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Challenges in Ultrasonic-Based Authentication of Palm Oil Seeds: Software Development and Experimental Findings

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Abstract

Fake palm oil seeds pose a substantial economic threat, which makes their authentication crucial. However, distinguishing between genuine and fake seeds remains a challenge. This study explored the potential of ultrasonic technology to measure shell thickness as a distinguishing factor based on the reported variations between the two types. Ultrasonic wave measurement software was developed using Arduino Uno to facilitate the analysis. The results highlight the complexity of accurately measuring the seed shell thickness owing to high attenuation. Micro-CT imaging confirmed the presence of pores within the seed structure, which significantly scattered and absorbed ultrasonic waves, limiting the penetration depth and accuracy. Despite these obstacles, the developed software exhibited promising capabilities, accurately determining the thickness or propagation speed with a high-resolution time-of-flight measurement of up to 62.5 nanoseconds. Additionally, the software is capable of sampling ultrasonic signals at frequencies up to 178 kHz. Although the software performs well under specific conditions, further advancements in ultrasonic technology are necessary to mitigate porosity-related limitations and enhance the effectiveness of seed authentication methods, particularly in transducer selection and measurement techniques such as Harmonic or QSC testing.

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1. Introduction

Palm oil is an important crop in the palm oil industry and is used in various products, such as cooking oil, margarine, soap, and biofuel. In addition, palm oil plants have other benefits, such as the use of wood as a building material, fuel, and leaves, which are used as animal feed (Kushairi et al., 2017). Palm oil continues to grow rapidly in Indonesia. Based on the Central Statistical Agency (Badan

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Pusat Statistik, 2022), the area of oil palm plantations in Indonesia during 2016–2021 increased rapidly from 11.201.500 hectares in 2016 to 14.663.600 hectares in 2021. One of the causes of this increase in land area is the pursuit of targets for future biodiesel applications (Hutapea, 2017). In addition, there is a replanting program for palm oil that requires a large number of palm oil seeds (Panggabean et al., 2023; Wibowo & Junaedi, 2017). Both have a direct impact on the need for palm oil seeds in Indonesia (Elidar & Purwati, 2021).

In the palm oil industry, legal and good palm oil seeds are produced by only a few parties who have been certified to meet various standards (Sarimana et al., 2021). However, several irresponsible parties produce palm oil seeds without paying attention to the standards that have been determined; these are called fake seeds. Fake seeds are a serious concern for the palm oil industry. Fake seeds circulate widely in Indonesia, especially in smallholder plantations, so their spread is quite difficult to monitor. The impact that will be felt by palm oil farmers is a decrease in income due to a decrease in plant productivity of up to 25%. This decline in productivity will be visible after 4-5 years and will continue until the oil palm reaches 25 years of age if fake seeds are used (Elidar & Purwati, 2021). According to Elidar (Elidar & Purwati, 2021), fake seeds are very similar to superior seeds; however, if you pay attention to fake seeds, they have the following characteristics: 1) a thin seed shell, 2) the seed surface is rougher and dirtier and contains fibers, and 3) seeds collected from the remains of Dura trees cannot be detected from the shell with the naked eye. In addition, fake seeds have low germination capacity (>85%), slow growth, and a high percentage of abnormalities, and each seed does not have the same size and is cheaper. The genetic identification of fake seeds is challenging, unless the plant has already begun to grow. However, this process is expensive and impractical for large-scale production (Babu et al. 2021; Sarimana et al. 2021).

Ultrasonic waves are sound waves with a frequency greater than 20kHz and humans cannot hear sounds at this frequency. Ultrasonic waves are a type of mechanical wave that require a medium to propagate, whether solid, liquid, or gas. Ultrasonic waves propagate at the speed of sound; however, this speed can change depending on various factors such as the type of medium, temperature, and pressure (Workman et al., 2007). The principle of ultrasonic waves is the same as that of other mechanical waves, that is, they can experience reflection, refraction, polarization, and other properties. Ultrasonic waves have been used for various purposes, such as detecting objects, measuring distance or thickness, and analyzing materials nondestructively (Massa, 1962).

According to Juansah et al. (2006), ultrasonic technology generates ultrasonic waves using a pulse generator, after which the waves are amplified and converted into ultrasonic waves with a transducer transmitter. Then, the ultrasonic waves propagate through the material, the waves are received back by the transducer receiver, and the received waves are amplified until they can finally be read and analyzed. In this study, an ultrasonic wave measurement software was developed using Arduino Uno to detect the authenticity of palm oil seeds. The ultrasonic device used in this study was developed by

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the Electrical Engineering Department at the University of Padjadjaran. It consists of a pulse generator with a one-shot pulse trigger, a peak detector with an amplifier and rectifier, and various transducers operating at various frequencies ranging from 200 kHz to 7.5 MHz (Hidayat et al., 2018).

Although ultrasonic technology has demonstrated potential for various industrial applications, its implementation in the authentication of palm oil seeds is limited. This is primarily because the palm oil industry has historically relied on genetic testing and seed identification certifications. The objective of this study was to assess the feasibility of using ultrasonic technology as a practical solution for palm oil seed authentication. This study examined whether ultrasonic measurements, such as shell thickness and internal structure, could effectively differentiate between authentic and fake seeds. This study seeks to significantly reduce risks, enhance productivity and profitability in the palm oil industry, and contribute to the long-term sustainability of the Indonesian palm oil sector.

