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Development of A Gyratory Bladed Grinding Machine for Ripe Plantain Processing

Aiki Habeebullahi Opeyemi[1,]*, Buliaminu Kareem[2], Adeola Adeyemi James[3]

Abstract

The processing of ripe plantains faces significant challenges, including inefficient grinding and mortar pasting methods, inconsistent paste quality, and maintenance difficulties with existing equipment. This paper presents the development of a gyratory bladed grinding machine specifically for ripe plantain processing. SOLIDWORKS CAD software was applied to create the machine's CAD, or computer-aided design, model. The design analysis of the machine components was conducted, and appropriate materials were selected to accommodate the unique properties of ripe plantains. Performance evaluation of the machine was conducted and through the series of tests, the machine has an operational efficiency of 73.32% and can grind 100 plantains within an hour. This machine bridges the gap between small-scale farming and industrial food production, contributing to localised food processing and enhancing agricultural advancement.

Keywords: Ripe plantains, gyratory bladed grinding machine, food production, grinding

INTRODUCTION

Plantain (Musa spp., family Musaceae) is a staple food crop cultivated in tropical and subtropical regions, playing a crucial role in food security and economic sustainability, especially in developing countries in Africa and Latin America (Ploetz et al., 2007; Adheka et al., 2018) [10]. With distinct culinary applications and nutritional benefits, plantains are versatile, consumable at various ripeness stages, and rich in carbohydrates, dietary fibre, and essential vitamins and minerals (Falade and Oyeyinka, 2015). Despite their importance, plantain cultivation and processing encounter significant challenges, such as fungal diseases like Black Sigatoka, Fusarium Wilt which is also known as Panama disease and the need for effective post-harvest processing techniques (Ploetz, 2015; WUR) [9]. Due to the country's rapid population growth and the non-farming urban populations' growing need for quick, simple, and wholesome meals, plantains have become much more fashionable in Nigeria in recent years. In addition to being a basic food for many people in more humid areas, the plantain are also a favorite snack and delicacy in other areas. Plantain chips are a rapidly expanding industry that is thought to be the cause of the strong demand now present in this country.

Plantain grinding is an essential process in plantain value chains, transforming raw fruit into paste or flour for various culinary uses, the process involves reducing plantains to smaller particles and can be used in different food preparations. Traditionally, plantain grinding involves manual pounding, a labour-intensive and time-consuming method. Mechanized solutions have been explored, improving efficiency, and meeting the rising demand for plantain products in West African countries. Plantains (Musa paradisiaca) are widely

***Author for Correspondence**
Aiki Habeebullahi Opeyemi
E-mail: aikiopeyemi@gmail.com

[1–3]Research Scholar, Department of Industrial and Production Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

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recognized for their significant nutritional value, making them an important staple food in many tropical and subtropical regions. Recent studies have provided comprehensive insights into the nutritional composition of plantains, highlighting their potential in addressing various nutritional needs. Adeolu and Enesi (2019), in their study on Nigerian plantain cultivars, reported that plantains are excellent sources of carbohydrates, dietary fibre, vitamins, and minerals [2].

Olutomilola E. O. (2019) researched on a machine design to eliminate manual peeling of plantain, and the design simulation results showed a maximum stress of 2.195 × 108 N/m2, which is lower than the yield strength of the selected frame material; a maximum resultant displacement of 0.6959 mm; and a FOS of 2.414. This shows that the machine will serve its intended purpose upon development [7].

Oyejide et al. (2018) worked on the development of an improved plantain processing machine which contains of several units such as Pulveriser, Dryer, Scraper, and Miller. The efficiency of the machine was 81.87% and it had a throughput of 0.3493kg/mins. The products obtained from the machine was of high quality [8].

Adefidipe et al. (2024) researched on the performance evaluation of a power rotary slicing machine, the machine is developed to aid production of chips in plantain, cocoyam, cassava, and other related farm products. The machine had an efficiency of 83% and a throughput of 22.8kg/hour [1].

Ezugwu et al. (2019) developed a motorized plantain slicer for optimal chips production to meet up with increased demand for plantain chips in Nigeria. The machine had a maximum efficiency of 96.84% with a throughput of 1087.72kg/hour [5].

MATERIALS AND METHOD

Multiple conceptual design ideas that could address the problem were generated. The most promising concept was chosen, and a detailed design was created using SOLIDWORKS. This involved developing engineering drawings, specifying dimensions, selecting appropriate materials, and deciding on manufacturing processes.

