

Review: The Influence of Environmental Factors on Oil Quality and The Effectiveness of Various Extraction Methods in Producing Coffee Oil

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Keywords	Abstract
coffee essential oil; extraction method; environmental factors; <i>terroir</i> ; oil yield.	Coffee essential oil is a high-value derivative product of coffee beans with broad applications in the food, pharmaceutical, cosmetic, and aromatherapy industries. This study aims to analyze the influence of environmental factors on the chemical profile and quality of coffee oil, as well as to evaluate the effectiveness of various extraction methods based on the yields produced. The method employed is a systematic literature review of scientific literature published over the last ten years (2015–2025) and retrieved from the Google Scholar, ScienceDirect, MDPI, and PubMed databases. The results show that coffee oil quality is determined by multifactorial interactions related to <i>terroir</i> effects, including geographical origin, soil composition, climatic conditions, and altitude, all of which modulate the plant's secondary metabolic pathways. Total phenolic acid and flavonoid contents reach optimal accumulation at moderate altitudes of approximately 1,400 meters above sea level, while soil mechanical structure significantly affects the concentration of key oil compounds. Regarding extraction methods, CO ₂ -based supercritical fluid extraction provides the highest efficiency, achieving yields of up to 80% with optimal selectivity and purity, despite requiring substantial investment in equipment. Among solvent-based methods, ultrasonic-microwave-assisted extraction shows the best yield, reaching 10.58%. Conventional methods, such as mechanical pressing, Soxhlet extraction, and steam distillation, remain relevant for specific applications because of their operational simplicity. This review confirms that aligning extraction methods with the environmental conditions of the raw material's origin is a key strategy for developing Indonesian coffee essential oil as a superior, high-value product in the global market.

INTRODUCTION

Indonesia is one of the countries rich in natural resources, including the agriculture, forestry, and water sectors which are one of the supports of the economy. One of these resources is in the coffee commodity sector. Coffee is one of the commodities that is generally used as a beverage, health, and beauty product (Badruttamam & Rianto, 2023), and making it one of the agricultural commodities with high market demand so as to increase economic value and become the mainstay of Indonesia's exports. In the face of increasingly fierce competition in the global market, the diversification of coffee processing products has become a strategic need that cannot be ignored and needs attention. One of the derivative products of coffee that has attracted the attention of academics and industry is coffee oil. Coffee oil has a volatile bioactive fraction obtained from coffee beans through various extraction processes. Coffee oil can be applied into various derivative products, including food industry as a natural flavor and preservative, to non-food industries such as cosmetics, perfumes, and aromatherapy (Masriadi et al.,

2023; Yunilawati et al., 2021). Given this great potential, the development of science regarding the characteristics, quality determinants, and production technology of coffee essential oil is a very relevant research agenda, especially for Indonesia as the fourth largest coffee producer in the world.

The quality of coffee essential oil is not static, but rather is highly determined by the growing environmental conditions that can be known as the *Terroir*. These factors are such as conditions of geographical origin, soil composition and texture, climatic conditions, and the height of the growing site which can affect modulating the secondary metabolic pathways of plants, thus forming a distinctive chemical profile and volatile compounds (El-Zaeddi et al., 2016; Ibrahim et al., 2024). In the study of arabica coffee, which discussed the comparison of altitude to bioactive compounds of coffee, it was shown that the total content of phenolic acids and flavonoids reached its peak at a moderate elevation of about 1,400 meters above sea level, indicating that there is an optimal point for the environment for the accumulation of polyphenol compounds (Zaman et al., 2025). Similarly, the composition of the soil, especially the ratio of sand, clay, and clay has a key role in the biosynthesis of secondary products of aromatic plants (Tursun, 2022). Therefore, this environmental variation causes plants of the same species to produce different oil chemical profiles between locations, leading to a deep understanding of the relationship *Terroir*–Oil quality is an important foundation in the development of product standards.