2. Material and Methods

2.1 Material

The materials used in this research included genuine palm oil seeds obtained from the Palm Oil Research Center (PPKS) and fake palm oil seeds sourced from marketplaces, where they were sold at unusually low prices. The tools used in this study consisted of an ultrasonic transducer, peak detector, pulse generator, oscilloscope, Arduino Uno, and laptop for data processing and analysis.

2.2 Method

The method used in this study was experimental and software engineering, with the following stages.

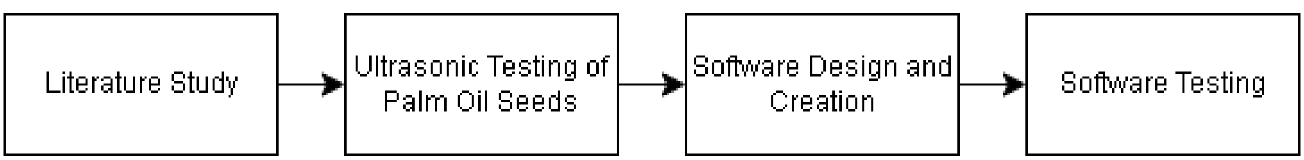

Figure 1. Research Stage Flowchart.

2.2.1 Literature Study

The preliminary stage entailed collection and analysis of relevant references, thereby establishing a foundation for the study. The literature review focused on ultrasonic applications in biomaterials, transducer selection, ultrasonic measurement techniques, and software design. The insights gained from this stage serve as a reference for subsequent research.

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2.2.2 Ultrasonic Testing of Palm Oil Seeds

This stage involved conducting ultrasonic measurements on palm oil seeds following the knowledge obtained from a literature study. The objective of this stage was to identify the most effective ultrasonic method, including transducer selection and measurement techniques, for assessing the characteristics of palm oil seeds.

Owing to the limited number of studies on the ultrasonic testing of palm oil seeds, this research references studies on other biomaterials with similar properties. Wood was the most comparable material. Sandoz (1996) demonstrated that low-frequency ultrasound is necessary for the effective penetration of wood owing to its high attenuation. However, lower frequencies are associated with longer wavelengths, which can reduce measurement resolution. Therefore, selecting an appropriate ultrasound frequency requires a balance between penetration depth and resolution to ensure an accurate assessment. According to Ng and Swanevelder (2004), determining the frequency based on the resolution can be performed mathematically and can be expressed as shown in Equation (1).

$$Frequency\ = \frac{Speed\ of\ propagation}{Desired\ Resolution \times 2} \tag{1}$$

Given the thin shell thickness of palm oil seeds (approximately 2 mm or 0.002 m), a minimum resolution of 0.002 m is necessary (Prastyo, Tamrin, & Oktafri, 2017). Although the propagation speed remains undetermined, it is provisionally assumed to be equivalent to that of wood, estimated to be 3500 m/s (Engineering ToolBox, 2004). Therefore, the required frequency was estimated as follows:

$$3.500.000\ Hz\ = \frac{3500\ m/s}{0{,}002\ m \times 2} \tag{2}$$

Therefore, to achieve the required resolution, a frequency of at least 3.5 MHz is required. However, this frequency is relatively high and may suffer from weak penetration owing to increased attenuation. Therefore, experimental validation is necessary to determine the optimal frequency that balances both penetration and resolution for effective ultrasonic testing of palm oil seeds.

Several measurement techniques can be employed for ultrasonic testing, each of which offers unique advantages depending on its application. The two most common methods are pulse-echo and through-transmission methods. The pulse-echo method is widely used for thickness measurement, relying on the reflection of ultrasonic waves from internal structures to determine material properties (Figure 2(A)). In contrast, the through-transmission method involves sending ultrasonic waves through the sample and analyzing the received signal to assess the propagation speed and attenuation (Figure 2(B)). These techniques provide critical insights into the internal structure and shell characteristics of palm oil seeds, which are essential for distinguishing genuine seeds from fake seeds. The selection of the appropriate measurement technique depends on the desired parameters, such as thickness estimation, structural integrity assessment, or attenuation analysis. Specific parameters are selected after the authentication model is developed to ensure optimal accuracy and reliability.

