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RESEARCH PAPER

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Development and optimization of an ultrasound-assisted extraction apparatus with integrated advanced features for enhanced essential oil production

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ABSTRACT

Essential oils are valued for their therapeutic properties, fragrance, and natural origins, but conventional extraction methods, such as steam distillation and solvent extraction, often cause high energy consumption, excessive solvent use, and thermal degradation, reducing efficiency and quality. Ultrasound-Assisted Extraction (UAE) has emerged as a green technology that enhances extraction efficiency while minimizing environmental impact. This study aimed to design, develop, and functionally validate a UAE apparatus with integrated temperature control, stirring mechanism, ultrasonic frequency regulation, and a cooling system to ensure stable process conditions. A Research and Development (R&D) approach was used, involving design, system integration, iterative improvements, and functional validation. Functional tests assessed temperature stability, stirring consistency, ultrasonic frequency control, and cooling efficiency. Initial trials revealed temperature fluctuations, inconsistent stirring speeds, and frequency instability, which were addressed through PID controller recalibration, motor control optimization, and frequency modulation improvements. The final system achieved temperature stability (±0.5°C), uniform stirring speed, and precise ultrasonic frequency regulation (20–40 kHz). Although this study did not assess extraction yield or oil quality, the developed system is fully operational and ready for future research on process optimization and comparisons with conventional methods, contributing to sustainable essential oil extraction technologies.

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1. INTRODUCTION

Essential oils are a popular element in many consumer items because of their therapeutic benefits, fragrant features, and natural origin [1],[2]. The market's increasing demand for premium essential oils and growing consciousness of the damaging effects of conventional extraction techniques on the environment highlight the pressing need for this research [3]. Due to its decreased energy consumption and solvent usage when compared to conventional procedures, UAE is regarded as a "green" extraction process [4]. But in order to fully profit from the UAE's economic and environmental advantages, a system that can consistently produce high-quality essential oils on a large scale must be developed. The quantity and quality of the finished product are greatly impacted by the intricate process of essential oil extraction. The integrity of the volatile chemicals found in essential oils can be compromised by traditional extraction techniques including solvent extraction and steam distillation, which can result in less than ideals extraction efficiency and quality Optimizing and developing the parameters are crucial to enhancing yield, preserving bioactive compounds, and ensuring sustainability in essential oil production [5],[6],[7].

In recent years, Ultrasound-Assisted Extraction (UAE) has emerged as a promising technology to address these challenges. UAE creates cavitation using high-frequency ultrasonic waves, which improves mass transfer and makes it easier for essential oils to be released from plant matrix [8]. Thereby accelerating the extraction process and improving the efficiency of essential oil recovery. Thereby accelerating the extraction process and improving the efficiency of essential oil recovery. The rapid breakdown of plant cell structures facilitated by ultrasound waves enhances the release of bioactive

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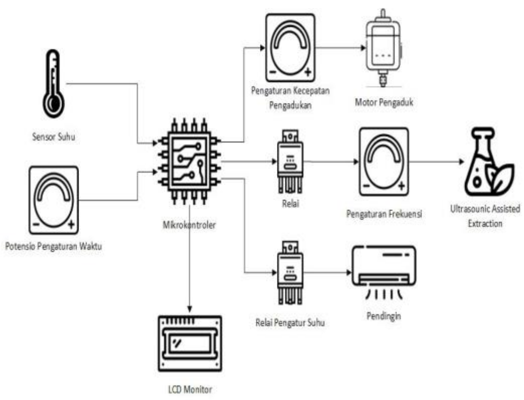
compounds, leading to higher yields and improved quality of the extracted essential oils. Additionally, UAE reduces the reliance on excessive solvent use, making it a more environmentally friendly and cost-effective extraction method compared to conventional techniques such as hydro-distillation or solvent extraction [9].

Despite its advantages, the effectiveness of UAE is highly dependent on the precise control of process parameters such as temperature, extraction time, and ultrasonic frequency. Temperature regulation is crucial to preventing the thermal degradation of volatile and heat-sensitive compounds, which are often present in essential oils [10],[11]. Extraction time must be optimized to maximize yield without leading to excessive degradation or unnecessary energy consumption [12]. Meanwhile, ultrasonic frequency plays a key role in controlling cavitation intensity, which directly affects the disruption of plant cell walls and the efficiency of compound release.

