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Mini Cutting Force Sensor: A Novel Approach for Predicting Cutting Forces of Agricultural Products

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ABSTRACT

Innovation in agricultural mechanization is crucial for the sustainable development of agricultural machinery in Indonesia. This study aims to design and develop a cutting force measurement device for agricultural products. The device consists of a mechanical system utilizing a linear actuator (5.88 mm/s) as a blade pusher and a control system employing a load cell as a force sensor. Testing was conducted using three blade types with cutting angles of 10°, 15°, and 20° on taro, chayote, and papaya. Measurement data were displayed as graphs on an LCD and stored as XLS files on an SD card. The tested materials had moisture content ranging from 85% to 95%. Results showed that taro required the highest cutting force (74.3 N), followed by chayote (39.77 N) and papaya (31.1 N), corresponding to their hardness and moisture content. In contrast, the highest cutting speed was observed in chayote (6.1 mm/s), followed by papaya (5.8 mm/s) and taro (3.5 mm/s) using a 20° blade. These findings confirm that harder materials with lower moisture content require greater cutting force than softer materials with higher moisture content.

1. INTRODUCTION

Agricultural mechanization is a stage that must be taken to achieve modern agriculture. According to Purba & Lisyanto (2022), agricultural mechanization is a step that must be considered in agricultural revitalization activities to maintain food security, agribusiness development, and farmer welfare. The development of agriculture in the current era cannot be separated from the use of various types of modern tools with a touch of technology that can facilitate and increase the effectiveness of agriculture. However, in Indonesia, the mastery and application of technology in the agricultural sector is still quite behind other countries. The low level of mastery of mechanization in the agricultural sector is one of the causes of the backwardness of agricultural sector in Indonesia.

The touch of mechanization in agriculture greatly affects the increase in efficiency and productivity of the agricultural sector. As a result of modernization in agriculture, the term agricultural technology emerged. Agricultural technology is closely related to food problems, so that the use of agricultural tools that are in accordance with needs will improve the welfare of farmers. The increase in agricultural and food production cannot be separated from the development of agriculture due to the modernization of agricultural technology. The high and low levels of agricultural production are determined based on the level of technology use in the agricultural sector (Lestari *et al.*, 2019). Designing and manufacturing agricultural tools are needed to increase the effectiveness and productivity of agriculture. All activities carried out in the agricultural sector are always related to agricultural tools and materials. Cutting activity cannot be separated from the farm sector. Cutting plays an important role in every activity carried out from land preparation to processing agricultural products. Therefore, the ability and skills of workshops or craftsmen are needed in creating or engineering farm machines and tools that are in accordance with the needs of farmers.

The design of appropriate agricultural tools cannot be separated from the use of tools that are in accordance with the needs of farmers in the field. By knowing the force needed to cut a material the design and manufacture of cutting tools will be easier because it can be adjusted to the force needed in the use of tools in the field, and the materials in making the tools can be determined properly. The selection of appropriate materials in making tools greatly affects the quality of the tool. Therefore, a cutting force measuring tool is needed to determine the force needed to cut an agricultural material. So that workshops/craftsmen/manufacturers can develop precise cutting tools according to the material to be cut with the tool. The purpose of this study is to design a rapid cutting force estimation tool and to conduct performance tests on the tool on several types of agricultural products. The expected benefits of this research are that the tools made are expected to help workshops/craftsmen/manufacturers/researchers in developing appropriate tools and machines that can be adjusted to the scale of use. In addition, this tool is also expected to help the research process such as determining the right knife for the material to be cut, as well as post-harvest research such as measuring the cutting force of agricultural products.

2. MATERIALS AND METHODS

2.1. Functional and Structural Design

In the research process of designing a Cutting Force Measurement (CFM) instrument based on a strain gauge sensor, several tools and materials are needed, namely; electric soldering iron, tin sucker, screwdriver, scissors and weights. The materials used are as follows: IC HX711, Arduino Mega, 12V 10A power supply adapter, 320x480 LCD, MP1584 DC step down, BTS7960 motor driver, 12V linear actuator, load cell, jumper cable, nuts bolts, aluminum profile, linear shaft, hollow iron, and three kind of cutting knife. Testing was conducted using three blade types with cutting angles of 10°, 15°, and 20° on taro, chayote, and papaya. The method used in this research is an experimental method with several stages; 1) Designing a prototype and making a cutting force measuring tool, 2) conducting an accuracy test of the tool for measurement results with higher precision, 3) observing the reading results by the LCD sensor, and 4) conducting an analysis of several materials using a cutting force measuring tool. The CFM device components can be seen in Figure 1 and the specification in Table 1.

2.2. Working Principle of the Tool

This cutting force measuring tool (Figure 2) has a working principle similar to compressive strength. This tool has a height of 50 cm with its components, namely the main plate, vise, linear actuator, knife, and lock. The working principle of this tool is to place the test material on the plate and then hold it using a vise.