Components of the Machine

Prior to design and then create, it is especially crucial to understand materials and their properties. The following criteria were taken consideration when determining the machine's components:

Physical and mechanical properties (physical characteristics include density, linear expansion coefficient, thermal conductivity, boiling point, etc.) and (Mechanical aspects include things like toughness, yield strength, shear stress, ductility, elasticity, strength, and flex.)

The materials' suitability for the sought operating conditions. For instance, whether or not rusting is a factor. Additional elements like the materials' cost, durability, availability, ease of maintenance, and manufacturing specifications

The components used in our plantain grinding machine are:

1. Hopper
2. Grinding Compartment
3. Gyratory Bladed Drum
4. Motor
5. Hopper Cover

Hopper

The Plantain fingers is fed through the hopper into the grinding compartment.

Grinding Compartment

It is the portion of the machine where the grinding process is carried out, and it consists of the gyratory bladed drum, extractor(outlet) with a cover which is bolted at both ends.

Gyratory Bladed Drum

It is the active or rotating portion of the machine. It consists of a cylindrical drum with an open end which is fixed on the threaded shaft of a motor and secured with a nut at the end of the shaft. The drum consist of four grooves distributed equidistantly around its circumference.

Motor

The machine makes use of a 1hp D.C motor. It uses a direct drive system; the drum is fitted directly onto the motor shaft.

Hopper Cover

This help to prevent the hopper from getting contaminated during use and when in storage.

DESIGN OF THE SYSTEM

The machine base/stand, grinding room hopper volume, and motor capacity are the main design elements. After that, the plantain grinding process was put together using bolts and welding. There are several components that make up the grinding machine.

These are the Body Casting, Hopper (feeding chute), electric motor, gyratory blade and some essential parts like bolts and watchers, Covers. The Grinding compartment consists of the drum and removable cover and the drum is powered directly by the motor shaft. The plantain is loaded into the hopper and is grinded through the grooves of the rotating gyratory blade as it falls through the sides of the chamber and the drum to the extractor below from where it is collected in a container [2,3].

Design of the Machine Frame

The machine frame carries the whole component of the plantain grinder therefore the strength and stability were considered. Human factor/ergonomics was a major factor considered when designing the frame for easy handling and operation.

Dimensions: 334 mm L x 230 mm W x 517 mm H
Estimated total weight of all components: 5kg.
Material: Stainless steel

1. Static Load Analysis
   Total weight = 5 kg
   Safety factor = 1.5
   Design load = 5 kg × 1.5 × 9.81 m/s² = 73.575 N
2. Beam Deflection (for base support)
   Using the simplified beam deflection formula:
   $\delta = (WL^3) / (48EI)$

   Where:
   δ = maximum deflection
   W = total load (73.575 N)
   L = beam length (334 mm)
   E = Young's modulus for stainless steel (193 GPa)
   I = Second moment of area (assuming 20 mm x 20 mm square tube with 1.5 mm wall thickness, I = 2,708 mm^4)
   $\delta = (73.575 \times 334^3) / (48 \times 193 \times 10^9 \times 2{,}708 \times 10^{-12})$
   $\delta = 0.076$ mm

This deflection is exceedingly small, indicating a sufficiently rigid frame.

Determination of Hopper Capacity

Where:
Required Capacity: 2.0 kg.
Shape of Hopper: Truncated pyramid
Material used: Stainless steel.

1. Hopper Volume:
   Density of plantain ≈ 980 kg/m³
   Required volume = 2.0 kg / 980 kg/m³ = 0.00204 m³ = 2.04 L
   Top opening(inlet): 180 mm x 180 mm
   Bottom opening(outlet): 70 mm x 70 mm
   Height: 200 mm
2. Actual volume = $1/3 \times h \times [A1 + A2 + \sqrt{(A1 \times A2)}]$
   Where:
   h (height) = 200 mm
   A1 (inlet area) = 180 × 180 = 32,400 mm²
   A2 (outlet area) = 70 × 70 = 4,900 mm²
   Actual volume = $1/3 \times 200 \times [32{,}400 + 4{,}900 + \sqrt{(32{,}400 \times 4{,}900)}]$
   = 3326666.667 mm3
   = 3.33L
   Density of Plantain = 980kg/m3 = 0.98kg/L
   Maximum mass capacity = 3.33 × 0.98 = 3.26kg
   The designed hopper is adequate for the required capacity.

