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EFFECT OF AIRFLOW RATE ON THE EXTRACTION OF WHITE PEPPER (*PIPER NIGRUM* L.) ESSENTIAL OIL USING THE MICROWAVE AIR-HYDRODISTILLATION METHOD

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ABSTRACT This study examines the effect of airflow rate on the extraction of white pepper (Piper nigrum L.) essential oil using the Microwave Air-Hydrodistillation (MAHD) method. The research aimed to optimize the extraction process by varying the airflow rate (1, 2, 3, 4, and 5 L/min) while maintaining a microwave power of 450 W and an extraction time of 100 minutes. The results indicate that airflow rate significantly influences essential oil yield, with the highest yield (2.4590%) obtained at 1 L/min airflow. Increasing airflow beyond this rate led to a decline in yield due to excessive volatilization and incomplete condensation of essential oil components. The extracted essential oil was analysed for color, density, ethanol miscibility, and acid number and compared with ISO 3061:2008 standards. The oil exhibited a blue color, a density of 0.8814 g/mL (within the ISO range of 0.861–0.885 g/mL), and an acid number of 1.2732 mg KOH/g, indicating good quality. However, the miscibility test deviated slightly, requiring 4–5 mL of ethanol instead of the standard 3 mL, suggesting possible differences in chemical composition. These findings confirm that MAHD is an efficient extraction method, offering shorter processing times and improved efficiency compared to conventional hydrodistillation. The study highlights the importance of optimizing airflow rate to balance yield, condensation efficiency, and volatile compound retention. Further research is recommended to refine extraction conditions for enhanced quality and industrial applicability.

Keywords: *Essential Oil, Microwave Air Hydrodistillation, White Pepper, Yield*

INTRODUCTION

Essential oils from natural plant sources are widely used in various industries, including pharmaceuticals, cosmetics, and food processing, due to their aromatic and bioactive properties. White pepper (Piper nigrum L.) essential oil is particularly valued for its distinct volatile compounds, which contribute to its characteristic aroma and potential health benefits. The efficiency of essential oil extraction largely depends on the extraction method used, as different techniques can significantly impact both yield and quality. One promising method is Microwave Air-Hydrodistillation (MAHD), a hybrid approach that combines microwave heating with air-assisted hydrodistillation to enhance extraction efficiency. However, the optimization of process parameters, particularly airflow rate, remains a critical factor in maximizing oil yield and preserving essential bioactive compounds.

Conventional extraction techniques such as steam distillation and Soxhlet extraction are commonly used for essential oil recovery but are often associated with long processing times, high energy consumption, and possible degradation of thermosensitive compounds. MAHD has been introduced as an alternative due to its faster extraction time, improved energy efficiency, and better preservation of heat-sensitive components. Despite its advantages, the role of airflow rate in the MAHD process remains insufficiently studied, particularly in the extraction of white pepper essential oil. Since airflow plays a crucial role in facilitating the volatilization of essential oil components, determining the optimal rate is essential to ensure an efficient and high-quality extraction process.

It is hypothesized that an increase in airflow rate during MAHD will enhance the extraction efficiency of white pepper essential oil by promoting faster volatilization of essential oil components. However, an excessively high airflow rate could lead to the loss of lighter volatile compounds, potentially affecting the overall chemical composition and aroma profile of the extracted oil. Therefore, an optimal airflow rate is expected to maximize oil yield while preserving its key bioactive constituents, providing a balance between efficiency and quality in the extraction process.

This study presents a novel investigation of airflow rate as a key parameter in the MAHD process for extracting white pepper essential oil. While MAHD has been explored as an alternative extraction method, the specific influence of airflow rate has not been extensively studied. By optimizing this parameter, this research aims to improve the efficiency of the MAHD technique while ensuring the preservation of essential oil quality. The findings of this study will contribute to the field of essential oil processing by providing new insights into the role of airflow in microwave-assisted extractions, which could be applied to various plant-based essential oils.

The main objectives of this research are to analyze the effect of different airflow rates on the yield and chemical composition of white pepper essential oil, to identify the optimal airflow rate that maximizes extraction efficiency, and to compare the performance of MAHD with conventional hydrodistillation methods. By addressing these aspects, this study seeks to provide a scientific basis for optimizing the MAHD process and advancing essential oil extraction technology for improved industrial applications.