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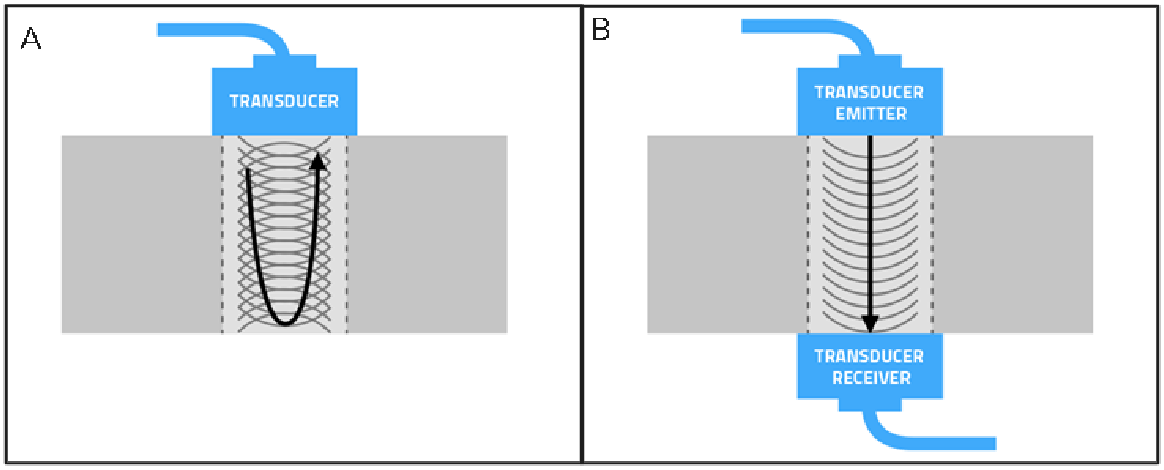
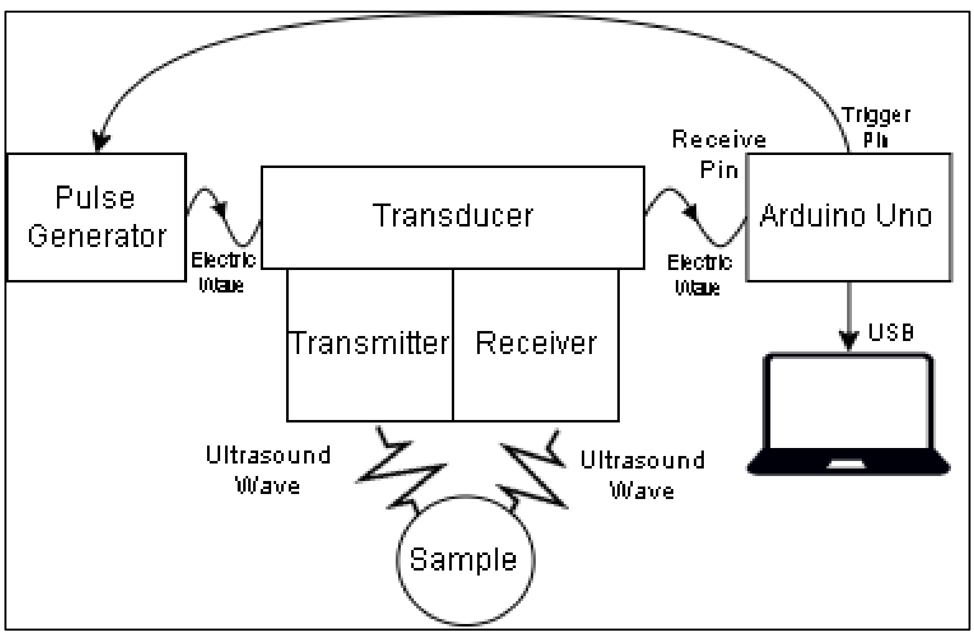


Figure 2. Pulse-Echo Technique (A) and Through-Transmission Technique (B).

2.2.3 Software Design and Development

As an initial step in developing an ultrasonic-based authentication system, software was designed to establish the working principles necessary for differentiating genuine and fake palm oil seeds. The system is shown in Figure 3, which integrates an ultrasonic measurement setup developed at the Department of Engineering, Padjadjaran University.



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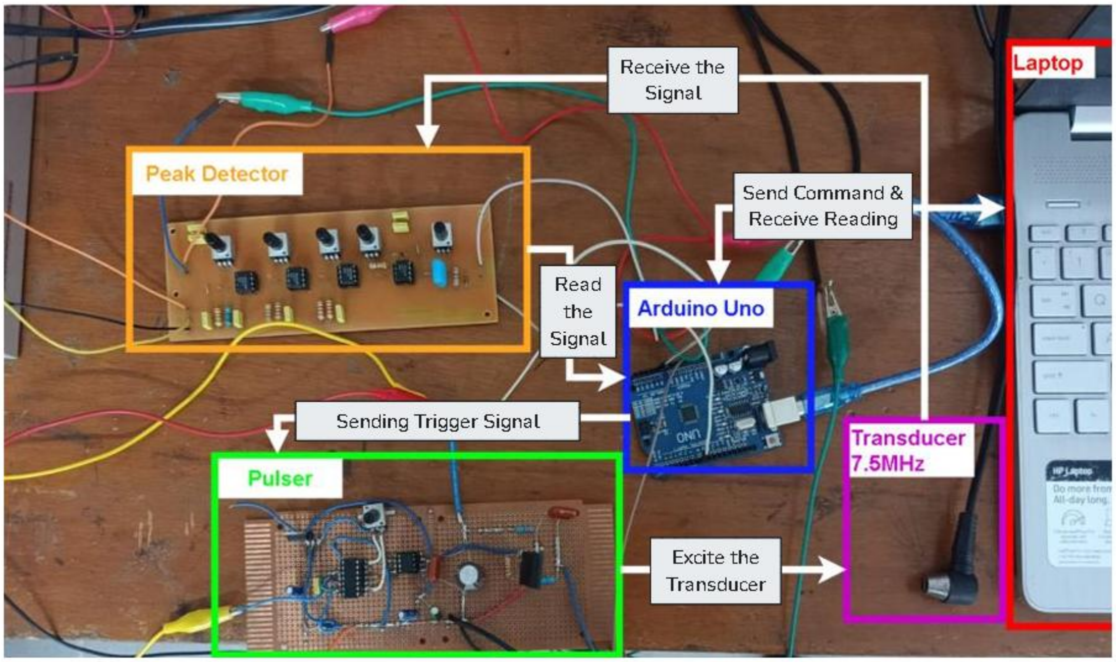

Figure 3. Block Diagram and Actual Ultrasonic System.