Determination of Grinding Disc Speed

Where d = Diameter of the drum
D = Disc Circumference
R = Rotational Speed
g = Acceleration due to gravity
$D = \pi \times d$
$R = g / D$

Determination of Power Requirement

Using Bond's Law for grinding:
$W = 10 \times Wi \times (1/\sqrt{P} - 1/\sqrt{F})$
Where:
W = Work input (kWh/ton)
Wi = Work index for plantain
P = Product size
F = Feed size assumed based on typical plantain thickness

Determination of Torque and Power Consumption

The machine uses a one hp (745.7 watts) D.C electric motor which is powered by a car battery (12V, 50Ah) and it is a direct drive system. Assuming a desired throughput, the motor speed must match the required disc speed. We used a speed controller to adjust the DC motor to this speed [4].

1. Torque
   $T = (P \times 60) / (2\pi \times N)$
   Where:
   T = Torque (Nm)
   P = Power (W)
   N = Speed (rpm)
2. Power Consumption
   Q = Throughput (kg/hour)

E = Energy required to process Q
W = Work input (kWh/ton)
Energy required = Work input × Throughput
E = W × Q

Determination of Machine Efficiency

Where:
Operational Efficiency (η_operation) = (weight of Input/weight of Output) × 100
Motor Efficiency:
Motor power: 1 horsepower = 745.7 watts
Assuming a typical DC motor efficiency of 80%
Efficiency of the motor (η_motor) = 0.80 or 80%
Operational Efficiency denoted as η_operation.
Overall Machine Efficiency:
η_overall = η_motor × η_operation

Design Drawing

The design drawing of the machine was conducted using SOLIDWORKS and the respective views and sections of the machine were produced. The orthographic view of the machine is shown in Figures 1 and 2.

