COMSERVA
JURNAL PENELITIAN DAN PENGABDIAN MASYARAKAT
Volume 5 No. 7 Juli 2025
e-ISSN: 2798-5210
p-ISSN: 2798-5652

A Preliminary Study of Green Cardamom Extraction Using Microwave Hydrodiffusion and Gravity: Effects of Extraction Time and Feed-to-Distiller

A. Abdurahman, M. Mahfud*
Institut Teknologi Sepuluh Nopember, Indonesia
Email: abdurahman.muladawilah@gmail.com, mahfud@chem-eng.its.ac.id*

DOI:

ABSTRACT
Microwave Hydrodiffusion and Gravity (MHG) is a solvent-free extraction technique that offers faster processing and lower energy consumption compared to conventional methods. Although MHG has been successfully applied to various botanicals, its use in extracting essential oil from green cardamom (*Elettaria cardamomum*) seeds remains limited. This study evaluates the effects of extraction time and the feed-to-distiller volume ratio (F/D) on the yield of essential oil using MHG with the addition of steam flow. Experiments were conducted using extraction times ranging from 40 to 240 minutes and F/D ratios of 0.15, 0.175, and 0.20 g/mL. Results indicate that both extended extraction durations and higher F/D ratios significantly improve oil yield, with the maximum yield reaching 2.08% under optimal conditions. The addition of steam was found to enhance heat distribution and vapor permeability within the distiller, preventing material scorching and ensuring uniform extraction. Compared to traditional techniques such as Soxhlet and hydrodistillation, the MHG method with steam flow demonstrated improved process efficiency and environmental compatibility. The presence of key bioactive compounds such as 1,8-cineole, α-terpineol, and limonene—confirmed by GC-MS analysis—further supports the suitability of this method for producing high-quality essential oils. These findings highlight the potential of MHG with steam flow as a sustainable and scalable approach for essential oil extraction from cardamom seeds, aligning with *green processing* principles for industrial applications.

Keywords: Green cardamom, Elettaria cardamomum, Extraction, Microwave Hydrodiffusion and Gravity.

INTRODUCTION

Indonesia's significant role in the global essential oil market is exemplified by its prominent production of spices and essential oils (Lutony, 2002). Essential oils are aromatic compounds derived from various plant parts, contributing to their diverse applications in sectors such as pharmaceuticals, cosmetics, food, and aromatherapy (Zandi et al., 2015; Al-Hilphy et al., 2022). These essential oils are revered not only for their fragrance but also for their therapeutic properties (Abdullah et al., 2021; Dhifi et al., 2016). Among the vast array of aromatic plants, green cardamom (Elettaria cardamomum) is distinguished as a vital spice often referred to as the "queen of spices" due to its aromatic qualities and health benefits (Ashokkumar et al., 2021; Hasanah et al., 2023). The essential oil obtained from green cardamom is notably rich in bioactive compounds, including 1,8-cineole and α-terpineol, which possess various biological activities such as antimicrobial and antioxidant properties (Ashokkumar et al., 2021; Teresa-Martínez et al., 2022; Molaveisi et al., 2020).

Traditionally, essential oils have been extracted using methods such as steam distillation and hydrodistillation (Tambunan, 2017; Variyana et al., 2024; Mahfud et al., 2017; Yuniati et al., 2024). While these techniques are common, they come with drawbacks like extended processing times and high energy consumption, in addition to requiring organic solvents that may pose environmental concerns (Hasanah et al., 2023; Noumi et al., 2018; Gao, 2021; Chemat et al., 2012). For example, steam distillation typically yields approximately 0.76% of essential oil from cardamom seeds (Noumi et al., 2018), whereas Soxhlet extraction can achieve higher yields, albeit with the use of solvents that may compromise ecological integrity (Latifasari et al., 2023). Emerging extraction technologies such as microwave-assisted extraction (MAE) and microwave hydrodiffusion and gravity (MHG) offer promising alternatives aimed at overcoming the limitations of traditional methods (Abdullah et al., 2021; Latifasari et al., 2023; Luque de Castro & Priego-Capote, 1998). MHG, in particular, is noted for its environmentally friendly, solvent-free operation and high extraction efficiency. This innovative method utilizes microwave energy to enhance the release of essential oils by rapidly heating plant tissues, facilitating the breakdown of cell walls, thus enabling a more efficient extraction process (Ivanović et al., 2021; Tanvir et al., 2017; Mahfud et al., 2025; Putri et al., 2003). However, challenges such as localized overheating of plant material can arise with MHG extraction. Incorporating steam flow during extraction can regulate temperature and maintain moisture levels, improving heat distribution and the overall quality of the extracted oil (Abdullah et al., 2021; Guerrero et al., 2019). Research involving MHG and steam flow has demonstrated effectiveness with various botanicals, indicating shortened extraction times and reduced energy consumption compared to conventional techniques (Variyana et al., 2024; Soh & Eckelman, 2016; Pujiarti & Kusumadewi, 2020).

