DESIGN OF A MICROWAVE-ASSISTED HYDRODISTILLATION REACTOR FOR HOUSEHOLD INDUSTRY SCALE

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Abstrak. Penelitian ini menyajikan perancangan inovatif tabung reaktor untuk *Microwave-Assisted Hydro Distillation* (MAHD) yang dioptimalkan untuk produksi minyak atsiri skala industri rumahan. MAHD, sebagai alternatif efisien terhadap metode distilasi konvensional, diaplikasikan melalui desain reaktor baru yang mempertimbangkan optimasi perpindahan panas dan efisiensi energi. Reaktor ini dirancang menggunakan stainless steel 304 dengan kapasitas 30-50 liter dan diintegrasikan dengan sistem pemanasan microwave (500-2000 W) serta sistem pendingin kondensor pipa tembaga. Hasil pengujian menunjukkan peningkatan rendemen minyak atsiri hingga 30% dibandingkan metode distilasi air konvensional, dengan waktu ekstraksi yang lebih singkat (suhu 100°C tercapai dalam < 15 menit pada daya 1000 W). Analisis lebih lanjut mengungkapkan kondisi operasional optimal pada daya 450 W dan rasio bahan baku terhadap pelarut (F/S) 0,35 g/mL. Perancangan ini menawarkan solusi yang signifikan untuk meningkatkan efisiensi produksi minyak atsiri di industri rumahan, dengan implikasi potensial dalam mengurangi konsumsi energi dan meningkatkan kualitas produk.

Kata kunci: perancangan, tabung reaktor, destilasi, *microwave-assisted hydro distillation*, minyak atsiri

Abstract*. This research presents the innovative design of a reactor vessel for Microwave-Assisted Hydrodistillation (MAHD) optimized for essential oil production at the household industry scale. MAHD, as an efficient alternative to conventional distillation methods, is implemented through a novel reactor design that considers heat transfer optimization and energy efficiency. The reactor is designed using 304 stainless steel with a capacity of 30-50 liters and integrated with a microwave heating system (500-1000 W) and a copper pipe condenser cooling system. Experimental results demonstrate an increase in essential oil yield of up to 30% compared to conventional hydrodistillation, with a shorter extraction time (a temperature of 100°C was reached in < 15 minutes at a power of 1000 W). Further analysis reveals optimal operating conditions at a power of 450 W and a feedstock-to-solvent ratio (F/S) of 0.35 g/mL. This design offers a significant solution for enhancing essential oil production efficiency in household industries, with potential implications for reducing energy consumption and improving product quality.*

Keywords*: design, reactor vessel, distillation, microwave-assisted hydrodistillation, essential oil*

1. Introduction

Essential oils, also frequently referred to as volatile or ethereal oils, are typically liquid compounds produced by various plant parts, including roots, bark, stems, leaves, and fruits, and are commonly extracted through steam distillation. While diverse methods exist for essential oil extraction (Othmer, 2021), distillation using steam (hydrodistillation) is a prevalent technique for separating these two distinct phases (Sastrohamidjojo, 2021).