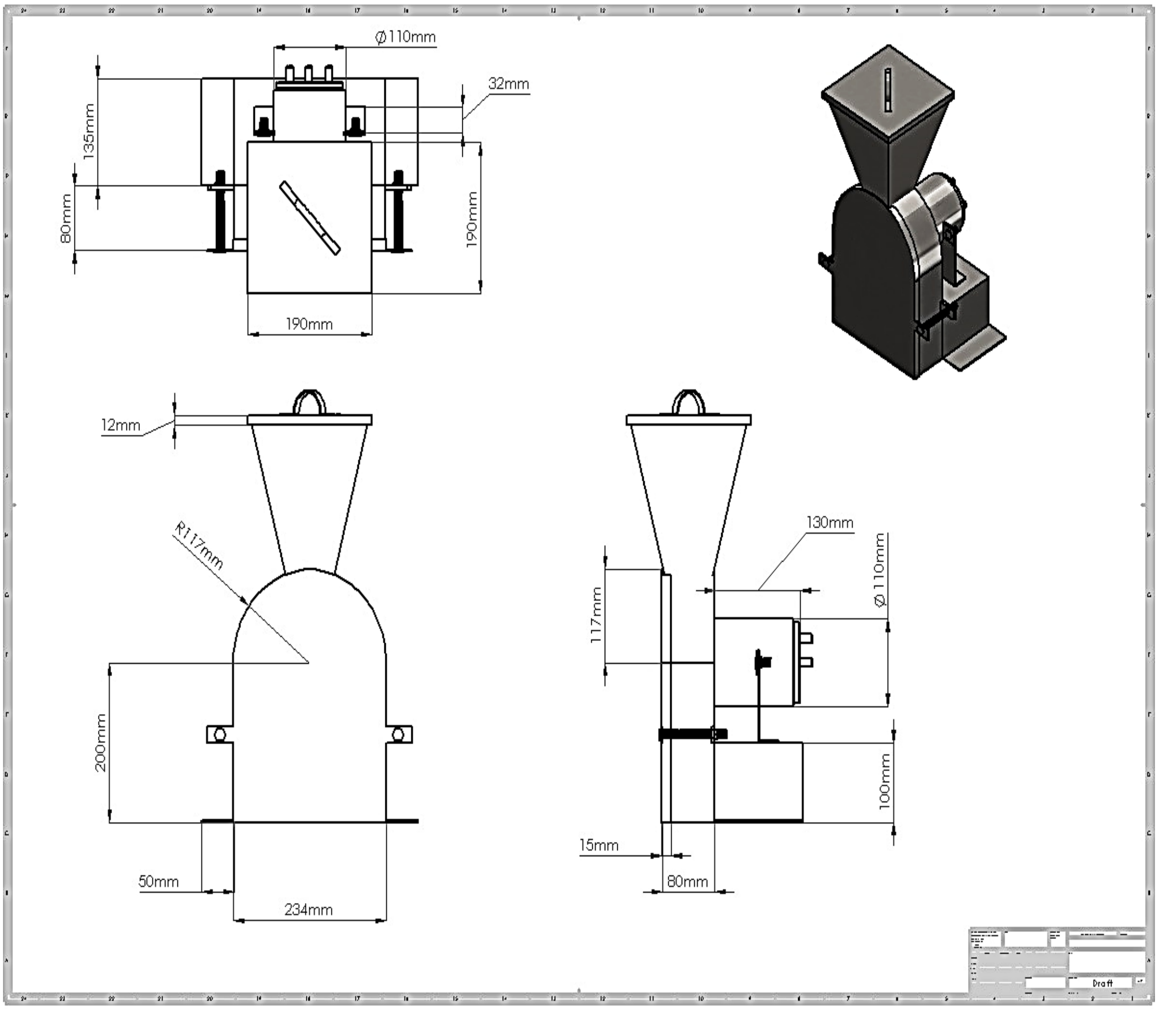

Figure 1. Orthographic View (a) of the Design.