Therefore, while essential oils—particularly those derived from green cardamom—demonstrate significant potential and applications across various sectors, advancements in extraction techniques represent a crucial evolution in the field. These innovations enhance both the sustainability and efficiency of oil production while preserving its quality. Although the MHG method has been applied to a variety of botanicals, research on its specific use for green cardamom seeds, especially with steam flow integration, remains limited. Understanding the influence of key parameters such as extraction time and the feed-to-distiller (F/D) ratio is essential for optimizing oil yield and overall process efficiency. Extraction time determines the extent of oil release, whereas the F/D ratio governs the interaction between microwave energy and the density of the raw material—both factors being critical to the extraction outcome. Hence, this preliminary study aims to investigate the effects of extraction time and feed-to-distiller volume ratio on the yield of essential oil from Elettaria cardamomum seeds using the MHG method with steam flow. The findings are expected to provide insights into the scalability and industrial applicability of this green extraction technology for cardamom essential oil production.

Indonesia's significant role in the global essential oil market is supported by various studies emphasizing the importance of efficient extraction techniques. Lucchesi et al. (2007) investigated solvent-free microwave extraction (SFME) of Elettaria cardamomum and demonstrated that SFME produces essential oils of comparable quality to traditional hydrodistillation while offering a shorter processing time and higher energy efficiency. However, their research did not address the potential challenges of localized overheating during microwave-based extraction processes, nor did it explore the integration of steam flow to enhance moisture balance and oil quality. Similarly, Abed (2020) examined the effect of microwave power on the yield of lavender essential oil and found that moderate microwave energy (around 150 W) optimized both yield and energy consumption. While this study provided valuable insights into microwave parameters, it did not focus on cardamom seeds and overlooked critical factors such as the interaction between extraction time and the feed-to-distiller (F/D) ratio.

These limitations highlight a research gap regarding the systematic study of MHG (microwave hydrodiffusion and gravity) with steam flow for green cardamom seeds. While prior research has confirmed the advantages of microwave-assisted techniques, there is still limited understanding of how extraction time and F/D ratio affect both the efficiency and quality of cardamom essential oil. Your study seeks to fill this gap by optimizing these key parameters under the MHG method with steam flow, aiming to improve yield while maintaining the bioactive properties of the oil.

The objective of this research is to examine the effects of extraction time and feed-to-distiller volume ratio on the yield of Elettaria cardamomum essential oil using the MHG method with steam flow. The findings are expected to advance green extraction technologies by offering an environmentally friendly, energy-efficient alternative for essential oil production. Practically, this research benefits industries by providing insights into scalable and sustainable extraction methods, ultimately enhancing the commercial value of cardamom essential oil while reducing its environmental footprint.

METHOD

Green cardamom (*Elettaria cardamomum*) seeds were obtained from a local market in Surabaya, Indonesia. Distilled water was used for steam generation, while tap water served as the coolant in the condenser system.