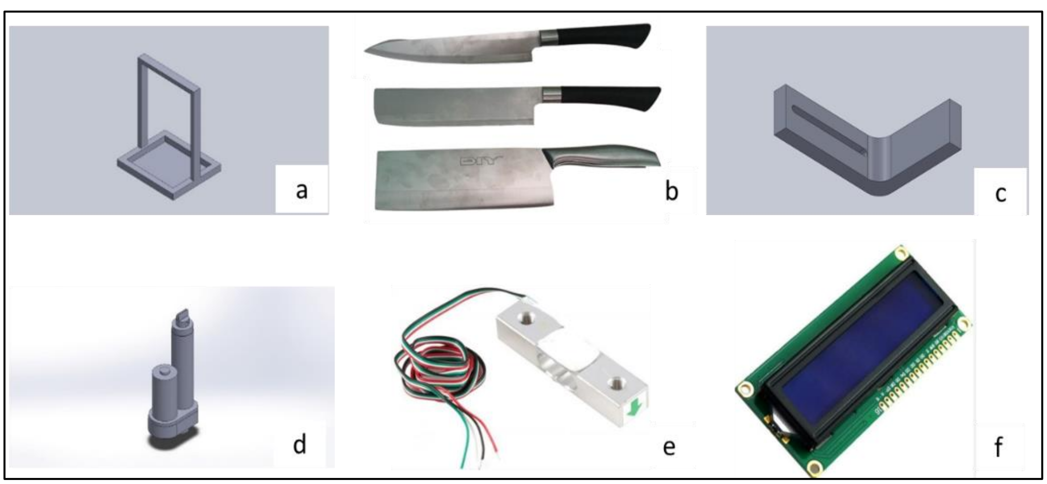


Figure 1. The CFM device components. [Description and specification for each component is in Table 1]

Table1. Specification of components to design the CFM device

No	Name	Functional design	Structural Design
a	Main Frame	The main plate is used to place the tool control system and to connect other components. This component also functions as a place to test materials when testing the large cutting force.	This component is made of metal plate with a thickness of 2 mm. The size of the main plate is 30 cm in diameter with a height of 40 cm
b	knife	For cutting material	Made of stainless steel with a thickness of 2 mm.
c	Clamp	The holder (clamp)) is located on the top of the main plate, which functions to hold the test material so that it does not move when cut	The holder/clamp is made of mild steel that is installed from four directions to increase the device resistance to the test material. The clamp is made of a 5 mm thick plate with a height of 4.6 cm and a width of 2.8 cm
d	Linear actuator	linear actuator functions to press the blade towards the material so that the material will be cut with a constant force	Linear actuator putter motor controller
e	Load cell HX711	As a weight sensor	Sensor type shear load cell (max capacity 20 kg)
f	LCD	Result display	TFT LCD 3.5 inch, 480x320

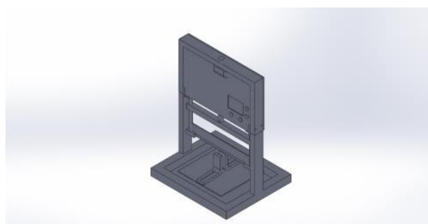


Figure 2. Prototype of cutting force measuring device

The working mechanism of this tool involves the load cell on the blade, so when the blade cuts the material, there will be a change in strain on the sensor, allowing the magnitude of the force to be measured during cutting. Before cutting, set the tool to the initial condition by pressing the offset button. The Linear Actuator will press the blade towards the material. When the knife touches and starts cutting the material, the amount of force needed to cut the material will be read by the sensor and then forwarded to the microcontroller. The data provided will be processed by the microcontroller, and the obtained data will be displayed on the display.

2.3. Observation and Measurement

Observation is done by directly observing to verify the accuracy of an experiment being conducted. Six basic rules of observation must be followed: (1) observation must be done individually (cannot be represented), (2) observation is conducted to achieve proportional results, (3) observation techniques must be based on direct experience, (4) there is often doubt when interpreting data, (5) observation helps researchers understand complex situations, and (6) observation serves as an alternative technique for communicating specific cases. The observations conducted in this study involved measuring the force required to cut various types of materials under different conditions and cutting directions. The specific observations in this study included: (1) cutting force analysis, and (2) The effect of cutting angle on cutting force, and (3) The effect of knife thickness on cutting force.

2.4. Power Requirement

Calculation of the power required to run the control system and linear actuator was needed to adjust the resources used to run the system so that it can be turned on. The electrical power P (watt) was determined from voltage V (volt) and current I (ampere) according to Equation 1.

$$P = V \times I \tag{1}$$

2.5. Calibration

Calibration is a method used to determine the accuracy of a tool by comparing the measuring instrument with national or international standards that have been verified. During calibration, calculations need to be made because there are factors that must be considered and need to be corrected.

2.6. Cutting Force Analysis

Cutting force analysis was conducted by observing the force required during the material cutting process. The analysis was carried out using various materials, including potatoes, taro, and carrots. Measurements were taken 25 times for each type of material.

2.7. Material Width

The physical parameters of the material measured in this study were the width of the material used. The width of the material refers to the length of the material passed by the cutting blade and was measured using a Vernier caliper.

2.8. Water Content

To determine the water content of each material, the oven method was used. The first step involved weighing an empty cup that has been dried in an oven at 105 °C. The material was then cut into several pieces, and 10 g of the material was weighed and placed into the dry cup. The cup was then placed in an oven at 105 °C. After drying, the sample was weighed again. This process was repeated until a constant weight is obtained for the sample. The water content was calculated from weight of sample before drying (a) and weight of dried sample (b) according to the following equation:

$$Ka = \frac{a-b}{b} \times 100\% \quad (2)$$

2.9. Cutting Speed

To find out the cutting speed, it is observed during the cutting process. The cutting speed S (mm/s) was determined by measuring the distance d (mm) covered by the tool to reach a certain point, divided by the time t (s) required to cover that distance. To calculate the cutting speed, the following equation was used:

$$S = d/t \quad (3)$$

2.10. Data Analysis

Data analysis was carried out to determine descriptive statistics calculated based on the mean, standard deviation, and coefficient of variation.