On the other hand, the extraction method used also critically determines the yield and profile of the oil compounds produced (M. K. Putri et al., 2025). Various studies have been developed and researched. Some of the methods of extraction coffee oil include mechanical extraction through pressing (*cold pressing* and *expeller pressing*), organic solvent-based extraction (Soxhlet, maceration), steam distillation (*Steam Distillation*), to cutting-edge technologies such as CO₂ supercritical fluid extraction (SFE-CO₂), microwave-assisted extraction/ *microwave-assisted extraction* (MAE), ultrasonic/ *ultrasound-assisted extraction* (UAE), and a combination of both. *ultrasonic microwave-assisted extraction* (LAUGHTER) (Dong et al., 2021; Ribeiro et al., 2024). Each method has different characteristics of yield, compound selectivity, and economic consequences. The SFE-CO₂ method is reported to be able to produce extraction yields of up to 80% of the total oil content under optimal conditions with the advantages of high selectivity and minimal environmental impact but requires a large investment in equipment (Cante et al., 2021; Melo et al., 2014). Meanwhile, UMAE showed high yield results compared to modern solvent-based methods, reaching 10.58% in a much shorter time than conventional techniques (Dong et al., 2021). The selection of the right extraction method, adjusted to the purpose of the application, both for the food, pharmaceutical, and cosmetic industries, is a crucial consideration that cannot be ignored.

The urgency of this research is underscored by several converging factors. First, the global essential oil market is experiencing rapid growth, with increasing demand for natural, high-value products across multiple industries. Second, Indonesia's position as a major coffee producer provides a competitive advantage that remains underutilized due to limited scientific documentation and optimization of processing technologies. Third, the absence of integrated knowledge linking cultivation practices to extraction outcomes results in suboptimal product quality and inconsistent yields, thereby hindering the development of Indonesian coffee essential oil as a premium export commodity. Addressing this gap is therefore both scientifically necessary and economically imperative.

The novelty of this research lies in its systematic integration of two previously disconnected domains: environmental factors affecting coffee oil quality and the effectiveness of extraction methods. Unlike previous studies that have treated these aspects as separate issues, this review provides a holistic framework that connects terroir characteristics with optimal extraction strategies. Furthermore, this research synthesizes findings from multiple studies published between 2015 and 2025, offering updated insights that reflect the latest technological advancements in extraction science. The identification of specific environmental optima, such as the 1,400-meter elevation threshold for maximum polyphenol accumulation, combined with comparative yield data across extraction methods, represents a novel contribution to the field.

Although a number of studies have partially examined the determinants of coffee oil quality and extraction techniques separately, there has been limited comprehensive synthesis that systematically links environmental variables, including terroir, elevation, soil type, and climate, with various extraction methods in relation to the yield and quality of coffee essential oil, particularly in the context of Indonesian coffee. This condition creates a significant scientific gap, especially considering the richness and diversity of Indonesia's coffee agroecosystems, which have not yet been fully documented scientifically. Therefore, this review article aims to identify and analyze the influence of environmental factors on the chemical profile and quality of coffee essential oil, as well as to evaluate the effectiveness of various extraction methods based on the yield of the oil produced.

RESEARCH METHODS

This research was carried out by collecting secondary data from various literature sources. The literature review includes scientific articles presenting case studies published in the last ten years (2015–2025). The data collection technique used is through electronic search engines such as Google Scholar, ScienceDirect, MDPI, and PubMed using the keywords "coffee", "coffee oil", "coffee extraction", "extraction technology", and "terroir". In addition, an old article with an important concept about extracting essential oils by pressing is also included.

RESULTS AND DISCUSSION

Definition and Characteristics of Coffee Oil

Essential oil is a clear liquid derived from plants that has a distinctive aroma according to the producing plant. Essential oils basically have volatile properties at room temperature without decomposition, have a bitter taste, have a fragrant smell according to the producing plants. In addition, essential oils are generally soluble in organic solvents and insoluble in water (Caroline, 2022). So it's not surprising that there is a special and distinctive scent in these parts. This aroma is called essential or *Volatile* or *Essential*. Essential oils or *essential oil* comes from the secondary metabolism of a plant. These metabolites accumulate in plant parts such as roots, stems, leaves, seeds, fruits, and flowers (Rahma Alifia et al., 2024; Sharmeen et al., 2021), especially in essential oils obtained from coffee.