The system consists of the following components:

1. Arduino Uno – Sends trigger signals to the pulse generator and reads results from the peak detector.
2. Pulse Generator – Excites the ultrasonic transducer.
3. Ultrasonic Transducer: Converts electrical signals into ultrasonic waves.
4. Peak Detector – Reduces noise and amplifies the received signal.
5. Laptop/PC: Visualize and analyze the ultrasonic reading results.

The software development process was as follows:

- Arduino programming for instrument control and real-time data acquisition was implemented using an Arduino IDE.
- A Windows-based application for data visualization and analysis of ultrasonic wave signals, developed in Visual Studio 2022 using C#.

The software follows a structured process for seed authentication. The software workflow is illustrated in Figure 4.

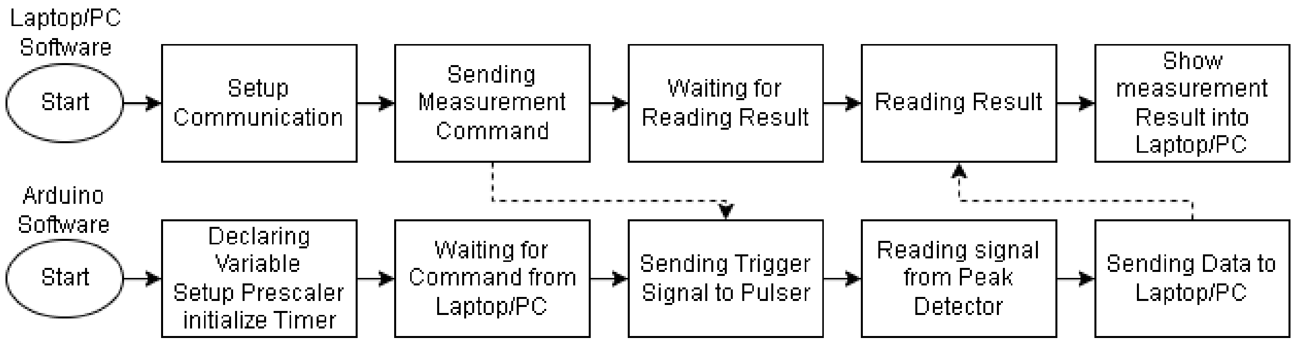

Figure 4. Software Workflow.

2.2.4 Software Testing

The developed software was tested to evaluate its sampling rate performance and time-of-flight resolution by using an Arduino-based hardware setup. The goal was to ensure that the system could effectively process the ultrasonic measurements and provide accurate results.

3 Results and Discussion

3.1 Software Development

3.1.1 Software Result

3.1.1.1 Arduino Program

The developed Arduino software operates in two modes: (1) as a high-resolution timer utilizing interruption functions and (2) as a data acquisition system using analog signal sampling.

In the first mode, the software employs an interrupt function to achieve high-resolution timing. By setting the prescaler to 1, the Arduino Uno can attain a timing resolution of 62.5 nanoseconds (Silva et al., 2015). This method is particularly suitable for pulse-echo measurements to determine shell thickness. For example, if the propagation speed of ultrasonic waves in palm oil seed shells is assumed to be similar to that in wood (3500 m/s), the system can achieve a theoretical thickness resolution of approximately 0.21875 mm. This level of resolution is sufficient for distinguishing fine structural variations in the seed shells.

The second mode utilizes Arduino’s Analog-to-Digital Converter (ADC) to sample ultrasonic signals. By setting the ADC prescaler to two, Arduino Uno achieved a maximum sampling rate of approximately 178.5 kHz (Silva et al., 2015). However, the sampling rate was relatively low for ultrasonic signal acquisition. According to Nyquist's sampling theorem (1928), the minimum sampling frequency should be at least twice the highest signal frequency. Consequently, the effective limit of the Arduino Uno is 89 kHz, making it unsuitable for high-frequency ultrasonic transducers.

3.1.1.2 Windows based Apllication

A window-based application was developed in NET framework to provide a graphical user interface (GUI) that facilitates user interaction with the ultrasonic measurement system. The application interface is shown in Figure 5.