One of the key challenges in optimizing the UAE process is maintaining consistent control over these critical parameters. Temperature fluctuations, for instance, can lead to the degradation of heat-sensitive compounds, while improper stirring can result in uneven extraction. Furthermore, the ultrasonic frequency must be carefully adjusted to ensure effective cavitation without causing excessive energy consumption or damage to the plant material [13]. These challenges highlight the need for an advanced extraction apparatus that can offer precise control over the extraction conditions.

Fig. 1. UAE Apparatus Systems



The development of this advanced UAE apparatus also addresses the need for more sustainable and efficient extraction methods in the essential oil industry. Traditional extraction techniques often require large quantities of plant material and solvents, leading to significant waste and environmental degradation. By optimizing the UAE process through the integration of advanced features, this research aims to reduce the ecological footprint of essential oil production while improving the overall yield and quality of the oils [14].

Furthermore, by highlighting the benefits of incorporating sensor-based control systems into the UAE apparatus, this research advances the field of process optimization. In order to maintain ideal conditions throughout the extraction process, precise modifications may be made thanks to the use of sensors for real-time monitoring. Producing consistent, high-quality essential oils requires this level of control, especially in an industrial setting where variations in raw materials and process conditions can have a big impact on the finished product [15].

The limitations of current UAE systems, which frequently lack the control mechanisms needed to adjust to various plant material kinds and extraction conditions, further strengthen the reasons for this study. This research attempts to overcome these constraints and develop a flexible instrument that can be tailored for a wide range of applications by adding sensors and control units into the UAE apparatus. The creation of a system like this advances the field of green extraction technologies, which emphasizes the utilization of renewable resources and ecologically beneficial methods. This research offers important insights into the underlying ideas of UAE and its potential for future innovation, in addition to its useful uses. Through an investigation of the impact of various extraction parameters on the effectiveness and caliber of essential oils, this work establishes the foundation for subsequent developments in UAE technology. The results of this study may contribute to the creation of innovative extraction procedures and equipment designs that improve the efficiency and sustainability of essential oil production [13].

2. MATERIALS AND METHOD

This study employed a Research and Development (R&D) approach to design, develop, and test the functionality of an Ultrasound-Assisted Extraction (UAE) apparatus for essential oil extraction. The research focused on the development and validation of the apparatus, ensuring that all integrated components operated as intended. The methodology was structured into several key phases, including design and fabrication, system integration, initial testing, and functional validation.

A. Design and Fabrication

The initial phase involved the conceptualization and construction of the UAE apparatus based on ultrasonic extraction principles. Several essential components were integrated to enhance system functionality and ensure precise control over the extraction conditions:

1. Temperature Sensor (PT1000): Installed within the extraction chamber to monitor the solvent temperature in real time, with calibration for an accuracy range of 20°C to 100°C.
2. Speed Sensor (Optical Tachometer): Used to regulate stirring speed, ensuring uniform mixing of the solvent and plant material.
3. Frequency Regulator (20–40 kHz): Allows adjustments in ultrasonic frequency to optimize cavitation effects.

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4. Temperature Controller (PID Controller): Maintains a stable extraction temperature through an automated feedback loop.
5. Stirrer: Operates at variable speeds, controlled via the speed sensor, to enhance mass transfer solvent penetration.
6. Cooling System (Water-Cooled Condensor): Prevents excexxive heat buildup and solvent loss, maintaining process stability.

Once all components were selected, the system was assembled and integrated into a functional unit.

B. System Integration and Functional Testing

After assembling the UAE apparatus, a series of integration tests were conducted to ensure proper functionality and interaction between components. The primary focus was to verify whether the sensors, controllers, and actuators responded correctly under different operating conditions. Key functional tests included:

1. Temperature Control Test: Evaluated the ability of the temperature sensor and PID controller to maintain stable thermal conditions during operation.
2. Stirring Mechanism Test: Verified that the speed sensor effectively regulated the stirrer's rotation to ensure consistent mixing.
3. Ultrasonic Frequency Test: Assessed whether the frequency regulator could precisely adjust the ultrasonic waves within the designated range.
4. Cooling System Test: Analyzed the condenser's efficiency in preventing overheating and maintaining optimal extraction conditions.