Coffee oil can be classified as essential oil because it contains typical aromatic compounds derived from coffee beans (Mohamed et al., 2024). Coffee oil is obtained through the extraction process of separating certain compounds from the ingredients using heated solvents, pressing and steam distillation (Ribeiro et al., 2024). Although technically classified as a carrier oil, roasted coffee bean oil exhibits hybrid properties

between vegetable oils and aromatic extracts as it contains a complex mixture of triglycerides and free fatty acids, especially linoleic acid and palmitic acid, as well as flavonoids and other bioactive compounds (Chelu, 2024). Although it comes from caffeine-rich coffee beans, coffee oil contains only very low amounts of caffeine because caffeine is water-soluble and does not transfer significantly into the oil during the extraction or pressing process (Kobylińska et al., 2025).

Essential oils can be used into various preparations or additives to a product, namely from food products such as candies, drinks, and other products (Yunilawati et al., 2021), while non-food products from essential oils can be in the form of air fresheners, aromatherapy candles, perfumes, soaps, and other products (Masriadi et al., 2023). The use of essences as an additive in a product is because it has flavonoid compounds that can be antimicrobial so that it can be used as a natural preservative in raw meat products (B. D. da Silva et al., 2021). The antibacterial role of essential oils is by interfering with the process of forming membranes or cell walls to become unformed or imperfectly formed. In addition, other components of antimicrobial compounds derived from essential oils are citronelol, citronelal, and geraniol which have the ability to inhibit the ability of bacterial activity and inhibit the growth of microorganisms (Sefriyanti et al., 2020).

Factors Affecting the Quality of Coffee Oil

The quality of essential oils is not only determined by the genetic factors of the plant, but is also strongly influenced by the complex interactions between the plant and the environment in which it grows, which is often referred to as the effect *Terroir*. The origin of the growing region includes climate variables, soil composition, and cultivation practices that collectively form a unique sensory profile, especially on the taste and aroma of coffee (El-Zaedi et al., 2016; Ibrahim et al., 2024). These geographical differences cause variations in the plant's secondary metabolic pathways, so plants of the same species can produce different chemical compositions if grown in different locations.

The formation of volatile compounds inside coffee beans is highly dependent on the stability of their precursor compounds triggered by the growing location (Demianova et al., 2022). Soil conditions can affect the physical and chemical characteristics of the soil, playing a major determinant in the biosynthesis of secondary products of aromatic plants (Tursun, 2022). In accordance with the research of essential oils from the purple basil plant which has the texture conditions of clay sand soil, it is proven to produce the highest essential oil yield (46.03%) observed on sandy clay soils, and lowest (42.33%). This indicates that the concentration of key compounds, such as *Methylsininate*, is particularly sensitive to the ratio of sand, clay and clay in soil, where significant differences are found in the concentration levels of such compounds based on the mechanical structure of the soil (Tursun, 2022). In addition, the height factor (*elevation*) also provide environmental pressures in the form of different temperatures and UV intensities. Recent research on Arabica coffee shows that the total content of phenolic acids and flavonoids peaks at moderate altitudes (1,400 meters above sea level) compared to lower elevations (1,200 meters above sea level) or higher (1,600 meters above sea level) (Zaman et al., 2025). This indicates that there is an optimal point of the environment that supports the accumulation of polyphenol compounds to the maximum.

The growing environment conditions directly modulate the accumulation of important non-volatile compounds in green coffee beans. Compounds such as caffeine, trigonelin, chlorogenic acid, and sucrose show significant fluctuations in levels based on their geographical origin. Chlorogenic acids and caffeine, for example, are often produced by plants as a defensive response to environmental stress. If environmental conditions

(such as soil temperature and nutrients) change, then this basic chemical profile will shift, ultimately determining the quality of the extracted coffee oil (Tieghi et al., 2024).