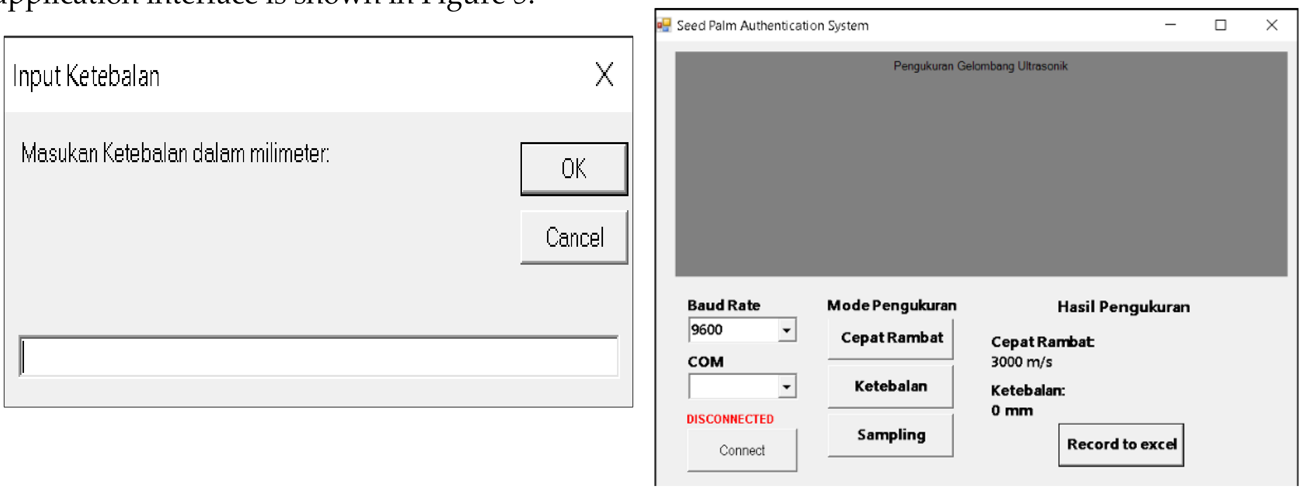

Figure 5. Graphical User Interface.

As shown in Figure. 5, the application includes several key features:

1. **Connectivity:** The application establishes a connection with the Arduino to control the measurement process. Users can configure the baud rate and select a COM port that connects them to the Arduino.
2. **Three Measurement Modes**: The system supported three distinct measurement modes.
   - **Propagation speed measurement**: The speed of the ultrasound propagation through the material was determined. The user must manually input the thickness (T) of the seed and the application calculates the speed using the following formula:

$$C = \frac{T \times 2}{ToF} \tag{3}$$

     Where **C** is the propagation speed (m/s), **T** is the material thickness (m), and **ToF** is the time-of-flight (s). This formula follows the principle of ultrasonic measurements described by Luciano et al. (2010).
   - **Thickness measurement**: The shell thickness was determined when the **propagation speed (C)** was known. This model uses the following formula:

$$T = \frac{C \times ToF}{2} \tag{4}$$

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where **T** is the thickness (m), **C** is the propagation speed (m/s), and **ToF** is the time-of-flight (s).

Both the propagation speed and thickness measurements utilized Arduino's high-resolution interrupt-timer mode. The results are presented in the *section on Hasil Pengukuran*.

- **Sampling Mode**: This mode enables ADC-based signal acquisition, displaying the sampled ultrasonic waveform as a graph within the application.

3. **Data Recording to Excel**: The application includes a feature to record sampled data into a CSV file for further analysis, such as attenuation measurement and signal processing.

3.1.2 Software Testing

Software testing was conducted to evaluate the functionality and performance of both the software and Arduino-based hardware systems. The testing process aimed to assess the accuracy of the ultrasonic measurement functions, particularly the thickness and propagation speed estimation. An artificial ultrasonic signal generated by a clock generator was used as the signal source for the controlled testing conditions.

3.1.2.1 Thickness and Propagation Speed Measurement Testing Based on Time of Flight (ToF)

The accuracy of the thickness and propagation speed measurements was tested by varying the ((ToF) values across different ultrasonic frequencies ranging from 100 kHz to 10 MHz. Each frequency was tested using five iterations to ensure consistency and reliability.

The measured ToF values obtained from the software were compared with actual ToF values recorded using an oscilloscope. The results indicate that the software accurately measured the ToF across all tested frequencies, including higher frequencies. This demonstrates that the interrupt-based timing method used in the Arduino implementation was effective for high-resolution ToF measurements. Specifically, the system achieved a temporal resolution of 62.5 nanoseconds, corresponding to the 16 MHz operating frequency of the Arduino Uno (Thothadri, 2021).

A summary of the measured versus actual ToF values across the different frequencies is presented in Table 1.

Table 1. Time of Flight-Testing Results.

Frequency	**100 kHz**	**500 kHz**	**1 MHz**	**2 MHz**	**4 MHz**	**10 MHz**	**Total**
Average Error	2,14%	1,31%	2,27%	1,79%	2,17%	2,63%	1,91%
Accuracy	97,86%	98,69%	97,73%	98,21%	97,83%	97,37%	98,09%

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The data in Table 1 confirm that the software's ToF measurements closely align with the oscilloscope readings with minimal error. This validates the reliability of the system for precise ultrasonic wave time-of-flight measurements.

3.1.2.2 Ultrasonic Signal Sampling Testing

Sampling testing was conducted to evaluate the performance of Arduino's data acquisition capabilities across various ultrasonic frequencies ranging from 20 kHz to 2 MHz. A sinusoidal signal with different ultrasonic frequencies and a 3-volt amplitude was used as the input. The signal was digitized using an Arduino 10-bit ADC and compared to a mathematically generated ideal sinusoidal waveform.