METHOD

Materials

The primary raw materials used in this study were white pepper seeds sourced from East Kalimantan, along with distilled water as the extraction medium. The essential oil extraction was performed using a Microwave Air-Hydrodistillation (MAHD) system, which included a 1270 W Electrolux brand microwave oven and a Lakoni air compressor with a 0.75 HP (550 W) motor capable of delivering a maximum airflow rate of 5 L/min. The extraction setup comprised a 1000 mL three-neck distillation flask, a Clevenger-type apparatus, a condenser, and a separatory funnel for oil-water separation. For the physical characterization of the extracted essential oil, laboratory equipment such as a pycnometer (for density measurement), measuring pipettes, an Erlenmeyer flask, and a burette were utilized. These instruments ensured accurate evaluation of essential oil properties, including color, density, solubility in alcohol, and acid number.

Extraction Process of White Pepper

The essential oil extraction was carried out using the Microwave Air-Hydrodistillation (MAHD) method under controlled conditions. White pepper seeds were ground to 80-mesh particle size, and 100 g of the ground material was placed into a three-neck distillation flask. Subsequently, 500 mL of distilled water was added as the solvent. The extraction process was initiated by heating the mixture in a microwave oven set to 450 W power, while compressed air was introduced at variable flow rates (1, 2, 3, 4, and 5 L/min) to enhance steam formation.

The generated vapor, containing volatile essential oil compounds, was condensed using a condenser to yield a distillate composed of an essential oil phase and a water phase. The separation of these two phases was performed using a separatory funnel, ensuring efficient collection of the essential oil. The extraction process was conducted over a total duration of 100 minutes, with sampling intervals of 20 minutes to monitor oil extraction progress.

Essential Oil Yield Calculation

The essential oil yield was determined by comparing the mass of the extracted oil with the dry weight of the raw material, using the following equation:

$$\textbf{Yield} = \frac{\textbf{Essential oil content obtained (g)}}{\textbf{Mass of raw materials (g)} \times (\textbf{1} - \textbf{moisture content}(\%))} \textbf{ x 100}\% \quad (1)$$

In addition to yield determination, the essential oil was characterized based on color, density, solubility in alcohol, and acid number to assess its quality. These parameters were analyzed using standard laboratory procedures to evaluate the physicochemical properties of the extracted white pepper essential oil.

RESULTS AND DISCUSSION

The Microwave Air-Hydrodistillation (MAHD) method used for extracting white pepper essential oil integrates the principles of microwave heating and air compression-assisted distillation. Compared to conventional heating methods, microwave heating offers higher energy efficiency and faster extraction rates. Microwaves exhibit selective heating, where only polar molecules absorb microwave energy, leading to rapid internal heating of the sample. Unlike traditional heating methods, where heat is transferred from the surface of the equipment to the solvent and material in a gradual and time-consuming manner, microwave heating ensures volumetric heating, where the entire sample, including the white pepper matrix and distilled water solvent, is heated simultaneously. This significantly reduces the extraction time while maintaining the quality and composition of volatile compounds (Destandau et al., 2013).

A key parameter influencing extraction efficiency in MAHD is airflow rate, which affects the volatilization and transport of essential oil vapors. By introducing compressed air at varying flow rates (1, 2, 3, 4, and 5 L/min), the interaction between steam and volatile components is enhanced, facilitating the release and condensation of essential oil vapors. Higher airflow rates are expected to increase the extraction efficiency by accelerating vapor transport. However, excessively high airflow may lead to the loss of lighter volatile compounds, potentially affecting the chemical composition and aroma profile of the essential oil.