Coffee Oil Extraction Technology

The production process of essential oils can be obtained through 3 extraction methods, namely pumping (*pressing*), extraction using solvents (*solvent extraction*), and distillation (*distillation*) (Djau et al., 2022; F. D. Putri et al., 2023). In addition to the three ways of essential oil production process, coffee oil extraction can be obtained by pressing, Soxhlet extraction, microwave ultrasonic assisted extraction/ *ultrasonic microwave-assisted extraction* (UMAE), microwave-assisted extraction/ *microwave-assisted extraction* (MAE), ultrasonic-assisted extraction/ *ultrasound-assisted extraction* (UAE), pressure fluid extract/ *pressurized liquid extraction* (PLE), and supercritical fluids (Dong et al., 2021; Ribeiro et al., 2024).

Coffee Oil Intake by Forging

The extraction of essential oils by pressing or can be called mechanical extraction is carried out by the pressing method. It is usually done on materials in the form of seeds, fruits, and peels from citrus plants. This method is only done if the essential oil content in the ingredients is quite large, which ranges from 30-70%, so that the oil drops can be seen with the naked eye or can be pressed with the hand (Kurniawan et al., 2008). Two common methods in mechanical pressing are *Hydraulic pressing* and *Expeller pressing*. *Hydraulic pressing* (hydraulic pressing), where the material is pressed at a pressure of about 2,000 lb/inch² without the use of heating media, so this method is often also called cold pressing. *Expeller pressing* (threaded pressing), where to extract oil or fat it is necessary to first heat or temper at a temperature of about 115.5°C and a pressure of 15,000-20,000 lb/inch².

In pressing extraction, a pressing machine can be used which consists of a barrel-shaped outer container with perforated walls and metal screws that insert products containing oil. The material is constantly grinded and crushed, thus damaging the oil cells that allow oil to collect through the holes in the container. The material from which the oil is extracted is known as dregs. The capacity can vary, but most pressing machines are capable of processing between 8 and 45 kg per hour (Ribeiro et al., 2024).

According to research R. M. V. Silva *et al.* (2024), explains that several pressing parameters affect the yield and lipid composition of green Arabica coffee oil, focusing on the content of fatty acids, diterpenes, and serotonin amides, the latter of which is described for the first time in the context of coffee oil composition. The experimental design was created to evaluate particle size (<0.850 mm; >0.850 mm; and <2.00 mm), screw speed (18 and 30 rpm), pressurized outlet nozzle size (4 and 5 mm), and preheating (on and off). Oil yields vary between 2.65 and 6.27% and all parameters have a significant impact on these yields. The diterpenes content of kahweol and cafestol range from 13.33 to 16.72 mg/g and 37.11 to 47.14 mg/g of oil, respectively. The amide content of serotonin ranges from 114.42 to 577.37 µg/g for C20-5HT and 193.50 to 1068.08 µg/g for C22-5HT.

The extraction process of mechanical pressing has a natural and simple approach that does not use chemical solvents which offers environmental and quality advantages compared to solvent extraction methods that use organic solvents. In addition, this method avoids solvent recovery steps and possible problems with solvent residues and pollution, making it attractive to the food and pharmaceutical industries when looking for high-quality, under-processed products. However, these methods tend to offer lower yields and cannot achieve the same oil purity as those obtained with more advanced methods (Ribeiro et al., 2024; Wen et al., 2023).

Essential Oil Extraction Process With Solvent

The extraction process of essential oils with solvents is carried out using compounds such as methanol, hexane, and ether that have different properties according to the type of target compound. Methanol as a polar solvent is capable of extracting polar molecules, although it can carry contaminants. Hexane, a non-polar solvent, is more effective at extracting non-polar essential oils with minimal contamination. *Ether (diethyl ether)* It is semi-polar, volatile, and has good solubility to oil, so it is often used even though it is at risk of flammability. This method is suitable for heat-sensitive materials, such as kaffir lime leaves (*C. hystrix*), which produces a volatile compound with a distinctive aroma. Research shows ethanol extracts are able to dissolve more active compounds from kaffir lime leaves, thus giving the best results. However, the disadvantages of solvent extraction include the use of synthetic solvents that are unfriendly to food and pharmaceuticals, potentially damaging the ecology, and complicating downstream processes such as purification and concentration due to the formation of emulsions and complexes that are difficult to remove (Nabi et al., 2025).