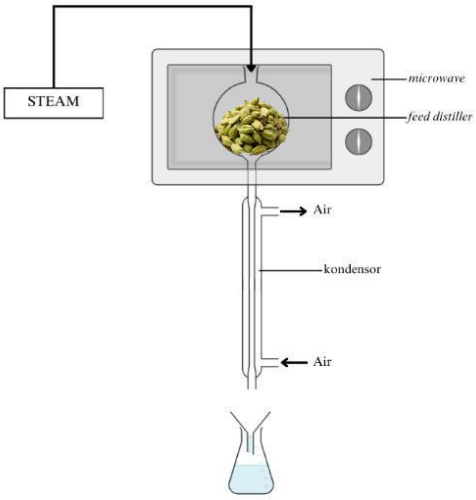

Figure 1. Schematic Diagram of the Extraction Equipment Using the MHG Method with Steam Flow Addition

The extraction was performed using a custom-built MHG system equipped with a Electrolux microwave oven operating at adjustable powers of 300 W, 450 W, and 600 W, presented in fig. 1, that used preview research (Mahfud et al., 2025). The setup included a modified 1000 mL distillation flask with perforations to facilitate steam distribution, a Liebig condenser, a 500 mL steam generator flask, silicone tubing for steam transport, a heating mantle for steam generation, and a separatory funnel for oil-water phase separation. The condenser was continuously cooled with running tap water to condense the volatile fractions efficiently.

Experimental Procedure

Cardamom seeds were weighed according to the desired feed-to-distiller (F/D) ratio, which varied across three levels: 0.15, 0.175, and 0.2 g/mL—corresponding to feed masses of 150 g, 175 g, and 200 g, respectively. The raw materials were placed inside the modified distillation flask. During the extraction, steam generated from distilled water in the steam generator was continuously introduced into the distillation flask to maintain sample hydration and prevent localized overheating. Each extraction run was conducted for a total of 240 minutes. Samples were collected at 40-minute intervals, starting from the first observable drop of distillate. After each collection, the essential oil was separated from the aqueous phase using a separatory funnel. The mass of the isolated essential oil was recorded to calculate the yield. The essential oil yield (%) was calculated using the following formula:

$$Yield\ (\%) = \left(\frac{mass\ of\ essential\ oil\ obtained}{dry\ weight\ of\ cardamom\ seeds}\right) \times 100$$

The dry weight of the raw material was determined prior to extraction by standard moisture analysis methods. And the physical properties of the extracted essential oil were evaluated by measuring its density using a pycnometer at room temperature and assessing its solubility in 70% ethanol. Chemical composition analysis was conducted using Gas Chromatography-Mass Spectrometry (GC-MS), which enabled the identification of major bioactive compounds present in the essential oil. Chemical composition analysis was performed using Gas Chromatography-Mass Spectrometry (GC-MS), which enabled identification of major bioactive compounds present in the essential oil.

RESULTS AND DISCUSSION

Effect of Extraction time on Oil Yield

Microwave energy accelerates the release of essential oil by rapidly heating the plant matrix, causing intracellular water to vaporize, rupture cell walls, and release volatile compounds. Figure 2 illustrates the influence of extraction duration (40–240 minutes) on oil yield at three F/D ratios (0.15, 0.175, and 0.2 g/mL). A consistent trend was observed where longer extraction times resulted in increased oil yield, regardless of the F/D ratio. At an F/D ratio of 0.15 g/mL and microwave power of 300 W, the oil yield increased from 0.14% at 40 minutes to 0.69% at 240 minutes. At 450 W and 600 W, the yields reached 0.85% and 1.00%, respectively. This trend was similarly observed for F/D ratios of 0.175 and 0.2 g/mL, with the highest yield (2.07%) obtained at 600 W and F/D ratio of 0.2 g/mL after 240 minutes. These findings align with the principle that prolonged microwave exposure enhances oil diffusion efficiency, up to an optimal point. Figure 2 using 300 W microwave power resulted in progressively higher yields throughout the 240-minute observation period. At the end of the observation, the 300 W power for the F/D ratio of 0.15 resulted in a yield of 0.69%, which was lower compared to 450 W (0.85%) and 600 W (1.00%).