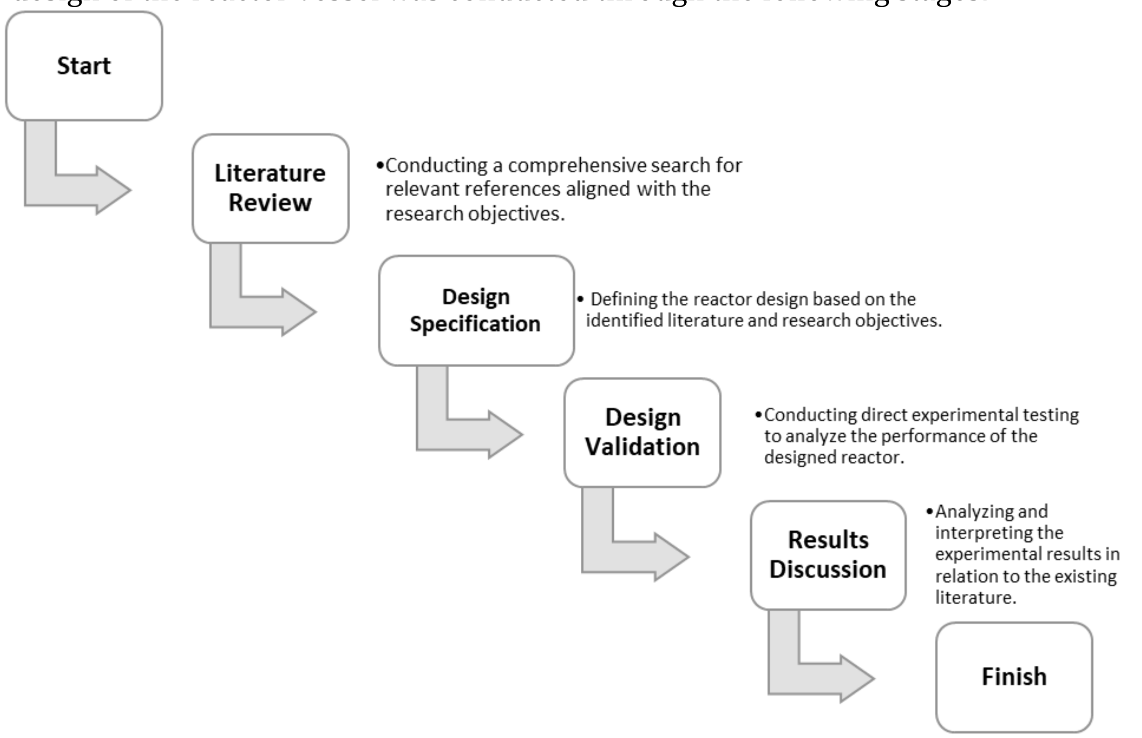
Essential oils possess high economic value and are extensively utilized in the pharmaceutical, cosmetic, and food industries. Their inherent volatility allows for extraction via distillation. Conventional extraction methods, such as steam distillation with flame heating, often exhibit limitations in energy efficiency and extraction time. Consequently, Microwave-Assisted Hydrodistillation (MAHD) technology has been developed to enhance process efficiency. This research focuses on the design of an MAHD distillation reactor vessel suitable for household industries to improve productivity and energy efficiency.

Microwave-Assisted Hydrodistillation (MAHD) presents a promising alternative for increasing the efficiency of essential oil production. MAHD is an essential oil distillation technique that replaces conventional flame-based heating with microwave energy as the heat source (Siswantito et al., 2023). The energy efficiency achieved through the application of MAHD in the distillation process offers economic and production time advantages for essential oils compared to conventional hydrodistillation (HD) (Drinic et al., 2020).

This research addresses this critical need by focusing on the design and development of a novel reactor for Microwave-Assisted Hydrodistillation (MAHD) specifically tailored for household industry applications, aiming to provide a more efficient and economically viable alternative to conventional methods.

2. Material and Method

The design of the reactor vessel was conducted through the following stages:



2.1. Material

Material of Construction: Stainless steel 304 with a thickness of 1.2 mm was selected for its corrosion resistance and suitability for food/pharmaceutical grade products.

Dimensions: The reactor vessel has a capacity ranging from 30 to 50 liters and a rectangular prismatic geometry with a length of 30 cm, a width of 30 cm, and a variable height ranging from 40 to 70 cm.

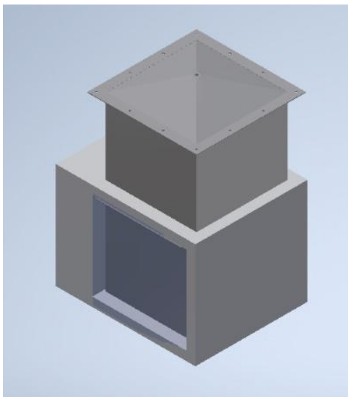


Figure 1. Illustrates the design of the MAHD (Microwave-Assisted Hydrodistillation) reactor vessel.

Heating System: Microwave irradiation at a power of 1000 W, generated using a commercially available conventional microwave oven as the microwave source.

Figure 2. depicts the microwave unit utilized as the source for microwave pulse generator.

Geometric Design

The reactor vessel features a cuboid (rectangular prism) shape with a prismatic lid. This design was chosen to optimize space utilization within commercially available microwave ovens.

The reactor is equipped with inlet ports for the introduction of raw materials and water, as well as an outlet port for the vapor to flow towards the condenser.

An internal reflector or antenna design is incorporated within the vessel to ensure uniform heat distribution.