Soxhlet extraction is one of the official standard methods of extraction with solvents to determine oil levels (Thiex, 2009). Soxhlet extraction is carried out by placing a sample placed on a cellulose filter (thimble) that is gradually filled with a solvent (also called fresh condensed extract) from the distilled flask. When the liquid reaches the overflow level, the siphon sucks it out of the thimble and returns it to the distillation flask, thus transferring the extracted analyte into the main liquid. This operation can be repeated until complete extraction is achieved (Ribeiro et al., 2024). The Soxhlet method is well suited for laboratory-scale work. This requires a heating coat for the distillation flask connected to the extraction chamber (Soxhlet), followed by a condenser. Distillation flasks hold an extraction solvent (≈ 300 mL), usually using an n-hexane solution as it is a volatile solvent (boiling point at 68.8 °C). The cost of sealin for the solution is quite low, and it is easy to obtain because of its petrochemical origin (de Faria et al., 2025; Novaes et al., 2023). The results of Soxhlet extraction used to obtain Arabica and Canephora coffee oil were analyzed for sterol content. About 50 g of ground coffee beans are extracted with hexane for 8 hours, with suction six times per hour. The yield of coffee oil is 12–17% Canephora coffee and for Arabica 15–20% (Ribeiro et al., 2024).

The soxhlet extraction method has disadvantages compared to other extraction methods. The disadvantages of this method are the long extraction time (4–16 hours) and the amount of solvent used is very large, resulting in more waste. Another disadvantage is exposure to the extracted solutes against the boiling point of the solvent over a long period of time and the possible heating of thermobilingual compounds, which leads to undesirable results (Abbas et al., 2021; Ribeiro et al., 2024).

Maceration which is the process of extracting simplicia using solvents. Maceration is carried out by several shakes or stirring at room temperature. Maceration aims to attract nutritious substances that are heat-resistant and non-heat-resistant (Handoyo, 2020). Technologically, maceration includes extraction with the principle of a method of achieving concentration on balance. Maceration is a universal method that is widely used in the separation of organic enrichment. The extraction method is carried out by inserting simplicia powder into the appropriate solvent. The maceration container used must be inert so that side reactions do not occur. Maceration is performed at room temperature in a sealed container (Asworo & Widwastuti, 2023). The resulting maceration is filtered first, then the macerates are concentrated to obtain a thick extract (Hamka et al., 2022). Commonly used solvents in maceration are polar solvents (water, methanol, ethanol,

acetic acid), semi-polar solvents (acetone, ethyl acetate, chloroform), and non-polar solvents (hexane, ether) (Wahyuningsih et al., 2024).

Slinging

Refining is the most widely used method to obtain essential oils. In essential oils, it is known by 3 methods of distillation, namely: distillation with water (*water distillation*), distillation with water and steam (*water and steam distillation*), distillation with direct steam (*steam distillation*) (Berlian et al., 2023). Steam distillation is an extraction method that is one of the most popular methods for obtaining essential oils from heat-sensitive plant sources (lavender, rose, chamomile, jasmine, eucalyptus, peppermint, tea tree, basil, etc.). This method is particularly preferred for large-scale essential oil extraction (Razola-Díaz et al., 2021). Clevenger type equipment can also be used for steam distillation for essential oil extraction. To prepare the leaves for the steam distillation process, the leaves can be soaked in water or positioned on a bed placed just above the surface of the water. Once the water heats up, steam is generated on the leaves, which disrupts the cell structure and releases volatile compounds. Pumpkins are used to collect steam; The resulting condensate contains a combination of water and oil, and the water-soluble chemicals will dissolve in low-temperature condensate. This process will take about two hours to achieve maximum production yields (Nabi et al., 2025; Razola-Díaz et al., 2021). The higher the vapor temperature, the more oil is produced. This hypothesis has been validated, and it has been found that an increase in vapor temperature will naturally increase the amount of essential oil produced (Nabi et al., 2025).