3. RESULTS AND DISCUSSION

3.1. Design of Cutting Force Measuring Instrument System

The components of CFM device are made of iron and aluminum. The frame is constructed with 2x4 cm and 4x4 cm hollow iron, and a 5 mm thick iron plate. Meanwhile, the parts in direct contact with the test material are made from aluminum plates, which serve as the cutting base, and aluminum profiles, which support the blade. Parts of the tool in contact with cutting materials use food-grade materials to ensure the cutting results are safe for consumption. The system design of the cutting force measuring tool outlines how the tool operates and how the cutting force can be measured. The diagram of the cutting force measurement process and components can be seen in Figure 3 and the specification is in Table 2. Based on Figure 3, the operation of the cutting force measuring instrument can be observed. The system consists of several interconnected components. The tool requires electrical power sourced from AC electricity, which is converted into DC current by an adapter with a maximum capacity of 12 volts and 10 A. This ensures that all components can function effectively. A switch is included to control the tool, and allowing the user to

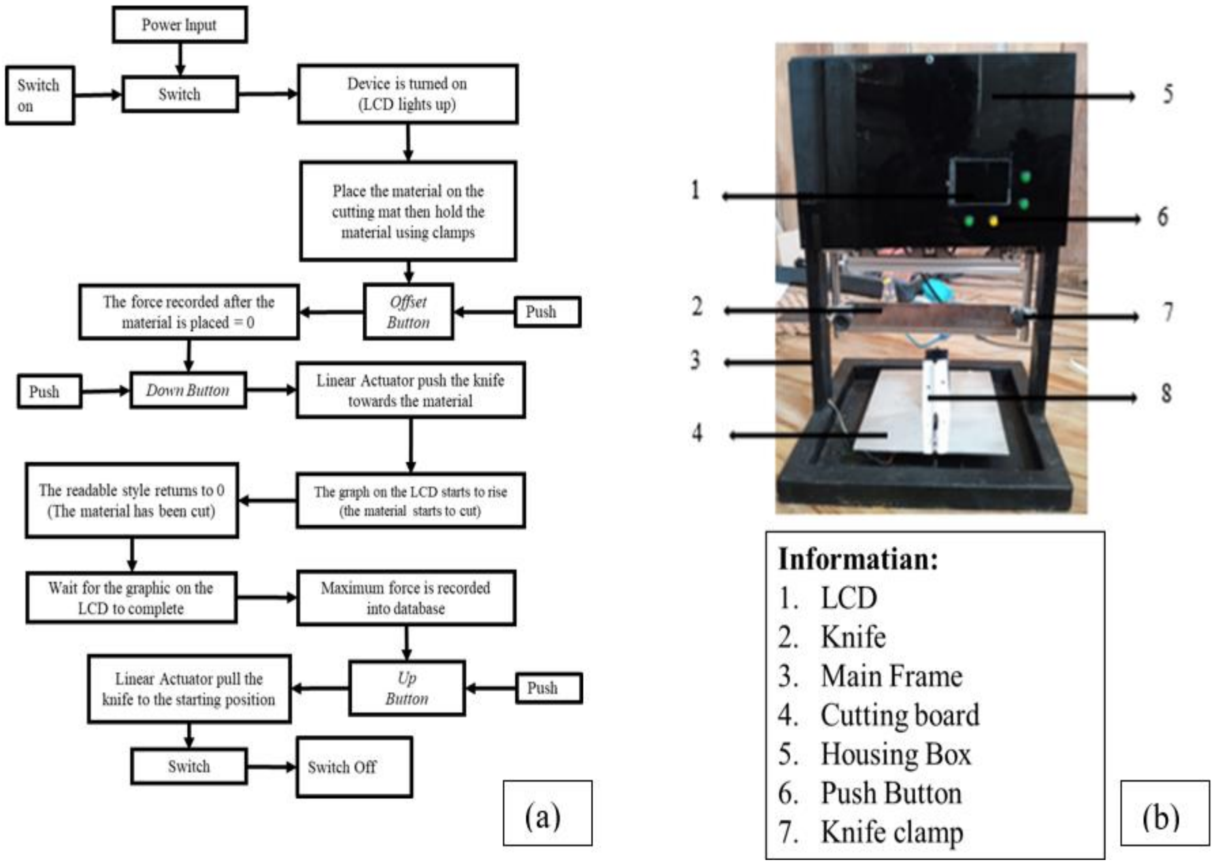


Figure 3. The Cutting Force Measurement device: (a) Working system, (b) Components

Table 2. Specification of CFM device

Specification	Information
Color	Black
Height	45 cm
Width	25 cm
Length	30 cm
Cutting mat width	20×20 cm
Maximum height material	10 cm
Weight	8 kg
LCD	320×480 pixel
Blade length	20 cm
Cutting speed	5.88 mm/s
Maximal force actuator	2000 N
Maximal force measured	200 N
Power	19.8 Watt

connect or disconnect the electrical current from the power source to the load. The placement of material onto the tool is done manually. To ensure that the material remains stationary during cutting, a clamp is utilized to secure it. The tool is equipped with four buttons that control the system: an offset button, buttons to raise and lower the linear actuator, and a start button. In addition to displaying measurement results directly on the LCD screen, the system also allows the measurement data to be accessed via a database in formats such as TXT or Excel files.