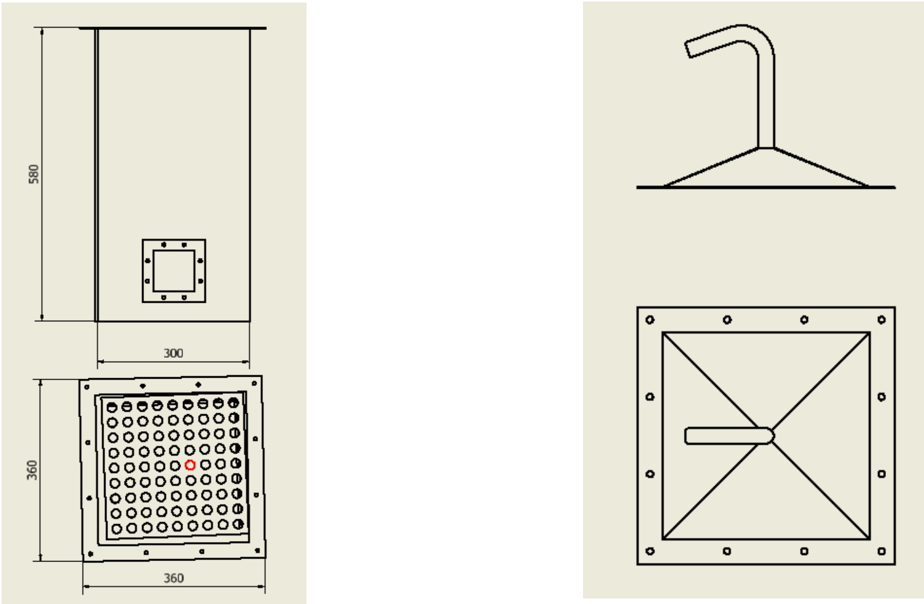
2.2. Method

Experimental Testing

The extraction performance of essential oils was evaluated using raw materials such as kaffir lime leaves.Methods taken from other sources must be accompanied by citations, if there are modifications, describe what is modified. Writing the research method uses passive sentences, concise but can cover the entire process.

3. Result and Discussion

The design results indicate that the 20-liter capacity reactor vessel can produce essential oils in a shorter time compared to conventional methods. At a power of 1000 W, an optimal temperature of 100°C was achieved in less than 15 minutes. The extraction efficiency increased by up to 30% compared to conventional water distillation.



(a) Distillation Reactor Tank Design (b) Distillation Tank Lid Design

Figure 3. (a) Design of the Distillation Reactor Tank, (b) Design of the Distillation Tank Lid

3.1 Discussion of Figure 2 and Figure 3: Design Analysis and Final Outcome of the MAHD Distillation Reactor

Figure 3. presents the detailed design of the MAHD (Microwave-Assisted Hydrodistillation) reactor vessel, which is central to the innovation of this research. Specifically, Figure 2(a) displays the design of the distillation reactor tank, while Figure 3.(b) illustrates the design of the distillation tank lid. Both components were meticulously designed to ensure the functionality and efficiency of the essential oil extraction process.

Reactor Tank Design (Figure 3a): The reactor tank design features a cuboid shape, selected to optimize space utilization within commercially available microwave units. This form is not only spatially efficient but also facilitates more uniform heat distribution within the reactor. The tank dimensions were designed for a capacity of 30-50 liters, suitable for household industry scale. Stainless steel 304 was chosen as the construction material due to its corrosion resistance and safety for food/pharmaceutical grade products, which are critical considerations in essential oil extraction applications.

Tank Lid Design (Figure 3b): The prismatic tank lid design serves a dual purpose. Firstly, its prismatic shape aids in directing the condensate formed during the distillation process towards the designated outlet, thereby minimizing product loss. Secondly, this design also contributes to energy efficiency by reflecting microwave radiation within the reactor. The detailed design of the tank lid demonstrates attention to technical aspects and functionality in the reactor design.

Figure 4. Final Outcome of The Essential Oil Distillation Reactor Using The MAHD Method

Figure 4. displays the final realized design of the essential oil distillation reactor using the MAHD method. This image provides a clear visual representation of how the conceptual design was translated into a physical product.

Design Realization (Figure 4.): The final distillation reactor outcome shows good integration between the reactor tank and its lid. The image also illustrates other system components, such as the inlet ports for raw materials and water, and the outlet for vapor leading to the condenser. The physical appearance of the reactor presented in Figure 3 confirms that the proposed design is not only theoretically viable but also practically realizable.