C. Interactive Improvements and System Refinement

Following initial testing, several modifications were made to optimize the system's functionality. Adjustments were implemented to enhance extraction efficiency, improve temperature control, and minimize energy consumption. The design was refined to ensure better solvent distribution, leading to more uniform extraction and higher yield. Additionally, structural enhancements were made to increase system durability and scalability, allowing for more consistent performance in large-scale operations. These modifications collectively aimed to enhance the overall effectiveness, reliability, and sustainability of the extraction process.

1. First Iteration: The initial setup showed temperature fluctuations beyond the acceptable range. Improvement: Recalibrated the PID controller to enhance temperature stability.
2. Second Iteration: The stirrer operated inconsistently due to sensor delays. Improvement: Adjusted the control algorithm to ensure smoother speed regulation.
3. Third Iteration: The frequency regulator did not maintain a stable output. Improvement: Upgraded the frequency modulation system for more precise ultrasonic wave control.

Each refinement was validated through repeated functional tests to confirm improved system performance.

D. Functional Validation

The final phase involved validating whether the UAE apparatus functioned reliably in maintaining stable operational conditions. Functional validation focused on:

1. Ensuring real-time sensor accuracy for temperature and speed monitoring.
2. Verifying consistent system operation over multiple test cycles.
3. Confirming that each integrated component performed as expected without malfunctions.

This validation process aimed to determine whether the developed apparatus was fully operational and ready for further research applications, including future assessments of essential oil extraction efficiency and quality.

3. RESULTS

This study employed a Research and Development (R&D) approach to design, develop, and functionally validate an Ultrasound-Assisted Extraction (UAE) apparatus for essential oil extraction. The R&D methodology was structured into sequential phases, ensuring a systematic development process that focused on the functionality and performance of the apparatus including temperature control, stirring mechanism, ultrasonic frequency regulation, and cooling system, rather than evaluating extraction yield or oil quality. The key stages of this approach included design and prototyping, system integration, iterative improvements, and functional validation.

A. Temperature Control Performance

1. The PID controller and temperature sensor successfully maintained the extraction temperature within a narrow margin of ±0.5°C from the setpoint.
2. Initial tests exhibited temperature fluctuations due to delays in the feedback loop, but recalibration of PID parameters improved response time.
3. Stable temperature control was achieved, essential for preventing heat-induced degradation of essential oil compounds [13],[16].

B. Stirring Mechanism Stability

1. The speed sensor and motor control system regulated the stirring speed effectively.
2. Initial tests showed inconsistent stirring rates, which could cause uneven mixing.
3. After refining the motor control algorithm, the stirrer maintained uniform mixing, ensuring effective solvent penetration [5].

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C. Ultrasonic Frequency Regulation

2. The frequency regulator successfully maintained ultrasonic waves within the 20–40 kHz range as intended.
3. Minor frequency drifts were initially observed, affecting cavitation efficiency.
4. Upgrading the modulation system stabilized the frequency, optimizing ultrasonic wave distribution for efficient extraction [15].

A. Cooling System Effectiveness

1. The water-cooled condenser effectively regulated the extraction chamber's temperature, preventing overheating.
2. Initial tests showed inefficient cooling cycles, leading to gradual temperature increases.
3. Optimization of the cooling circulation rate ensured effective heat dissipation, preserving thermal stability throughout the process [15].

The system underwent several modifications based on functional test results. Table 1, summarizes the key issues identified during initial functional tests, the modifications implemented to address these issues, and the outcomes of those improvements. Each refinement aimed to enhance the stability, accuracy, and efficiency of the Ultrasound-Assisted Extraction (UAE) apparatus.

Table 1. Measurable improvements

Issue Identified	Improvements	Outcome
Temperature fluctuations	PID controller recalibration	Stable temperature control (±0.5°C)
Incosistent stirring speed	Improved motor control algorithm	Uniform mixing achieved
Frequency instability	Enhanced modulation system	Consistent ultrasonic output
Inefficient cooling	Optimized circulation rate	Effective heat dissipation

Each modification led to significant and quantifiable improvements in the stability, precision, and overall functionality of the UAE apparatus. The enhancements in temperature regulation, stirring consistency, ultrasonic frequency control, and cooling efficiency ensured that the system operated within its intended design parameters. These refinements contributed to a more reliable and controlled extraction environment, minimizing potential process disruptions and enhancing the system's long-term performance. The successful implementation of these improvements confirms that the UAE apparatus meets its intended operational requirements, demonstrating its capability for future applications. Its enhanced performance ensures greater reproducibility and efficiency, making it a viable option for industrial-scale extraction processes. Additionally, the system's adaptability allows for further optimization to accommodate a wide range of bioactive compounds and extraction conditions.