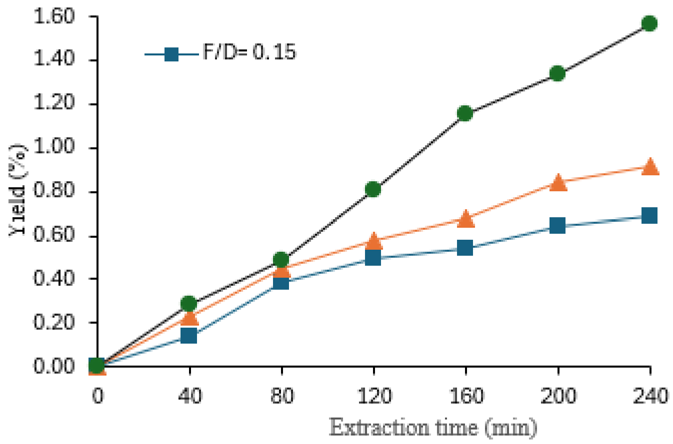

Figure 2. Effect of Extraction time on Cardamom Oil Yield for F/D 0.15; 0.175; 0.2

Compared to a previous study by Tambunan (2017), which used the conventional steam distillation method for 4–5 hours with 500 grams of raw material and only obtained a yield of

0.76%, cardamom oil extraction using the MHG method with microwave powers of 450 W and 600 W achieved yields ranging from 0.78% to 2.08%. These results are significantly higher, obtained in a shorter time and with a smaller amount of raw material. This indicates that the use of microwave is more efficient in terms of yield, extraction time, and the quantity of raw material required in the extraction process.

Effect of Feed to Distiller (F/D) Ratio

This study investigated the influence of varying the feed-to-distiller (F/D) volume ratio on the yield of essential oil from green cardamom seeds using the Microwave Hydrodiffusion and Gravity (MHG) method with steam flow. F/D ratios of 0.15, 0.175, and 0.20 g/mL were tested, corresponding to feed masses of 150 g, 175 g, and 200 g, respectively, within a constant distiller volume of 1000 mL. The objective was to assess how increasing the feed mass, under fixed volume conditions, affects extraction efficiency over time. As illustrated in Figure 3, essential oil yield increased with both longer extraction durations and higher F/D ratios. At 80 minutes, yields were recorded at 0.39% (F/D = 0.15), 0.45% (F/D = 0.175), and 0.49% (F/D = 0.20). After 160 minutes, the trend persisted, yielding 0.54%, 0.68%, and 1.15%, respectively. The most significant increase occurred at 240 minutes, with the yield reaching 1.56% for F/D = 0.20, followed by 0.92% (F/D = 0.175) and 0.69% (F/D = 0.15).

These results confirm that higher F/D ratios—which indicate greater feed mass—enhance essential oil recovery due to the increased number of oil-bearing cells interacting with microwave energy. The consistent upward trend across all F/D ratios and time points also suggests that the distiller volume remained sufficient and did not constrain vapor flow. The use of steam flow further contributed by improving heat distribution and vapor penetration, supporting efficient release of volatile compounds from within the biomass. Hence, these findings reinforce that feed mass is a more critical determinant than distiller capacity in optimizing MHG-based essential oil extraction, especially when combined with steam-assisted processing.

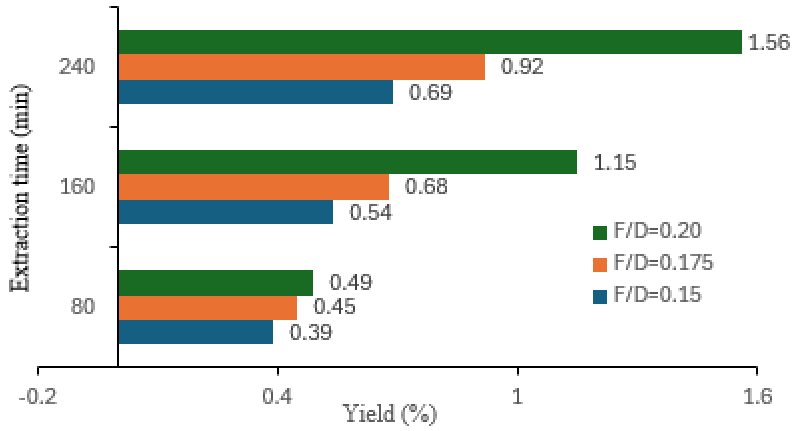

Figure 3. Effect of Feed to distiller ratio on Cardamom Oil Yield for t=80; 60; 240 min

The increase in extraction yield along with the increase in feed mass is supported by the study conducted by some authors Putri et al. (2003) and Kusuma et al. (2016) which revealed that essential oil extraction from orange peel with 150 grams of raw material produced more oil compared to using 50, 75, 100, and 125 grams. This occurs because the greater the amount of raw material used, the more essential oil can be extracted. On the other hand, a study by Kusuma et al. (2017) Kusuma et al. (2017) using the solvent-free microwave extraction method showed that increasing the F/D ratio reduced the yield. This was caused by the density factor, where a large amount of raw material filled the distiller space, hindering the movement of essential oil vapor toward the condenser, ultimately leading to a lower extraction yield.

