis of secondary metabolites can be affected by fertilization activity (Ahmed, Shalaby & Shanan, 2011) and environmental changes, including several changes in daily temperatures, rainfall, drought, and the length and intensity of the sunlight (Marsic et al., 2011). The other study showed that effective environmental factors such as altitude and temperature were related to 1.8-cineol, menthone, and limonene content (Mollaei et al., 2020).

The light intensity and photoperiod also significantly affect the accumulation of plant secondary metabolites (Moghaddam & Mehdizadeh, 2017). Nitrogen and phosphorus are the main nutrients in fertilizers, serving as main factors in controlling the production of primary and secondary metabolites (Omer et al. 2014). Stress under certain environmental conditions, including drought, heat, and high or low light intensity in vegetation, encourages the production of high amounts of reactive oxygen species (ROS) through certain mechanisms, thus generate higher specific secondary compounds. ROS plays a key role in the plants' acclimation process to abiotic stress, which enables them to regulate and adjust their metabolism and fits a proper acclimation response in specific conditions (Verma, Kumar & Saresh, 2021; Pant, Pandey & Dall'Acqua, 2021).

Light-intensity stress under the shade effect can stimulate the production of secondary metabolites, which positively impacts the content of secondary metabolites in plants under the stands. Plants can adapt to changes in light radiation by accumulating and releasing different secondary metabolites, such as terpenoids and phenolic compounds, which have high economic value and use related to their antioxidant properties (Jan, Asaf, Numan, Lubna & Kim, 2021). Environmental conditions with limited light intensity under the shade of *F. moluccana* stands, and limited nutrients in the cultivation process without manure fertilizer application can stimulate and increase the secondary metabolite content and 1.8-cineol content of CLEO in this research.

Table 2 showed that the FC treatment in agroforestry systems generated the highest yield of the two other types of planting patterns, amounting to 78.9 liters of CLEO per hectare. Based on the selling price of around IDR 400 thousand or $27.6 per 100 ml of CLEO (price range according to the marketplace or online platform), the potential income earned from CLEO yield reaches IDR 316 million per hectare. This amount will significantly increase the farmers' livelihood. Meanwhile, the monoculture yielded amounting to 50.6 liters per ha, generating the lowest income of IDR 202 million per ha. This reveals that agroforestry practices can increase the yield and 1.8-cineol content of CLEO, providing a higher income. The production cost of CLEO in this study is low enough, around $0.88 per 10 mL, hence, the profits to the community are higher based on the selling price. It is lower than the production cost of *Cratoxylum formosum* leaf essential oil which reaches $ 4.84 in other studies (Hidayat, Fauzi, Saragih & Harianja, 2023). The use of pruned leaves from cardamom tending activities in agroforestry systems provides added value to increase farmers' income in addition to cardamom fruit with high selling value.

The existence of crop diversification in agroforestry systems, especially those developed in SF areas, increases the community's income from monthly, quarterly, and semi-annual yields. The higher the yield and 1.8-cineol content in CLEO under the agroforestry system, the greater the benefits will be obtained from the utilization of cardamom leaves, both from pruning leaves in tending activities and the litter fallen. This condition provides added value for its development in supporting SF implementation and forestry multi-business.

IV. CONCLUSION

The main results of this research could be summarized as follows: the highest yield of CLEO produced from the *F. moluccana* + cardamon (FC) agroforestry planting pattern was 3.16%, which was 27-56% higher than that from the monoculture cardamom (MC) planting pattern (2.02%). Likewise, the highest 1.8-cineol content was produced from the *F. moluccana* + cardamon + arrowroot (FCA) agroforestry pattern amounting to 47.2%, which was 4-9% higher than that in the MC planting pattern (43.2%). Interaction between FC agroforestry planting patterns (A1) without manure applications (B1) provided the highest yield of CLEO amounting to 4.82%. Likewise, interaction between FCA agroforestry planting patterns (A2) without manure applications (B1) provided the highest 1.8-cineol content of CLEO amounting to 53.47%. Agroforestry practices had the potential to increase the yield and 1.8-cineol content of CLEO which provided added value in its development with the potency to increase farmer's income. Furthermore, this agroforestry model also contributed to the success of social forestry program, by increasing the potential of community multi-business development. Based on these findings, it is important to perform further research to analyze the influence of agroforestry planting pattern on the content of bioactive compounds, including the oil yield and 1.8-cineol, in other parts of cardamom, such as the stem or fruit bunch. They were usually wasted in pruning and harvesting activities and not counted as crop yield, but had the opportunity to be further used.

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