3.2. Structural Design

The design results of the cutting force measurement tool can be seen in Figure 4. The cutting force measurement tool consists of several main components, including the main frame, cutting base, housing box, material clamp, blade, and control system. The control system serves as a core component in the cutting force measurement system utilizing a strain gauge sensor. This system manages all the components within the tool. The control system comprises several key components, including the Arduino Mega, TFT LCD 320x480, HX711 IC, Start Button, 10-kΩ Resistor, Offset Button, Load Cell, Linear Actuator, Step down LM2596, and BTS7960B 43A Motor Driver. The control system functions to regulate the overall operation of the cutting force measurement tool. In addition to controlling data readings from the sensor and displaying them on the LCD, the system also manages the mechanical motion performed by the linear actuator. The linear actuator drives the blade toward the material until the material is fully cut. The sensor measures the force required during the cutting process in the form of analog data. The analog data read by the sensor is converted into digital data by the HX711 module. The measurement results are displayed on the LCD as a graph representing the cutting force magnitude over time. The graph on the LCD continuously updates throughout the cutting process until the material is completely severed. Once the process is complete, all data are stored in a database using a microSD card installed in the device. The cutting force testing was conducted using three stainless steel knives with a thickness of 3 mm and cutting angles of 10, 15, and 20 degrees.