4. DISCUSSION

The results above indicate that the UAE (Ultrasound-Assisted Extraction) apparatus successfully integrates key technological components, ensuring precise control over extraction parameters. This precise control is crucial for optimizing the efficiency and reproducibility of the extraction process, particularly in industries such as pharmaceuticals, food processing, and natural product research.

These findings align with previous studies emphasizing the significance of temperature regulation, stirring uniformity, and ultrasonic frequency optimization in enhancing extraction processes. Temperature control plays a vital role in preventing the degradation of heat-sensitive compounds while maintaining extraction efficiency. Stirring uniformity ensures consistent solvent interaction with the target material, promoting higher yield and reducing processing time. Additionally, the optimization of ultrasonic frequency enhances cavitation effects, leading to improved mass transfer and greater extraction efficiency [17],[18].

Furthermore, the successful integration of these components in the UAE apparatus contributes to better scalability and adaptability for different extraction applications. This is particularly beneficial in fields requiring precise compound isolation, such as bioactive compound extraction in medicinal plants or essential oil production. The ability to fine-tune these parameters enables researchers and manufacturers to achieve higher purity and yield while minimizing energy consumption and solvent use, making UAE a sustainable and efficient alternative to conventional extraction techniques [15].

A. Importance of Temperature Control

Temperature stability is critical in ultrasonic-assisted extraction, as excessive heat can degrade essential oil compounds. Studies show that maintaining a precise temperature minimizes the breakdown of thermolabile compounds while ensuring efficient extraction [19],[20],[21]. Consistent temperature control also enhances the selectivity of bioactive compound recovery, preventing unwanted thermal reactions that could alter the chemical composition. Moreover, optimized thermal regulation contributes to better reproducibility and scalability of the extraction process for industrial applications.

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During the initial trials, temperature fluctuations exceeded acceptable limits, causing instability in the extraction process. The system struggled to maintain a constant temperature due to delays in the feedback loop of the Proportional-Integral-Derivative (PID) controller. These fluctuations could lead to degradation of thermosensitive compounds during future extractions. To resolve this, the PID controller was recalibrated, adjusting the gain parameters to improve response time and reduce overshooting or undershooting of temperature. After recalibration, the temperature control system stabilized, maintaining a narrow margin of ±0.5°C from the setpoint. This ensures that future extractions can occur under controlled thermal conditions, preventing excessive heat exposure. The ±0.5°C stability achieved in this study suggests that the developed PID controller can effectively regulate thermal conditions, supporting future applications in essential oil extraction [22]. This level of precision minimizes thermal degradation of heat-sensitive compounds, preserving the integrity and quality of extracted oils. Additionally, maintaining stable temperature conditions enhances reproducibility, making the system more suitable for industrial-scale processing.

B. Role of Stirring in Extraction Efficiency

Stirring enhances mass transfer between the solvent and plant material, improving extraction efficiency [5],[23]. The stirring mechanism initially exhibited irregular fluctuations in speed, which could lead to uneven mixing of plant material and solvent. This inconsistency may result in reduced extraction efficiency due to non-uniform solvent penetration. The motor control algorithm was improved to enhance the response accuracy of the speed sensor. As a result, the stirring speed became more stable, ensuring consistent mixing and optimizing solvent contact with the plant material for improved extraction efficiency.

Adjustments were made to the microcontroller program, ensuring that the stirring motor maintained a steady rotational speed under varying resistance loads. The results confirm that the motor speed sensor effectively maintains a uniform stirring rate, which is essential for achieving consistent extraction performance. The iterative improvement of the stirring mechanism aligns with prior research that suggests controlled stirring enhances extraction kinetics and yield [24]. Consistent and uniform agitation facilitates better solvent penetration, promoting efficient mass transfer and reducing extraction time. Moreover, optimizing stirring speed prevents localized overheating, preserving the integrity of heat-sensitive bioactive compounds.