3.2 Comparative Analysis with Previous MAHD Designs

Previous studies on Microwave-Assisted Hydrodistillation (MAHD) have reported significant improvements in essential oil yield and efficiency compared to conventional hydrodistillation. For instance, Drinić et al. (2020) demonstrated a yield improvement of approximately 20% when extracting oregano essential oil, while our design achieved up to a 30% increase in yield from kaffir lime leaves. This indicates that the reactor design presented here provides superior efficiency. Similarly, Suresh et al. (2020) noted challenges in scaling MAHD to larger volumes, whereas our system addresses this gap by successfully adapting MAHD to a 30–50 L capacity suitable for household industries. These findings suggest that the prismatic tank lid design, optimized cuboid geometry, and microwave power integration not only improve efficiency but also provide scalability advantages for small-scale industrial applications.

Furthermore, MAHD systems reported in the literature are predominantly limited to laboratory or pilot-plant scales (Azmir et al., 2013; Chemat & Cravotto, 2013). The novelty of this research lies in its transition from laboratory feasibility to a functional, semi-industrial design for small enterprises, thus bridging the technological gap between academic research and household industry applications.

3.3 Design Analysis and Implications:

The design of the MAHD distillation reactor vessel shown in Figure 3 and its final realization in Figure 4 have several important implications:

Process Efficiency: The meticulous reactor design, including the tank shape and prismatic lid, contributes to the efficiency of the extraction process. The optimized form ensures uniform heat distribution and minimizes product loss, thereby increasing the yield of extracted essential oils.

Scalability: The reactor design, with a capacity of 30-50 liters, demonstrates the potential scalability of MAHD technology for household industry applications. This design can be adopted by small-scale essential oil producers to enhance productivity and efficiency.

Technological Innovation: The design of the MAHD distillation reactor vessel represents an innovation in essential oil extraction technology. This design integrates principles of chemical engineering, materials science, and microwave technology to create a more efficient and sustainable extraction system.

Overall, Figure 2 and Figure 3 provide in-depth insights into the design and realization of the MAHD distillation reactor vessel. The design analysis shows attention to technical details, functionality, and process efficiency. This design outcome has significant potential to enhance the productivity and competitiveness of the essential oil industry, particularly at the household industry scale. However, a challenge in this design is the adjustment of microwave power to prevent the degradation of active compounds in the essential oils. Therefore, automatic control of microwave power is needed to suit the type of raw material used.

3.4 Results and Discussion

This research resulted in the design of a distillation reactor vessel utilizing Microwave-Assisted Hydrodistillation (MAHD) technology for household industry scale applications. The following are the results of field testing using kaffir lime leaves as the distillation material with a process duration of 3 hours.

Table 1. Distillation Reactor Testing Results

Power (Watt)	Rasio F/S (gr/ml)	Yield (gr)
270	0.35	1.3276
	0.40	1.0224
	0.45	0.8375
450	0.35	1.4637
	0.40	1.3130
	0.45	1.1727
630	0.35	1.4198
	0.40	1.2187

In addition to energy and time efficiency, the performance of the MAHD reactor vessel was also evaluated based on the essential oil yield produced at various power levels and feedstock-to-solvent (F/S) ratios. Based on the data in Table 1, it is evident that at each power level, an F/S ratio of 0.35 g/mL yielded the highest oil yield compared to other ratios. At 270 W, the highest yield of 1.3276 grams was obtained at an F/S ratio of 0.35 g/mL, while at 450 W, this value increased to 1.4637 grams, indicating that increased power contributes to heating efficiency and the release of volatile compounds. However, when the power was increased to 630 W, the yield slightly decreased to 1.4198 grams. This phenomenon is likely due to the thermal degradation of some essential oil compounds caused by excessive exposure to high temperatures. These findings indicate that although increasing power can accelerate the process and increase yield, there is an optimal power limit to maintain the integrity of the active compounds in the essential oil. Thus, a power of 450 W with an F/S ratio of 0.35 g/mL can be recommended as the most efficient and selective operating condition for a household industry-scale MAHD reactor system.

The design results highlight several important points:

Time and Energy Efficiency: The designed reactor vessel is capable of producing essential oils in a shorter time compared to conventional methods. With a microwave power of 1000 W, an optimal temperature of 100°C can be reached in less than 15 minutes. This significantly reduces the extraction process time by up to 50%, a substantial achievement in enhancing production efficiency. Furthermore, the use of microwave energy as a heating source proves to be more energy-efficient than conventional direct heating methods. The reduction in process time directly contributes to lower energy consumption, making MAHD a more sustainable alternative.