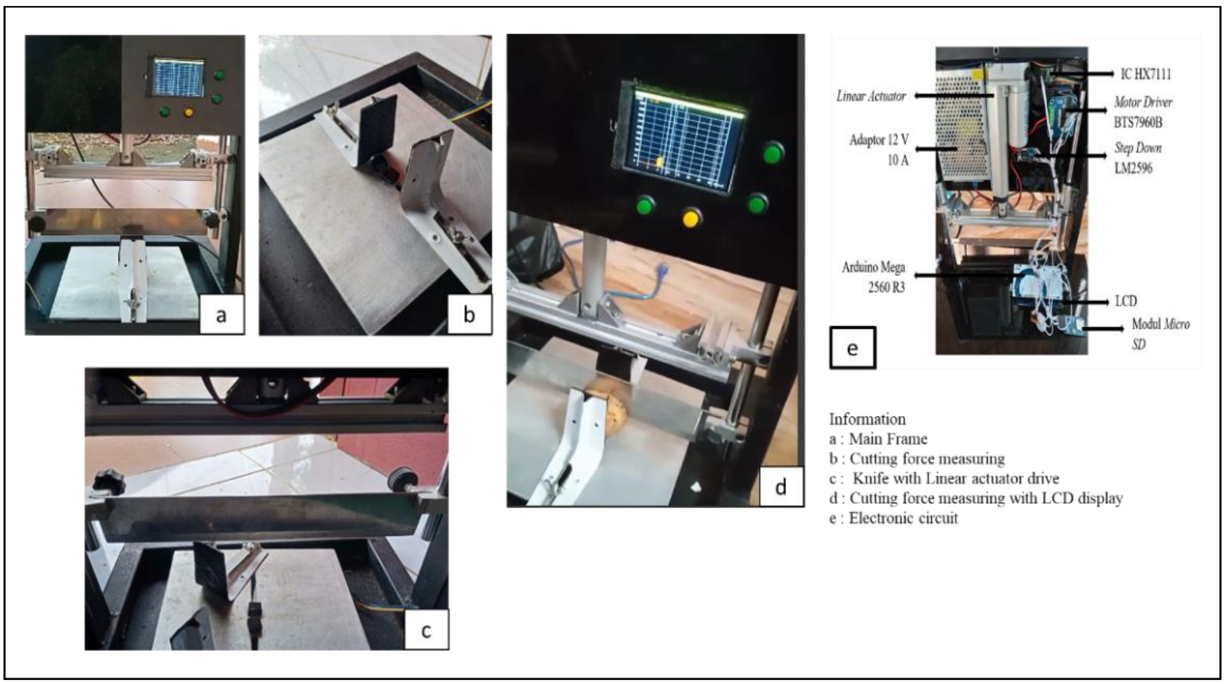


Figure 4. Structural design of CFM device

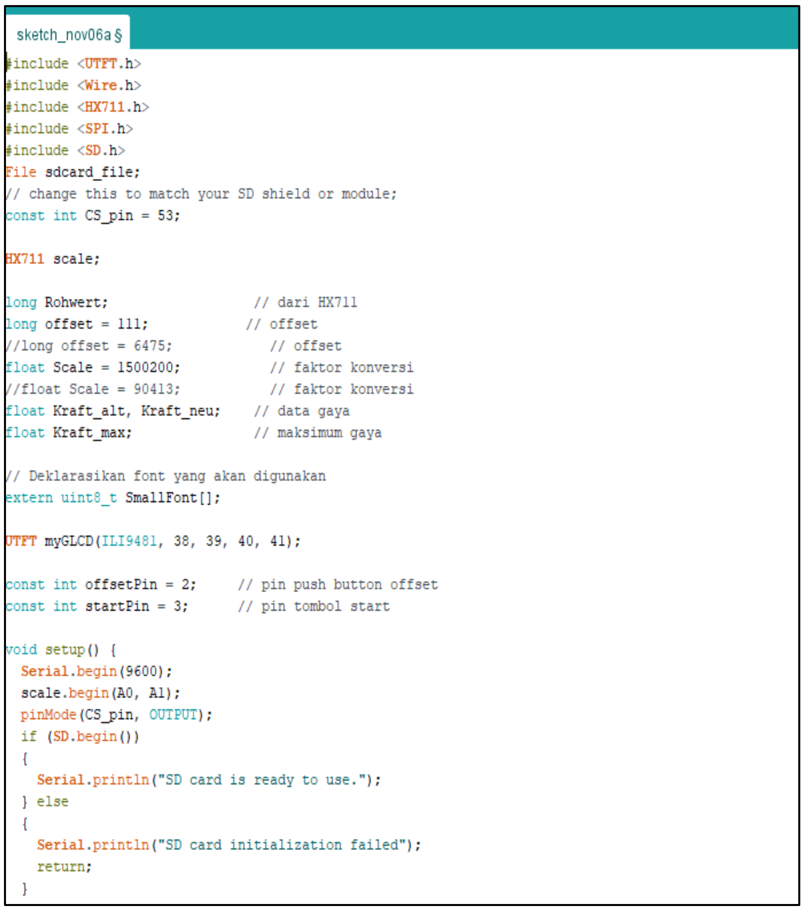
3.3. System Power Requirement

The power in the system is distributed using an AC power source, which is converted into DC electricity via an adapter. According to the adapter specifications, it operates at a voltage of 12V and requires a current of 10 A. The main component requiring electrical power is the linear actuator, with an input of 12 volts and a minimum current requirement of 1.5 A. The Arduino Mega has a voltage limit of 5 volts, with each input and output pin requiring a current of 40 mA. A total of 9 digital and analog pins are used, namely D2, D3, A0, A1, D38, D39, D40, D41, and D53, which are connected to a 5-volt supply. Hence, the power required to operate the entire system during operation can be calculated using the Equation below.

$$\text{Power} = (12\ \text{volt} \times 1.5\text{A}) + (5\ \text{volt} \times (0.04 \times 9)\ \text{A} = 19.8\ \text{W}$$

3.4. Calibration and Validation

Calibration is performed to determine the accuracy of force readings by the sensor by comparing the sensor readings (predicted value) with the actual measurements (true value). The calibration process is conducted 10 times using the actual force. Calibration of this tool is carried out using weights, which serve to determine the actual value of the material used for calibration. The readings from the sensor can be observed on the Serial Monitor in the Arduino IDE application. To ensure the actual force applied by the weights matches or approximates the force displayed on the Serial Monitor, the scale in the program must be accurate or close to the true value. The calibration programming in the Arduino IDE application is shown in Figure 5 and calibration graph in Figure 6.


sketch_nov06a §

```
#include <UTFT.h>
#include <Wire.h>
#include <HX711.h>
#include <SPI.h>
#include <SD.h>
File sdcard_file;
// change this to match your SD shield or module;
const int CS_pin = 53;

HX711 scale;

long Rohwert;                 // dari HX711
long offset = 111;           // offset
//long offset = 6475;           // offset
float Scale = 1500200;          // faktor konversi
//float Scale = 90413;          // faktor konversi
float Kraft_alt, Kraft_neu;    // data gaya
float Kraft_max;              // maksimum gaya

// Deklarasikan font yang akan digunakan
extern uint8_t SmallFont[];

UTFT myGLCD(ILI9481, 38, 39, 40, 41);

const int offsetPin = 2;     // pin push button offset
const int startPin = 3;      // pin tombol start

void setup() {
  Serial.begin(9600);
  scale.begin(A0, A1);
  pinMode(CS_pin, OUTPUT);
  if (SD.begin())
  {
    Serial.println("SD card is ready to use.");
  } else
  {
    Serial.println("SD card initialization failed");
    return;
  }
```

Figure 5. Sensor calibration program

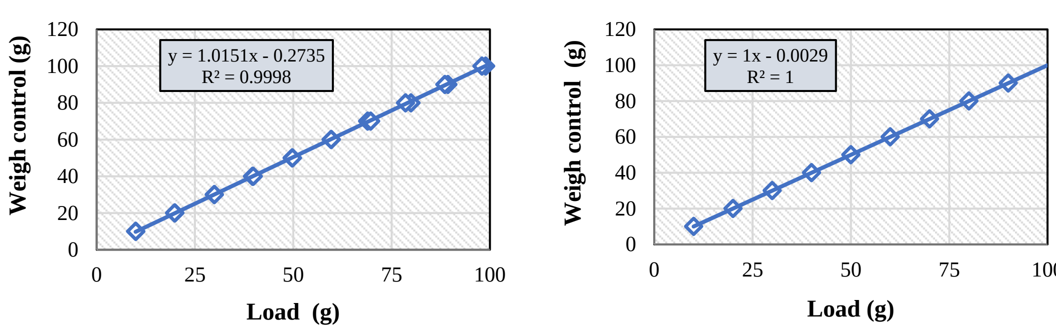


Figure 6. Sensor calibration (left) and validation graph (right)

Based on the calibration results and validation shown in Figure 6, it can be observed that, after 20 trials with different loads, an R^2 value of 0.9998 was obtained. Since the regression value is close to 1, the sensor readings can be considered highly accurate (Sandri, 2022). For the validation, the value of R^2 was 1. Therefore, the comparison between the measured values and the actual load values indicates that the sensor readings are correct.