C. Optimation of Ultrasonic Frequency

The ability to adjust ultrasonic frequency is crucial in UAE, as different plant materials respond optimally to varying cavitation intensities [15],[25]. Initial tests showed minor frequency drifts in the ultrasonic waves, which could affect the cavitation effect necessary for cell wall disruption. If the ultrasonic frequency is not stable, it may reduce the efficiency of the Ultrasound-Assisted Extraction (UAE) process. To address this issue, a frequency stabilization mechanism was integrated to minimize fluctuations and maintain consistent ultrasonic energy. This improvement ensures more uniform cavitation, leading to enhanced extraction yield and better preservation of bioactive compounds. The ultrasonic modulation system was enhanced, incorporating a more precise frequency regulator that maintained stability within the targeted 20–40 kHz range, ensuring optimal energy distribution and improved extraction efficiency.The frequency regulation became more stable, ensuring consistent ultrasonic wave distribution throughout the extraction process. This improvement enhances the potential efficiency of future extractions by maximizing the cavitation effect. Previous studies have also highlighted that stable frequency modulation improves cell wall disruption efficiency, leading to higher extraction rates [5],[26].

D. Cooling System and Thermal Stability

Effective cooling is necessary to maintain consistent extraction conditions, especially during extended operation. The water-cooled condenser successfully prevented overheating, a common challenge in ultrasound-assisted processes. By dissipating excess heat efficiently, the cooling system helped preserve the integrity of heat-sensitive compounds, ensuring high extraction efficiency. Additionally, maintaining optimal temperature conditions contributed to the reproducibility of results, which is crucial for industrial-scale applications. [14]. This confirms that the system can sustain prolonged extraction cycles without compromising stability, an essential factor for future large-scale applications. The ability to maintain operational consistency over extended periods enhances process reliability and scalability. Furthermore, this stability minimizes fluctuations in extraction parameters, ensuring uniform product quality and efficiency.

The initial cooling system was not sufficient to maintain a stable thermal environment, leading to gradual temperature buildup during prolonged operation. Without effective cooling, excessive heat could accumulate, potentially affecting future extractions [27],[28]. The water circulation rate was optimized, improving heat dissipation efficiency by increasing the flow rate of the cooling medium within the condenser. The cooling system effectively managed thermal conditions, ensuring that heat generated by ultrasonic waves and mechanical agitation did not accumulate [29]. This modification enhances long-term operational stability and prevents overheating

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Dahmoune et al in 2015, highlighted that effective cooling is necessary in UAE systems to preserve volatile compounds and maintain consistent extraction conditions. Without proper cooling mechanisms, excessive heat generated during the process can degrade sensitive bioactive compounds, leading to reduced extraction efficiency and lower essential oil quality. Similar studies have also demonstrated that high extraction temperatures can lead to the degradation of volatile compounds. For instance, research on the volatile profile of human milk subjected to high-pressure processing or thermal treatment has shown that elevated temperatures can alter the profile of volatile compounds [30]. Additionally, other studies highlight the importance of process parameters in essential oil extraction. For example, research on optimizing ultrasound-assisted extraction conditions for phenolic compounds from sweet orange peels using the response surface methodology has demonstrated that parameters such as extraction time, extraction amplitude, and solvent concentration significantly influence extraction yield

5. CONCLUSION

This study successfully designed, developed, and functionally validated an Ultrasound-Assisted Extraction (UAE) apparatus, integrating key technological components such as temperature control, a stirring mechanism, ultrasonic frequency regulation, and a cooling system. The development process involved systematic iterative improvements, which significantly enhanced the precision, stability, and reliability of the apparatus. Each modification, from PID temperature calibration to frequency modulation optimization, contributed to refining the system's overall functionality, ensuring that it operates within the intended parameters.

Despite the scope of this study being limited to functional validation, the findings confirm that the UAE apparatus is fully operational and capable of maintaining controlled extraction conditions. The successful validation of its core features establishes a strong foundation for future research, where the apparatus can be further explored to assess extraction efficiency, yield optimization, and the chemical composition of extracted essential oils. Future studies can build upon these findings to compare UAE with conventional extraction methods, analyze its effectiveness across different plant materials, and fine-tune process parameters to enhance oil quality and bioactive compound retention.

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