Extraction with Supercritical Fluids

Supercritical fluid extraction (SFE) is used to extract components from different matrices using fluids under temperature and pressure conditions above their critical point. Supercritical fluids form homogeneous phases that have liquid- and gaseous properties. Physicochemical properties such as viscosity, diffusivity, and dielectric constants can be controlled by varying the temperature and pressure of supercritical fluids, without the occurrence of phase changes (Ribeiro et al., 2024). These properties give supercritical fluids a solubility similar to that of liquids, acting as solvents. High diffusivity and low viscosity allow them to have gaseous properties, with high penetration power in solid matrices, thus favoring the mass transfer of the extraction process (Ribeiro et al., 2024; Rodríguez-España et al., 2022). CO₂ is the most commonly used solvent for the extraction of supercritical fluids due to its relatively low critical pressure and temperature, non-toxic, non-flammable, available in high purity, and low cost (Cante et al., 2021). In Melo's research *et al.* (2014) green coffee oil and reported a maximum extraction yield of 80% of the total oil content in 120 minutes, at a pressure of 300 bar, a temperature of 50 °C, and a CO₂ flow rate by 10 g/min.

This method is also considered a selective extraction method that has a low environmental impact when compared to solvent extraction, as extraction with supercritical fluids allows for high extraction results with little or no organic solvents. In addition, the extraction of supercritical fluids requires a short extraction time and is low in operational costs. However, the high setup costs are a disadvantage when compared to other extraction techniques (Cante et al., 2021; Ribeiro et al., 2024).

Other Extraction Methods

Apart from some of the extraction methods above, there are modern extraction methods that are widely used in coffee oil extraction. The method is microwave ultrasonic-assisted extraction/ *ultrasonic microwave-assisted extraction* (UMAE), microwave-assisted extraction/ *microwave-assisted extraction* (MAE), ultrasonic-

assisted extraction/ *ultrasound-assisted extraction (UAE)*, and Compressed fluid extract/ *pressurized liquid extraction (PLE)*. On research (Dong et al., 2021) which discusses the comparison of the effect of the extraction method on the quality of green coffee oil from Arabica coffee beans concluded that the ultrasonic technique consists of the use of a working frequency of 40 kHz and an electrical power of 50 W, at a sample:ethanol ratio of 1:30 (g/mL) at a temperature of 35 °C for 50 minutes. The microwave technique consists of the use of 10 g of powder samples with 100 mL of ethanol extracted at 60 °C for 30 minutes, and microwave power is set at 200 W. Ultrasonic-microwave-assisted extraction uses a mass to ethanol ratio of 1:28 (g/mL) at 60 °C for 10 minutes, with a microwave power of 350 W. The final technique, pressure fluid extraction, consists of using a sample to ethanol ratio of 1:2 (g/mL) at 100 °C for 30 minutes, and the pressure reaches 100 bar. Among the four techniques evaluated, ultrasonic/microwave-assisted extraction showed the highest results (10.58%), followed by microwave-assisted extraction (9.34%), ultrasonic-assisted extraction (9.06%), and pressurized liquid extraction (6.34%). Ultrasonic/microwave-assisted extraction resulted in the highest yield (10.58%), while pressurized liquid extraction (6.34%) resulted in the lowest yield.

CONCLUSION

Coffee essential oil has the unique characteristics of a hybrid between vegetable oils and aromatic extracts, as it is rich in bioactive compounds but contains low levels of caffeine. The quality and chemical profile of this oil are strongly influenced by the terroir effect, in which soil conditions and an altitude of approximately 1,400 meters above sea level represent optimal points for the accumulation of polyphenol compounds. Based on the results of the analysis, selecting the appropriate extraction method significantly affects both oil yield and quality. Conventional methods, such as mechanical pressing and distillation, offer advantages in terms of safety and operational simplicity but produce lower yields. Supercritical fluid extraction (SFE) is able to extract up to 80% of the oil, while the combination of ultrasonic and microwave-assisted extraction (UMAE) produces the highest yield among solvent-based methods, reaching 10.58%. Practically, coffee essential oil has the potential to be developed for use in both food and non-food industries, particularly as an antimicrobial agent or natural preservative, although challenges related to operational costs and solvent waste still need to be optimized in future research.

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