3.5. Connection to Database

The Arduino Mega 2560 is not equipped with a Wi-Fi module or a micro SD module; therefore, additional modules are required for database creation. In this study, a micro SD module was used to store the database. Cutting force measurements were conducted using a load cell sensor to determine the force needed during the cutting process. Once the sensor measures the force and generates analog data, the data is transmitted to the HX711 module, where it is converted into digital data before being sent to the Arduino Mega for processing. Subsequently, the processed data is transferred to the micro SD module for storage in micro SD card. The stored data is formatted as a .txt or .csv file, making it easily accessible using applications such as WPS or Microsoft Excel. Database program is in Figure 7.

```
program_alat_ukur_gaya_potong

if (Kraft_neu > Kraft_max) {
  Kraft_max = Kraft_neu;
  Serial.print("Berat max :");
  Serial.print(Kraft_neu);
  Serial.println("\t n");
  myGLCD.setColor(255, 0, 0);
  myGLCD.print("        ", 180, 18);
  myGLCD.printNumF(Kraft_neu, 3, 180, 18);
  myGLCD.setColor(0, 255, 0);
  if (sdcard_file) {
    sdcard_file.print ("Berat Max: ");
    sdcard_file.print (Kraft_neu);
    sdcard_file.print ("Newton: ");
    sdcard_file.print (Kraft_max);
    sdcard_file.println (" N");
    sdcard_file.close();
  }
  // if the file isn't open, pop up an error:
  //     else {
  //       Serial.println("error opening data4.xls");
  //     }
}
```

```
  myGLCD.print("        ", 70, 18);
  myGLCD.printNumF(Kraft_max, 2, 70, 18);
  sdcard_file = SD.open("Alat_Geo_Potong.xls", FILE_WRITE);
  if (sdcard_file) {
    sdcard_file.print ("Berat Max: ");
    sdcard_file.print (Kraft_neu);
    sdcard_file.print ("Newton: ");
    sdcard_file.print (Kraft_max);
    sdcard_file.println (" N");
    sdcard_file.close();
  }
  // if the file isn't open, pop up an error:
  //    else {
  //      Serial.println("error opening data4.xls");
  //    }
  Serial.print("Newton :");
  Serial.print(Kraft_max);
  Serial.println("N");
  Serial.println();

  if (Kraft_neu >= 0 && Kraft_neu <= 200) {
    myGLCD.drawLine(50 + (i - 1), 290 - Kraft_alt, 50 + i, 290 - Kraft_neu);

    Kraft_alt = Kraft_neu;
  }
}
```

Figure 7. Database program

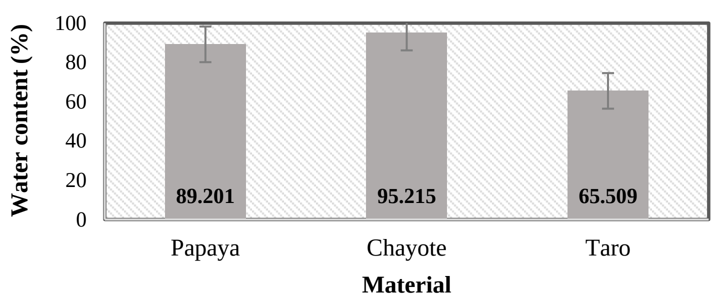


Figure 8. Water content of product

3.6. Water Content

The results of moisture content measurement (Figure 8) for each type of material was conducted to determine the initial moisture condition of the material prior to the cutting process. As shown in Figure 8, the moisture content for each material varies, with chayote having the highest average moisture content at 95.215%, followed by papaya at

893.2%, and taro at 65.5%. Moisture content measurements were conducted on five samples for each material. Tubers generally have relatively high moisture content, particularly when they are fresh. The moisture content of tubers decreases after storage (Solihin *et al*., 2015).

3.7. Cutting Force

Cutting force is vital information required in the design and analysis of cutting tools and machines for optimization purposes (Nasution *et al*., 2021). This information is highly beneficial for predicting the energy required and the costs incurred during the cutting process. Cutting force is measured to determine the force necessary to cut a material using a cutting blade. The measurement of cutting force is conducted using a specially designed tool equipped with a graph display feature, allowing the required force during the cutting process to appear periodically, with the maximum force displayed at the center of the screen. The maximum force required during the cutting process is automatically recorded into the database, enabling users to access cutting force data more conveniently. A comparison graph of cutting forces for Taro, Chayote, and Papaya for three kind of knife are shown in Figure 9, 10, and 11. The figures show the cutting process on a knife with 3 different commodities. In each figure, the measurements are shown at 3 different knife blade angles. The left is for the knife angle 10°, the middle for knife angle is 15°, and the right side for the sharpness angle of 20°. In each graph there are results of measuring the cutting force for 5 repetitions.