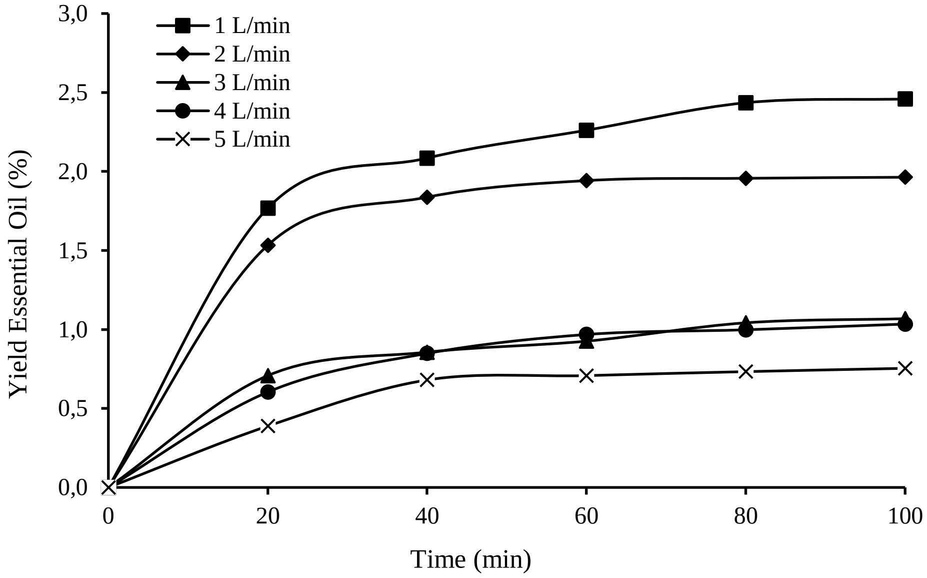

Figure 1. Effect of airflow rate on white pepper essential oil yield at power 450 W

Effect of Airflow Rate on Essential Oil Yield of White Pepper

The effect of varying airflow rates (1, 2, 3, 4, and 5 L/min) on the yield of white pepper essential oil was evaluated at 450 W microwave power, with an extraction time ranging from 0 to 100 minutes and data collection at 20-minute intervals. The results are illustrated in Figure 1. The yield and quality of white pepper essential oil extracted at different airflow rates were analysed to determine the optimal operating conditions for MAHD. The results indicated that airflow rates (1–2 L/min) provided the highest oil yield and retention of bioactive compounds, while higher airflow led to losses of volatile components. The chemical composition of the extracted oil was further evaluated based on density, solubility, and acid number, providing insights into the impact of airflow variation on essential oil characteristics. Therefore, the findings highlight the advantages of MAHD over conventional extraction techniques. The combination of microwave-induced rapid heating and controlled airflow significantly enhances extraction efficiency while minimizing thermal degradation of essential oil constituents. Further optimization of microwave power, extraction time, and airflow rate could refine this method for industrial-scale essential oil production, ensuring higher yields, lower energy consumption, and better retention of key bioactive compounds

Yield Trends and Comparison with Conventional Methods

As observed in Figure 1, the yield of white pepper essential oil increased significantly in the early phase of extraction and stabilized between 60 to 100 minutes, regardless of the airflow rate applied. This rapid initial increase indicates that microwave heating effectively accelerates the volatilization of essential oil compounds, leading to shorter extraction times compared to conventional hydrodistillation. In contrast, previous studies using traditional hydrodistillation (Li et al., 2020) required 5 hours to achieve a 2.25% essential oil yield, highlighting the efficiency of Microwave Air-Hydrodistillation (MAHD) in reducing extraction time while maintaining high oil recovery. Furthermore, the introduction of airflow during extraction was found to enhance the overall yield of white pepper essential oil. This is attributed to the fact that the injection of air helps to improve mass transfer, particularly in facilitating the release of essential oil components from plant cell structures. The increased turbulence caused by airflow optimizes the stirring effect, thereby enhancing diffusion of heavier fractions from the cell membrane and plant tissues into the extraction medium (Kusuma & Mahfud, 2017). Additionally, the stirring effect is directly linked to mass transfer in the solvent phase, promoting convection in the vapor-liquid equilibrium system, which results in faster attainment of phase equilibrium (Chemat et al., 2009).