Table 1 presents a comparison of various extraction methods for obtaining essential oil from Elettaria cardamomum, highlighting differences in yield and extraction duration. The Soxhlet method achieved the highest yield (8.8%) but required the longest duration (8.8 hours) and involved the use of organic solvents, which is less environmentally friendly. Conventional hydrodistillation (Clevenger) resulted in a lower yield of 1.4% over 6 hours. In contrast, Ultrasound-Assisted Hydrodistillation (UAHD) produced a 2.5% yield in only 1.5 hours, demonstrating superior time efficiency through enhanced oil diffusion facilitated by ultrasonic cavitation.

Tabel 1. Comparison Elettaria cardamomum oil yield using some extraction methods

Extraction Methods	Yield (%)	Duration	References
1. Soxhlet	8.8	8.8 h	[28]
2. Hydrodistillation in Clevenger	1.4	6 h	[29]
3. Ultrasound-assisted Hydrodistillation	2–5	1.5 h	[30]
4. Supercritical CO_2 dan subcritical propane	5.4–6.6	3h	[31]
5. Microwave Asissted Hydrodistillation (MAHD)	3.3	4h	[32]
6. Microwave Hydrodiffusion and Gravity (MHG)	1.0 - 2.1	5h	Present work

Supercritical CO_2 and subcritical propane extraction methods yielded between 5.4% and 6.6% within 3 hours. These methods are advantageous for extracting thermolabile compounds with high purity and without solvent residue, although they require expensive high-pressure equipment. Microwave-Assisted Hydrodistillation (MAHD) showed a balanced performance, yielding 3.3% in 4 hours. Meanwhile, the Microwave Hydrodiffusion and Gravity (MHG) method applied in this study achieved yields ranging from 1.0% to 2.1% within the same duration, without solvent use and with promising energy efficiency.

The comparatively lower yield of MHG in this study, as opposed to some prior reports, can be attributed to the feed-to-distiller (F/D) ratios of 0.15–0.2 g/mL, which allowed for remaining space in the distiller. The integration of steam flow played a crucial role in enhancing extraction efficiency. Steam helped reduce the packing density, promoted uniform heat distribution across the material, and improved vapor permeability—allowing more effective penetration of heat and pressure. This resulted in a steady increase in oil yield across the applied F/D ratios. Overall, microwave- and supercriticalbased extraction methods offer significant advantages in process efficiency and sustainability. While the yield from MHG is relatively lower than solvent-based methods, it aligns with green extraction principles and holds strong potential for industrial-scale application following further optimization.

CONCLUSION

The extraction of essential oil from green cardamom (*Elettaria cardamomum*) using the Microwave Hydrodiffusion and Gravity (MHG) method with integrated steam flow has demonstrated notable advantages in terms of process efficiency and sustainability. The addition of steam enhances heat distribution, reduces material density, and improves vapor permeability within the distiller, thereby preventing localized burning and promoting more uniform oil release. These effects contribute to improved extraction efficiency without the use of organic solvents. Experimental findings revealed that higher microwave power, longer extraction time, and increased feed-to-distiller (F/D) ratios (0.15–0.2 g/mL) consistently enhanced oil yield, with the highest yield reaching 2.08% under optimized conditions. While this yield is relatively lower than that achieved by some solvent-based methods, it aligns with *green extraction* principles and demonstrates strong potential for scale-up. The Gas Chromatography-Mass Spectrometry (GC-MS) analysis confirmed the presence of key bioactive compounds—1,8-cineole, α-terpineol, and limonene—known for their antimicrobial and antioxidant properties. In comparison to conventional methods such as Soxhlet, hydrodistillation, and supercritical CO_2 extraction, MHG offers a balance of shorter processing time, energy efficiency, and environmental friendliness. Although yield optimization remains an area for further refinement, the MHG method with steam flow presents a viable and sustainable alternative for industrial-scale essential oil production from green cardamom.