The results were analyzed using the root-mean-square error (RMSE) and RMSE% to determine the error rate and accuracy percentage. The summarized data are listed in Table 2.

Table 2. RMSE and Accuracy Percentage of Digitized Ultrasonic Signals.

Frequency	20 kHz	40 kHz	100 kHz	200 kHz	1MHz	2MHz
RMSE	34,4	63,55	212,64	234,9	180,15	179,48
Accuracy	91%	83%	38%	31%	39%	39%

During testing, the Arduino consistently achieved a sampling rate of 178.9 kHz, which aligns with the previous findings by Silva et al. (2015). According to Nyquist's sampling theorem, this implies that the effective limit of the Arduino Uno is approximately 89 kHz for accurately reconstructing signals. The data in Table 2 further confirm that the accuracy significantly declines beyond 100 kHz, making the system unreliable for high-frequency ultrasonic signals.

A visual representation of the sampled waveforms at different frequencies is shown in Figure. 6. The figure demonstrates that at 200 kHz, aliasing effects became prominent, causing the waveform to resemble a lower-frequency signal. At even higher frequencies, the waveform lost its original shape, further confirming the sampling limitations of the system.

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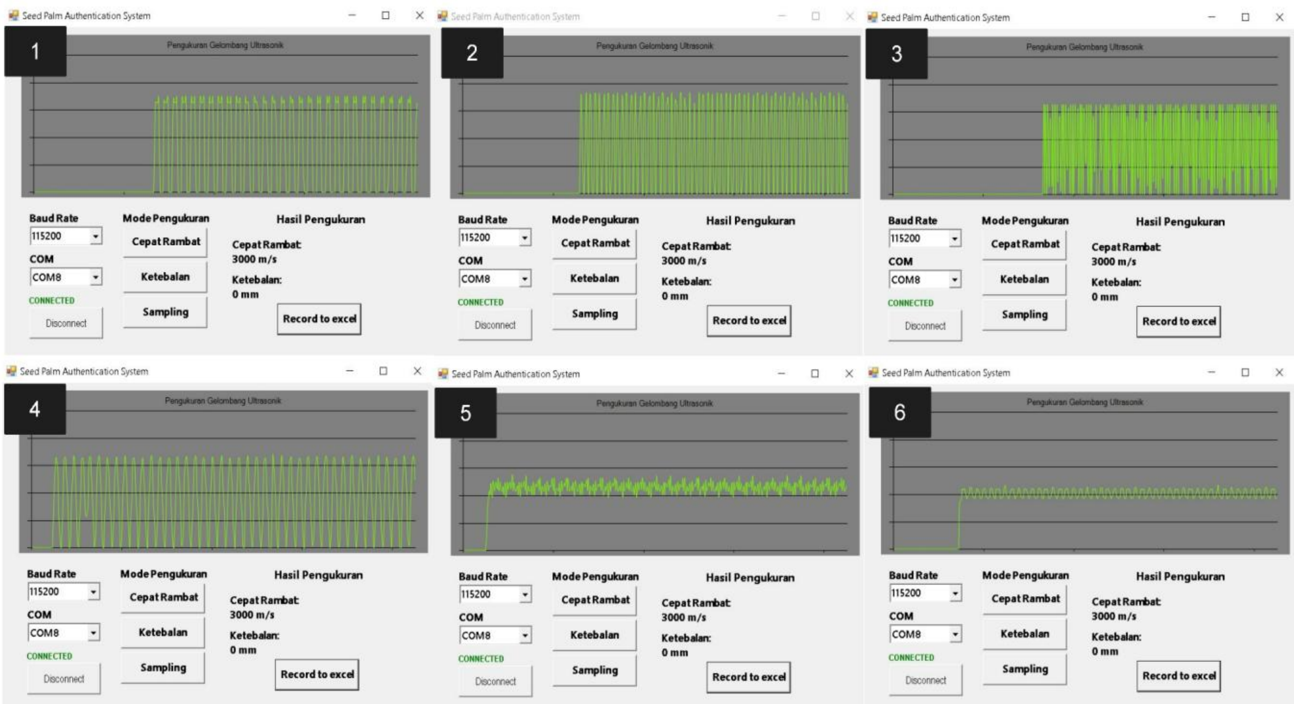

Figure 6. Sampling at various frequency signals (1) 20kHz, (2) 40kHz, (3) 100kHz, (4) 200kHz, (5) 1MHz, (6) 2MHz.

Furthermore, Svilainis (1998) suggested that, for effective ultrasonic data acquisition, the sampling frequency should be at least four times greater than the actual signal frequency. This highlights the limitation of using an Arduino Uno for high-frequency ultrasonic measurements because it lacks the necessary sampling rate to accurately capture signals beyond 89 kHz.