Impact of Higher Airflow Rates on Essential Oil Yield

Despite the initial increase in essential oil yield with airflow variation, the overall yield trend at 100 minutes showed a decline with increasing airflow rate, as illustrated in Figure 2. The highest yield recorded in this study was 2.4590%, obtained at an airflow rate of 1 L/min with an extraction time of 100 minutes. The observed decline in yield at higher airflow rates is likely due to excessive evaporation of essential oil components, which may escape before complete condensation occurs. The rapid increase in vapor flow rate leads to insufficient condensation time, resulting in oil loss. Moreover, excessive airflow can cause a reduction in localized heating, as the cooling effect introduced by increased air velocity may lower the temperature of the extraction medium, reducing overall oil recovery. This suggests that while airflow is beneficial in enhancing mass transfer, excessive airflow disrupts the condensation efficiency, leading to yield losses.

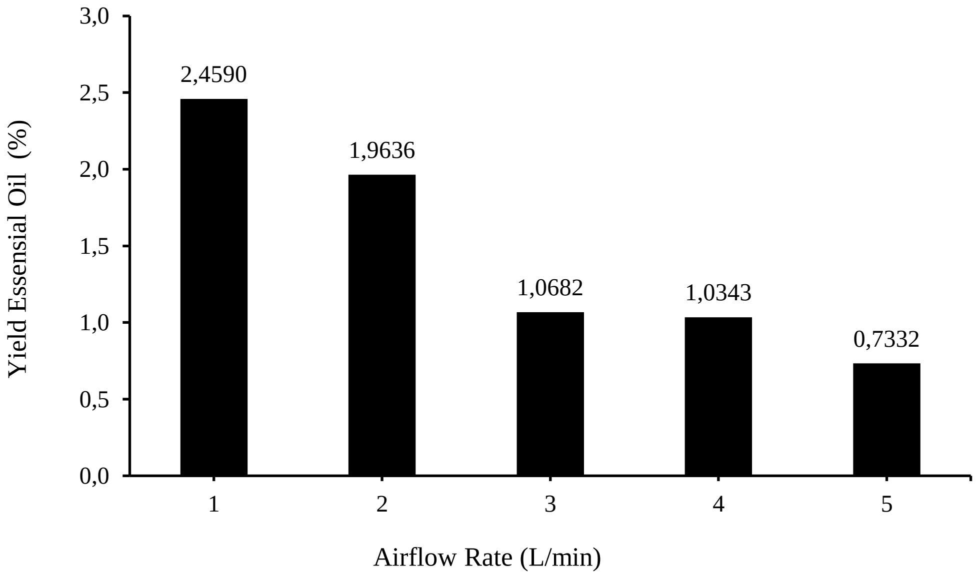

Figure 2. Effect of air flow rate on the yield of white pepper essential oil at 450 W with extraction time 100 minute

Comparison with Standardized Essential Oil Characteristics

The characteristics of the white pepper essential oil extracted under optimal conditions (1 L/min airflow, 100-minute extraction time, and 450 W microwave power) were analyzed and compared to the ISO 3061:2008 essential oil standards. The detailed comparison is presented in Table 1. The physicochemical properties, including density, solubility, and acid number, were evaluated to assess the quality and compliance of the extracted essential oil with international standards. Therefore, this study confirms that airflow rate plays a crucial role in optimizing white pepper essential oil extraction using MAHD. While moderate airflow improves mass transfer and yield, excessively high airflow can result in essential oil loss and reduced efficiency. Therefore, careful optimization of airflow rate is necessary to maximize oil recovery while preserving volatile bioactive compounds.

Table 1. The characteristics of white pepper essential oil obtained (450 W, 100 min, 1L/min)

	Parameter	ISO 3061:2008	Result
1	Colour	Colourless or light coloured (yellow, green, blue)	Blue
2	Density (g/mL)	0,861 – 0,885	0,8814
3	Miscibility with 95% (Volume fraction) ethanol	1 mL essential oil in 3 ml 95% ethanol	1 mL essential oil in 4-5 mL 95% ethanol
4	Acid Number (mg KOH/g)		1,2732

Based on the data presented in Table 1, the characteristics of white pepper essential oil extracted using the Microwave Air-Hydrodistillation (MAHD) method at 450 W power, 100 minutes extraction time, and 1 L/min airflow rate were analyzed and compared to the ISO 3061:2008 standard. The analysis confirms that the extracted oil meets the standard criteria in terms of color, density, and general quality parameters, with a slight deviation in miscibility with ethanol.