REFERENCES

Abdullah, A., Ali, A., Algburi, A., Huang, Q., Ahmad, T., Zhong, H., Javed, H. U., Ermakov, A. M., & Chikindas, M. L. (2021). Essential oils as antimicrobial agents: Myth or real alternative. *Frontiers in Microbiology*, *12*, 738346.

Al-Hilphy, A. R., Ahmed, A. K., Gavahian, M., Chen, H., Chemat, F., Al-Behadli, T. M., Nor, M. Z. M., & Ahmad, S. (2022). Essential oil extraction from aromatic plants by microwave-generated hydrodistillation. *Journal of Food Process Engineering*, *45*(3), e13992.

Ashokkumar, K., Vellaikumar, S., Murugan, M., Dhanya, M. K., Ariharasutharsan, G., Aiswarya, S., Akilan, M., Warkentin, T. D., & Karthikeyan, A. (2021). *Elettaria cardamomum* (cardamom): A promising remedy for various human ailments especially diabetes and cancer. *Frontiers in Sustainable Food Systems*, *5*, 668026.

Chemat, F., Vian, M. A., & Cravotto, G. (2012). Green extraction of natural products: Concept and principles. *International Journal of Molecular Sciences*, *13*(7), 8615-8627.

Dhifi, W., Bellili, S., Jazi, S., Bahloul, N., & Mnif, W. (2016). Essential oils' chemical characterization and investigation of some biological activities: A critical review. *Medicines*, *3*(4), 25.

Gao, J. (2021). Environmental impact of conventional extraction methods of essential oils. *Environmental Science and Pollution Research*, *28*(42), 59436-59445.

Guerrero, A., Ferrero, S., Barahona, M., Boito, B., Lisbinski, E., Maggi, F., & Sañudo, C. (2019). Effect of the addition of quebracho tannin extract on the antioxidant capacity and meat quality of fresh lamb sausages. *Journal of the Science of Food and Agriculture*, *100*(2), 656-666.

Hamdan, S., Daood, H. G., Toth-Markus, M., & Illes, V. (2008). Extraction of cardamom oil by supercritical carbon dioxide and subcritical propane. *The Journal of Supercritical Fluids*, *44*(1), 25-30.

Hasanah, N. U., Tafrihani, A. S., Zulfin, U. M., Salsabila, D. U., Wardani, R. K., Ikawati, M., Meiyanto, E., & Jenie, R. I. (2023). Green extraction techniques for essential oils: A comprehensive review. *Indonesian Journal of Biotechnology*, *28*(2), 86-98.

Ivanović, M., Makoter, K., & Razboršek, M. I. (2021). Innovative extraction techniques using deep eutectic solvents and analytical methods for the isolation and characterization of natural bioactive compounds from plant material. *Plants*, *10*(3), 501.

Kumar, A., Tandon, S., Ahmad, J., Yadav, A. K., & Kahol, A. P. (2005). Essential oil composition of cardamom (*Elettaria cardamomum* Maton) from different geographical regions of India. *Journal of Essential Oil Bearing Plants*, *8*(2), 204-210.

Kusuma, H., Putri, D., Dewi, I., & Mahfud, M. (2016). Solvent-free microwave extraction of essential oil from orange peel: Optimization of extraction time and feed to solvent mass ratio. *Chemistry and Chemical Technology*, *10*(2), 213-218.

Kusuma, H. S., Syahputra, M. E., Parasandi, D., Altway, A., & Mahfud, M. (2017). Optimization of microwave-assisted extraction of essential oil from dried lemongrass (*Cymbopogon citratus*) using response surface methodology. *Rasayan Journal of Chemistry*, *10*(4), 1071-1077.

Latifasari, N., Faizah, F., & Kurniawati, A. D. (2023). Green extraction methods for essential oils: A sustainable approach to natural product extraction. *Journal of Applied Food Technology*, *11*(1), 1-12.