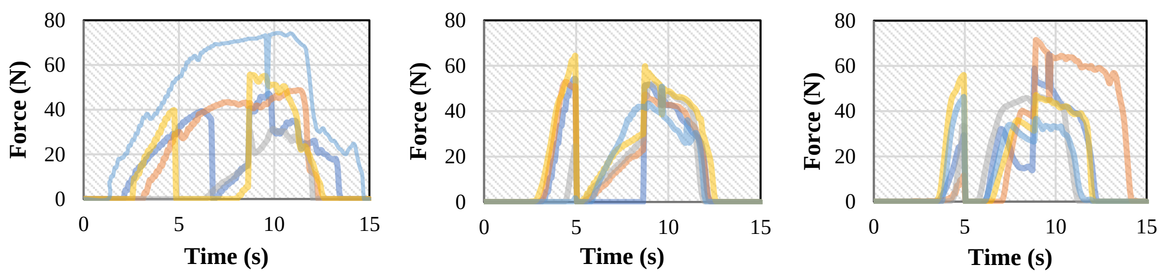


Figure 9. The comparison of cutting force for taro using three blade angles. From left: 10°, 15°, and 20°

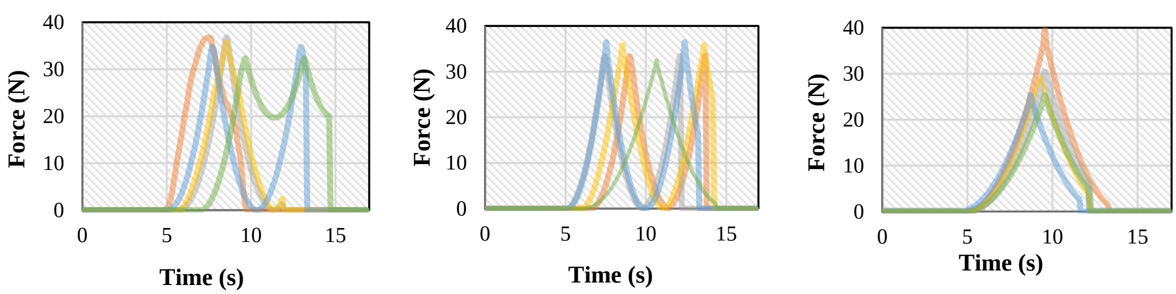


Figure 10. The comparison of cutting force for chayote using three blade angles. From left: 10°, 15°, and 20°

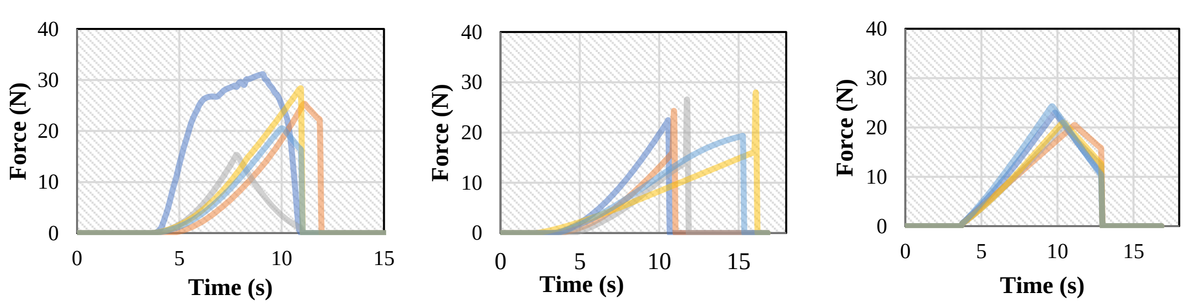


Figure 11. The comparison of cutting force for papaya using three blade angles. From left: 10°, 15°, and 20°

From Figure 9, 10, and 11, the cutting results of the materials can be observed, where in image 9, it is evident that the cutting result for taro is uneven. Based on figures, taro exhibits a higher cutting force compared to other materials. The characteristics of materials significantly influence the cutting force; taro has a coarser texture than the other materials, which affects the cutting result. In addition to taro characteristics, the thickness of the fruit-cutting blade caused the taro to crack before being fully cut, resulting in uneven cuts. During the cutting process, cracking sounds were repeatedly heard before the material was completely cut. According to (Aboubakar *et al*., 2009) taro has a dense cell structure and strong fibers. These physical characteristics make it susceptible to fractures caused by the blade, leading to the audible cracking sounds.

Based on the graph comparing the cutting processes of various materials, it can be observed that before the material is cut, the graph indicates zero force, measured at 0 Newton. At this stage, the cutting system is in a ready state without any resistance from the material to be cut. When the knife starts to make contact with the material, the graph shows a gradual increase corresponding to the force required during cutting. As the linear actuator pushes the knife toward the material, the force reading stabilizes at 0 Newton until the knife begins to penetrate the material, after which the graph shows a steady rise. This continues until the graph reaches the peak force, representing the maximum resistance encountered while cutting the material. This change reflects the material resistance intensity against the blade during the cutting process. Over time, all changes in the required force during the cutting process are depicted in the graph. After the cutting process is completed and the material is successfully cut, the graph instantly returns to 0 Newton. This occurs because no further pressure is exerted on the sensor after the material is cut, and thus no force is detected by the sensor. This is facilitated by pressing the offset button before initiating the cutting process. The offset button resets the sensor to read a baseline force of 0 Newton. Consequently, the graph accurately displays force variations throughout the cutting cycle, from the initial state to zero upon completing the process.