In terms of color, the ISO 3061:2008 standard specifies that white pepper essential oil should be colorless or light-colored, with possible shades of yellow, green, or blue. The result obtained in this study was blue, which is within the acceptable range. The color variation is often influenced by the presence of specific volatile compounds and pigments, and the blue hue suggests a higher concentration of sesquiterpenes or other bioactive compounds that contribute to the oil's unique properties.

The density of the extracted oil was measured at 0.8814 g/mL, which falls within the standard range of 0.861 – 0.885 g/mL. This indicates that the extracted oil has a composition consistent with high-quality essential oil, confirming effective extraction without significant thermal degradation. Density is a crucial parameter in evaluating purity, consistency, and volatility, and the result suggests that the MAHD method successfully preserves the integrity of the extracted essential oil.

For the miscibility test with 95% ethanol, the standard specifies that 1 mL of essential oil should be miscible in 3 mL of 95% ethanol. However, in this study, 1 mL of essential oil required 4-5 mL of ethanol for complete solubility, indicating a slight deviation from the standard. This could suggest a higher concentration of less-polar compounds or the retention of heavier molecular weight fractions that affect ethanol solubility. While this does not necessarily indicate poor quality, it suggests differences in chemical composition compared to conventionally distilled essential oil.

The acid number of the extracted essential oil was recorded at 1.2732 mg KOH/g. Although ISO 3061:2008 does not specify a strict limit for acid number, this value serves as an indicator of free fatty acid content and oxidation stability. A moderate acid number suggests that the extracted oil is chemically stable and has undergone minimal degradation during the extraction process. A higher acid value could indicate oxidation or hydrolysis, but the result obtained in this study confirms that the MAHD method effectively preserves the quality and stability of the essential oil.

Hence, the white pepper essential oil extracted using the MAHD method aligns well with the ISO 3061:2008 standard, particularly in terms of color, density, and overall composition. The only minor deviation observed was in the miscibility test, which may indicate slight differences in chemical composition due to the unique extraction conditions. The results confirm that MAHD is an efficient extraction method, offering shorter processing times, improved energy efficiency, and minimal thermal degradation compared to conventional methods. Future optimization of airflow rate and ethanol miscibility could further enhance oil purity and ensure even closer compliance with industry standards.

CONCLUSION

This study investigated the effect of airflow rate on the extraction of white pepper (Piper nigrum L.) essential oil using the Microwave Air-Hydrodistillation (MAHD) method. The results demonstrated that airflow rate significantly influences essential oil yield, with moderate airflow rates (1–3 L/min) enhancing oil recovery, while excessive airflow (>3 L/min) led to a decline in yield due to increased evaporation and reduced condensation efficiency. The highest yield (2.4590%) was obtained at an airflow rate of 1 L/min with an extraction time of 100 minutes and 450 W microwave power, confirming that optimized airflow improves mass transfer and accelerates oil release from plant tissues.The extracted essential oil was analyzed and compared to the ISO 3061:2008 standard, revealing that the color, density, and acid number met the required specifications. The oil exhibited a blue coloration, which aligns with the acceptable range in the standard and indicates the presence of valuable volatile compounds. The density (0.8814 g/mL) was within the ISO range (0.861–0.885 g/mL), confirming the integrity of the extracted oil. However, a slight deviation was observed in miscibility with ethanol, as 1 mL of essential oil required 4–5 mL of ethanol instead of the standard 3 mL. This suggests possible differences in chemical composition, potentially due to the retention of heavier or less-polar compounds during extraction. Overall, the MAHD method proved to be an efficient alternative to conventional hydrodistillation, offering shorter extraction times, improved energy efficiency, and better preservation of thermosensitive compounds. The study confirms that controlled airflow enhances extraction performance but requires optimization to balance yield, condensation efficiency, and volatile compound retention. Future research could focus on refining extraction conditions to further improve essential oil quality and ensure maximum compliance with industry standards for broader commercial applications.

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