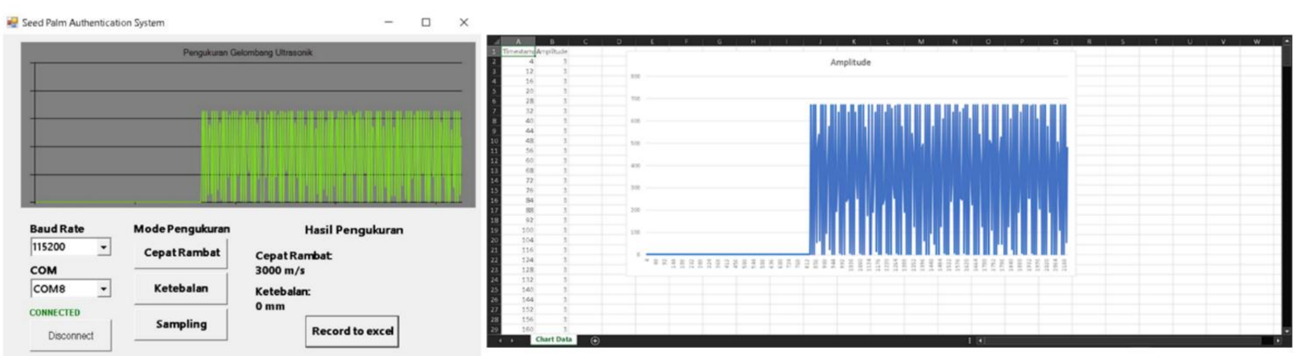

Figure 7. Sampling features and recorded data.

However, the results obtained from the Windows-based application confirmed its capability to capture ultrasonic waveforms successfully. As shown in Figure 7, the acquired waveform data were accurately displayed in the graphical interface and recorded in CSV files for further analysis. This functionality ensures that signal characteristics such as amplitude variations and frequency content can be systematically analyzed and processed for authentication purposes.

3.2 Experimental Findings

3.2.1 Ultrasonic transducer and Technique selection

An experimental study was conducted to determine the optimal ultrasonic configuration for the measurement of palm oil seeds. Key parameters, such as transducer type, operating frequency, and transducer diameter, were evaluated. The investigation was conducted across multiple ultrasonic measurement facilities using a trial-and-error approach. Table 3 summarizes the experimental conditions and results.

Table 3. Ultrasonic testing results of palm oil seeds.

Transducer Used	Technique	Result
Transducer 1 MHz diameter 24mm single element	Pulse-Echo	Can not be read
Transducer 2 MHz diameter 17mm Dual Element	Pulse-Echo	Can not be read
Transducer 5 MHz diameter 6mm dual element	Pulse-Echo	Can not be read
Transducer 7,5 MHz diameter 6mm dual element	Pulse Echo	Can not be read
Transducer 15 MHz diameter 3mm single element	Pulse Echo	Can not be read

Table 3 summarizes the results of ultrasonic testing of palm oil seeds using different transducers and techniques. The experimental results indicate that a transducer with a small diameter, preferably less than 6 mm, is required for effective measurements to ensure full contact with the seed surface. Typically, transducers with smaller diameters operate at higher frequencies, which is advantageous for achieving a higher resolution.

However, despite the advantages of high-frequency transducers in improving resolution and ensuring proper contact with the seed surface, high-frequency ultrasonic waves suffer from weak penetration power, especially in materials with high attenuation (Nadrljanski et al., 2024). This limitation poses a significant challenge for obtaining clear ultrasonic readings. The experimental results indicated that no detectable ultrasonic waves were observed across all tested transducers, ranging from 200 kHz to 2 MHz. This suggests that the attenuation properties of palm oil seeds

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significantly affect ultrasonic wave propagation, highlighting the need for further investigation into alternative frequency ranges or measurement techniques to achieve reliable results.

3.2.2 Micro-CT Imaging

Micro-Computed Tomography (micro-CT) scanning was conducted to further investigate the internal structure of palm oil seeds. This technique provides high-resolution imaging to analyze the physical composition and density variations within the seeds. The test was performed at the X-Ray Micro-Computed Tomography (X-Ray μ-CT) Laboratory of the Bandung Institute of Technology using a Skyscan Micro-CT 1173. The scan results are shown in Figure. 8.

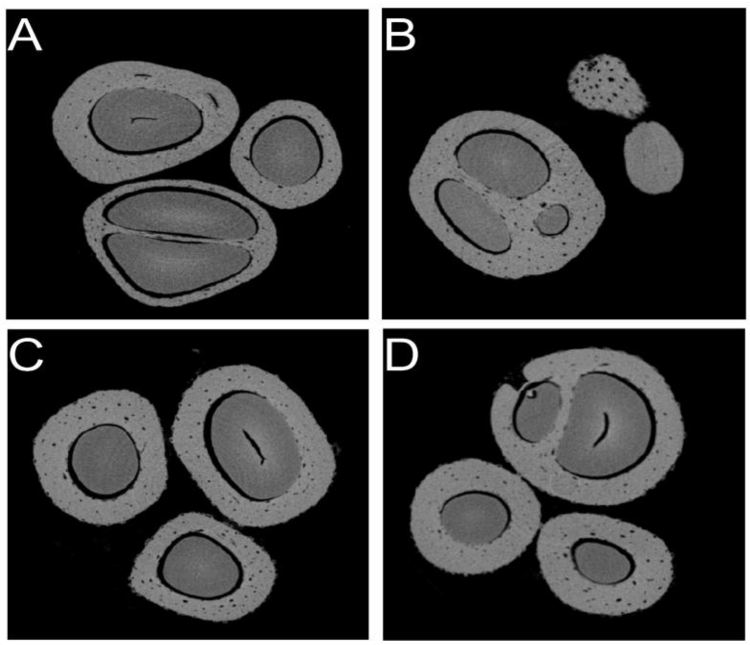

Figure 8. Micro-CT scan results of palm oil seeds (A & B) genuine palm oil seeds (C & D) fake palm oil seeds,