Based on the graphs above, it is evident that taro exhibits a higher cutting force compared to the other materials which is 74.3 N, 39.77 N for chayote, and 31.1 N for papaya. According to the moisture content data, taro has a lower moisture content than the other materials, resulting in significantly higher hardness. Additionally, larger size of taro compared to the other materials prolongs the cutting process, thereby requiring a higher force to complete the cut. This is primarily due to the characteristics of the material being cut. Apart from material characteristics, cutting force is also influenced by the type of knife used. In this cutting force measurement, a knife commonly used for cutting fruits was employed. During the cutting process, the material wall adhered to the knife, increasing the force required. According to Umroh *et al*. (2019), the knife sharpness angle and cutting angle significantly affect the cutting force. Moreover, the material and thickness of the knife also influence the cutting force, as the knife characteristics determine the cutting outcome. The cutting results are shown in Figure 12.

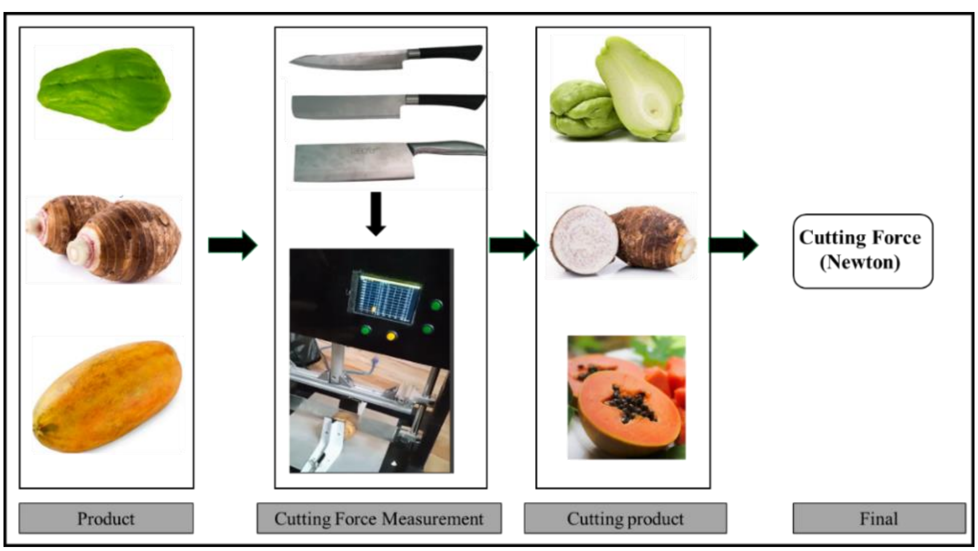


Figure 12. Cutting force measurement

3.8. Cutting Speed

The cutting speed is measured by recording the time required for the linear actuator to fully extend its shaft. The linear actuator used in this tool has a shaft length of 100 mm. To determine the cutting speed, the time needed for the shaft to fully extend was measured using a stopwatch. The graph depicting the cutting speed measurement results can be seen in Figure 13. The graph above illustrates differences in cutting speed among papaya, chayote, and taro. The highest cutting speed was observed for chayote at 6.1 mm/s, followed by papaya at 5.8 mm/s, and taro at 3.5 mm/s when using a blade with a 20° cutting angle. Blades with cutting angles smaller than 20° exhibited lower cutting speeds. This indicates that using blades with larger cutting angles facilitates the cutting process, resulting in higher cutting speeds.

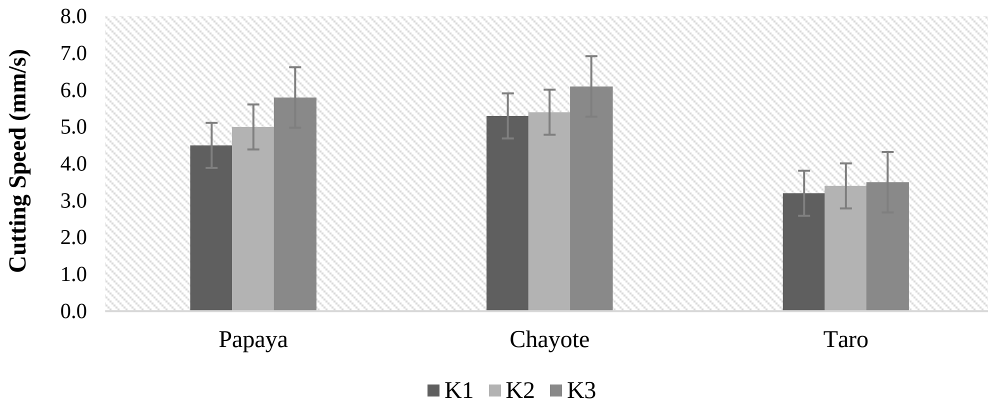


Figure 13. Cutting speed for three material at different blade angles (K1 = 10°, K2 = 15°, K3 = 20°)

4. CONCLUSION

Based on the conducted research, the following conclusions can be drawn: The Cutting Force Measurement device is capable of measuring cutting force on various materials. The load cell sensor readings are close to the actual values, with an R^2 value of 0.9998. The database system can effectively store the measurement data and is accessible through any device that can open .txt files, such as Microsoft Excel or WPS. The highest cutting speed was observed for chayote at 6.1 mm/s, followed by papaya at 5.8 mm/s, and taro at 3.5 mm/s when using a blade with a 20° cutting angle. Further research still provides the opportunity to develop a stronger frame by adding a more precise cutting force sensor.

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