Leblebici, M. E., Machmudah, S., Sasaki, M., & Goto, M. (2012). Extraction of essential oil from cardamom seed using supercritical CO_2: Experiments and modeling. *Separation Science and Technology*, *48*(2), 328-339.

Luque de Castro, M. D., & Priego-Capote, F. (1998). Soxhlet extraction: Past and present panacea. *TrAC Trends in Analytical Chemistry*, *17*(8-9), 593-602.

Lutony, S. (2002). *Minyak atsiri sebagai sumber aroma alami*. Rineka Cipta.

Mahfud, M., Darmawan, M. D., Diamanta, D. H., & Kusuma, H. S. (2017). Steam distillation extraction of essential oil from pandan leaves (*Pandanus amaryllifolius*) using microwave heating. *Journal of Chemical Technology and Metallurgy*, *52*(5), 791-799.

Mahfud, M., Nabila, A. R., & Variyana, Y. (2025). Microwave hydrodiffusion and gravity extraction of essential oil from cardamom seeds: Process optimization and quality analysis. *Rasayan Journal of Chemistry*, *18*(1), 52-62.

Mande, P., & Sekar, N. (2021). Microwave assisted hydrodistillation of essential oil from *Elettaria cardamomum*: Optimization and kinetic modeling. *Journal of the Indian Chemical Society*, *98*(11), 100201.

Molaveisi, M., Avval, M. N., Noghabi, M. S., & Mohammadi, M. (2020). Optimization of microwave-assisted extraction of cardamom essential oil using response surface methodology. *Infection, Epidemiology and Microbiology*, *6*(1), 51-60.

Morsy, N. F. (2015). Ultrasound-assisted extraction of essential oil from cardamom seeds: Optimization and characterization. *Industrial Crops and Products*, *65*, 287-293.

Noumi, E., Snoussi, M., Alreshidi, M., Rekha, P. D., Kanekar, S., Caputo, L., Martino, L. D., Souza, L. F., Msaâda, K., Mancini, E., Flamini, G., Al-Sieni, A. I., & Feo, V. D. (2018). Chemical composition and biological activities of *Elettaria cardamomum* essential oil. *Molecules*, *23*(11), 2818.

Pujiarti, R., & Kusumadewi, A. (2020). Green extraction methods for essential oils from Indonesian medicinal plants. *Wood Research Journal*, *11*(1), 35-45.

Putri, S., Risang, P., Bhuana, D., & Mahfud, M. (2003). Microwave hydrodiffusion and gravity extraction of essential oil from orange peel: Effect of feed to distiller ratio. *Proceedings of the International Conference on Chemical Engineering*, 3849-3854.

Soh, L., & Eckelman, M. J. (2016). Green solvents in biomass processing. *ACS Sustainable Chemistry & Engineering*, *4*(11), 5821-5837.

Tambunan, R. (2017). Conventional steam distillation of cardamom essential oil: Process evaluation and yield optimization. *Indonesian Journal of Science and Technology*, *2*(2), 45-52.

Tanvir, E. M., Hossen, M. S., Hossain, M. F., Afroz, R., Gan, S. H., Khalil, M. I., & Karim, N. (2017). Antioxidant properties of popular turmeric (*Curcuma longa*) varieties from Bangladesh. *Journal of Food Quality*, 2017, 8471785.

Teresa-Martínez, G. D., Cardador-Martínez, A., Téllez-Pérez, C., Allaf, K., Jiménez-Martínez, C., & Alonzo-Macías, M. (2022). Essential oil extraction from cardamom using supercritical fluid extraction: Process optimization and bioactivity evaluation. *Molecules*, *27*(11), 3433.

Variyana, Y., Fitria, M., Muchammad, R., & Mahfud, M. (2024). Microwave-assisted extraction of essential oils: Recent advances and applications. *Results in Engineering*, *24*, 103294.

Yuniati, Y., Variyana, Y., Qadariyah, L., & Mahfud, M. (2024). Sustainable extraction of essential oils using microwave technology: A comprehensive review. *AIP Conference Proceedings*, *3071*(1), 020045.

Zandi, M., Dardmeh, N., Pirsa, S., & Almasi, H. (2015). Essential oils in food preservation: Antimicrobial and antioxidant properties. *Journal of Food Process Engineering*, *40*(2), e12456.