The micro-CT scan results revealed that the palm oil seeds exhibit a highly attenuative physical structure. Notably, the seed shell contained a porous structure filled with air, which significantly influenced ultrasonic wave propagation. Pores or air cavities contribute to high attenuation, as reported by Yousefian et al. (2018). When ultrasonic waves travel through a solid medium, the wave energy displaces molecules within the material. However, upon encountering pores, waves undergo scattering, leading to energy loss and reduced wave transmission. Consequently, the ultrasonic waves emitted by the transducer dissipate within the medium, thereby preventing successful signal reception.

Moreover, the micro-CT data further indicated that the structural thickness of fake palm oil seeds (average: 2.46 mm) was greater than that of genuine seeds (average: 1.69 mm). Additionally, the object

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surface density of fake seeds (average: 0.92 1/mm) was lower than that of genuine seeds (average: 1.21 1/mm). These findings provide empirical support for the prevailing assumption that shell thickness is a key parameter in authenticating palm oil seeds.

3.2.3 Future Consideration for Ultrasonic-Based Palm Oil Seed Authentication

Genetic analysis is the most widely adopted method for authenticating palm oil seeds because of its high accuracy in identifying genetic markers that differentiate genuine seeds from fake seeds. However, as noted by Kahler and Rasmusson (as cited in Wong & Bernardo, 2008), genetic analysis is both costly and time-intensive, making it less accessible for smallholder farmers.

In contrast, ultrasonic testing presents a non-destructive and cost-effective alternative for assessing structural differences, such as shell thickness and internal composition. Although genetic analysis remains the industrial standard, ultrasonic methods have the potential to provide a faster and more scalable solution at a lower cost. A detailed comparison of these methods is presented in Table 4.

Table 4. Comparison of Genetic Analyses and Ultrasonic Testing for Palm Oil Seed Authentication

Criteria	Genetic Analysis	Ultrasonic Testing
Accuracy	Very high, identifies genetic markers precisely	Still unknown, depends on seed structure differences
Cost	Expensive due to specialized equipment and reagents	Lower cost, requires only ultrasonic hardware and software
Processing Time	Time-consuming, requires laboratory analysis	Rapid, results obtained in real-time or within minutes
Destructiveness	Requires seed destruction for DNA extraction	Non-destructive, maintains seed integrity
Scalability	Less scalable, limited by lab resources and costs	Highly scalable, suitable for large-scale seed screening
Field Applicability	Limited, requires lab access and skilled personnel	Suitable for field use with portable ultrasonic devices

Unfortunately, at this time, ultrasonic testing is not yet a viable method for authenticating palm oil seeds. This is because of the limitations in wave penetration caused by the highly attenuative nature of the internal structure of the seed. Further research on transducer selection is necessary to address this issue by selecting a transducer that balances the penetration power, resolution, and small diameter tip. In addition, innovative techniques can provide potential solutions. For instance, Wang et al. (2023) proposed the use of an acoustic radiation-induced quasi-static component (QSC) of a primary longitudinal wave (PLW) at high frequencies to measure the thickness of a high-attenuation rubber. This approach may offer valuable insights for overcoming the penetration challenges associated with ultrasonic testing of palm oil seeds.

4. Conclusion

This study explored the feasibility of using ultrasonic-based techniques for the authentication of palm oil seeds, focusing on software development, experimental findings, and future considerations. The software was successfully developed and consisted of an Arduino-based data acquisition system and a windows-based application for measurement, visualization, and data recording. Testing confirmed the reliability of the software in measuring time-of-flight (ToF) and acquiring ultrasonic signals. However, hardware limitations, particularly the sampling rate of the Arduino Uno, restrict the effective frequency range of the system to 44 kHz, thereby limiting its ability to capture high-frequency ultrasonic waves with sufficient accuracy.

The experimental findings revealed significant challenges in ultrasonic testing of palm oil seed authentication. Various transducers and measurement techniques were tested; however, no readable ultrasonic signals were obtained within the tested frequency range (200 kHz–2 MHz). Micro-CT imaging provided crucial insights into the structural characteristics of the seeds, confirming that their porous nature and air-filled cavities contribute to significant ultrasonic wave attenuation. Furthermore, it validates the hypothesis that shell thickness and surface density differ between genuine and fake seeds, thereby supporting the potential of structural analysis for authentication.

Although ultrasonic testing is a non-destructive, cost-effective alternative to genetic analysis, its current feasibility remains limited owing to penetration issues. Future research should focus on optimizing transducer selection to enhance penetration while maintaining resolution and small tip diameters. Additionally, innovative approaches, such as the acoustic radiation-induced quasi-static component (QSC) method proposed by Wang et al. (2023), could offer potential solutions for measuring high-attenuation materials such as palm oil seeds. With further advancements, ultrasonic-based authentication has become a viable and scalable alternative to traditional genetic analysis.

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