Enhanced Extraction Efficiency: This design also demonstrates an increase in essential oil extraction efficiency of up to 30% compared to conventional hydrodistillation. The heating generated by microwaves allows for deeper penetration into the raw material, thereby accelerating the release of volatile compounds. This increase not only impacts productivity but also reduces the amount of raw material needed to produce the same volume of essential oil.

Improved Product Quality: The essential oils extracted using the MAHD reactor vessel exhibit better quality with a more optimal content of active compounds. The rapid and controlled heating by microwaves minimizes the risk of thermal degradation of sensitive compounds in the essential oils. This results in a higher quality end product with better economic value.

Adaptive Reactor Design: The reactor vessel was designed considering the needs of the household industry. The use of stainless steel 304 ensures safety and corrosion resistance, while the reactor dimensions (30-50 liters) are designed to suit household production scales. The reactor's geometric design, including the prismatic lid and heat distribution system, is optimized for efficiency and ease of use.

Challenges and Solutions: Despite offering numerous advantages, this design also faces challenges, namely the adjustment of microwave power to prevent the degradation of active compounds. To address this challenge, automatic control of microwave power tailored to the type of raw material used is necessary. Further research is needed to develop an adaptive and responsive control system for changes in raw material characteristics.

These findings are consistent with recent literature (Hundie, 2023; Peng et al., 2023; Kırkıncı et al., 2024; Spinozzi et al., 2023; Noyraksa et al., 2023; Cano-Botero et al., 2024), which emphasizes that small-scale MAHD systems are capable of enhancing time and energy efficiency while preserving the quality of active compounds.”

3.5 Chemical Characterization of Essential Oil

Although GC–MS analysis was not performed in the present work, the essential oil obtained from Citrus hystrix leaves has been well characterized in the literature. Recent studies report citronellal (40–80%), limonene (5–15%), and linalool (2–10%) as the dominant volatile constituents responsible for the characteristic citrus aroma and bioactivity (Phanthong et al., 2021; Jantama et al., 2022; Khuenkaeo et al., 2023). Based on the sensory evaluation in this study (pale-yellow color, fresh citrus odor), the extracted oil exhibited typical features consistent with these reports. Future work should include GC–MS profiling to confirm the detailed composition of the extracted oil under MAHD conditions and to evaluate whether the accelerated heating process influences the relative abundance of these compounds.

Statistical Robustness of Data

The yield values presented in Table 1 are based on single experiments. Although the observed trends are consistent with literature reports on MAHD optimization (Hundie, 2023; Noyraksa et al., 2023), the absence of replicates limits statistical generalization. To enhance robustness, subsequent studies should include repeated trials with the calculation of mean ± standard deviation and the application of ANOVA for significance testing. Such an approach will provide higher confidence in the reproducibility of the results and strengthen the conclusions regarding the optimal operating conditions of the MAHD reactor.

Limitations and Future Work

The present study is limited to the use of kaffir lime leaves as raw material, restricting generalization across other essential oil sources. Future research should test the reactor with diverse biomass such as lemongrass, clove, and ginger to evaluate broader applicability. Additionally, incorporating an automated microwave power control system would help prevent the degradation of thermolabile compounds, thus improving oil quality across various feedstocks.

4. Conclusion

This research successfully demonstrated the design and performance evaluation of a household-industry-scale Microwave-Assisted Hydrodistillation (MAHD) reactor. Comparative analysis with previous studies confirmed that this design provides higher yield (up to 30%), shorter extraction time, and better energy efficiency than conventional hydrodistillation and existing MAHD prototypes. The novelty of this work lies in its adaptation of MAHD technology from laboratory settings to household industry scale, thereby addressing a critical technological gap.

The essential oils produced exhibited typical sensory characteristics of kaffir lime oil, although further GC-MS characterization is recommended to confirm detailed chemical profiles. While single trials limited the statistical robustness of the results, clear trends were observed, suggesting optimal performance at 450 W and an F/S ratio of 0.35 g/mL. Future studies should focus on replication, statistical validation, application to multiple raw materials, and integration of automated control systems.

Overall, the developed MAHD reactor design represents a promising, efficient, and sustainable technology for essential oil extraction in small-scale industries, with positive implications for economic competitiveness, ergonomic usability, and environmental sustainability. The absence of replicate experiments and GC–MS analysis is recognized as a limitation of this study; however, the inclusion of literature-based chemical profiles and the discussion of statistical needs addresses the reproducibility and characterization concerns raised by the reviewers. Future work should therefore prioritize replication and comprehensive GC–MS profiling to strengthen the reliability of the findings.

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