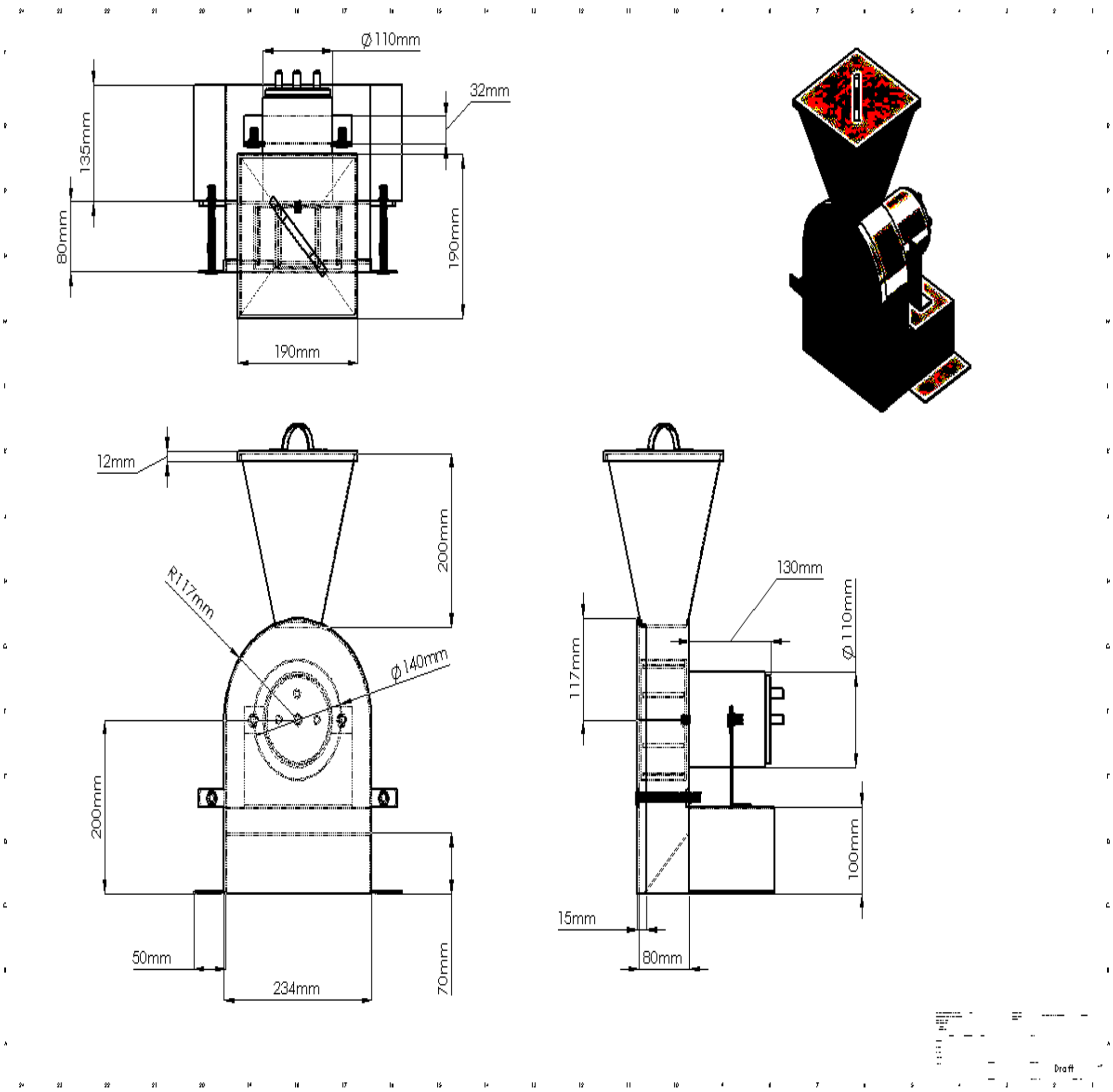

Figure 2. Orthographic View (b) of the Design

Fabrication Procedures

Fabrication means the permanent joining of materials to form the structural or machine parts. The fabrication of this machine was conducted at an engineering workshop in Federal University of Technology, Akure (FUTA) where the rigorous activity of joining and welding was conducted [5,6].

1. *Fabrication of Machine Frame/Base:* Marking out the dimensions of the base plate to be formed as specified on the design, the length of the base is 230 mm, having a width of 135 mm and a height of 100 mm.The base is in form of a seat formed through bending from a stainless-steel sheet of length 530 mm and width 135 mm.
2. *Fabrication of Hopper and Cover:* The grinding machine hopper was constructed using a stainless-steel plate and the hopper opening with dimension 180 mm by 180 mm, the hopper inlet (to the grinding compartment) with dimension 70 mm by 70 mm. The various parts of the hopper were cut and joined together using an electric arc welding machine. The hopper cover was fabricated using a stainless-steel plate with dimensions of 200 mm by 200 mm of which 10 mm was folded round the edges and a piece of steel was riveted onto it to form a handle (Figure 3, 4).
3. Fabrication of Grinding Compartment: This is where the grinding disc is fixed and is the compartment where already peeled plantain is processed before been ejected through the outlet.

It has an overall dimension of height 290 mm by Width 230 mm by Depth 80 mm. It is made from stainless-steel plates, and it comprises majorly of the main compartment, cover, and outlet. The cover is attached to the main compartment by the means of two bolts.

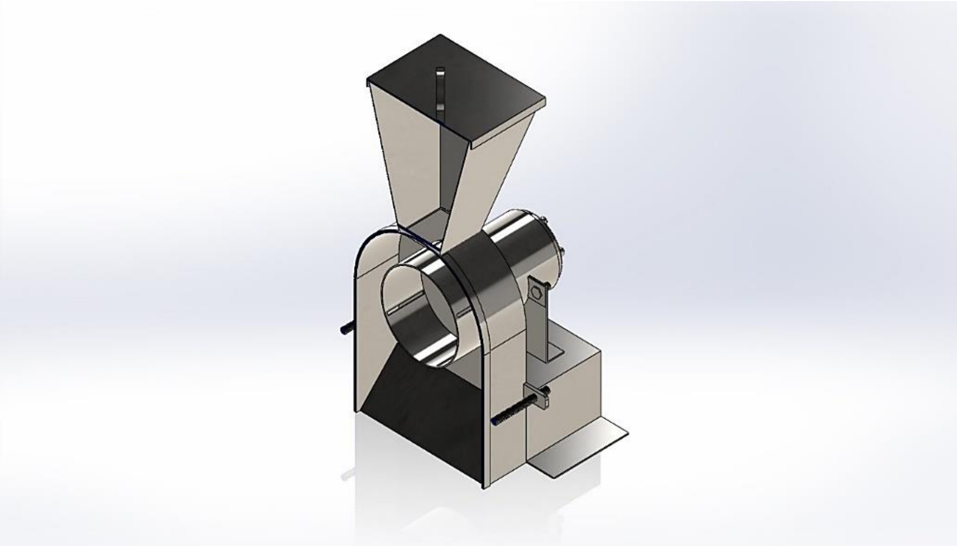

Figure 3. Sectional View of the Machine.

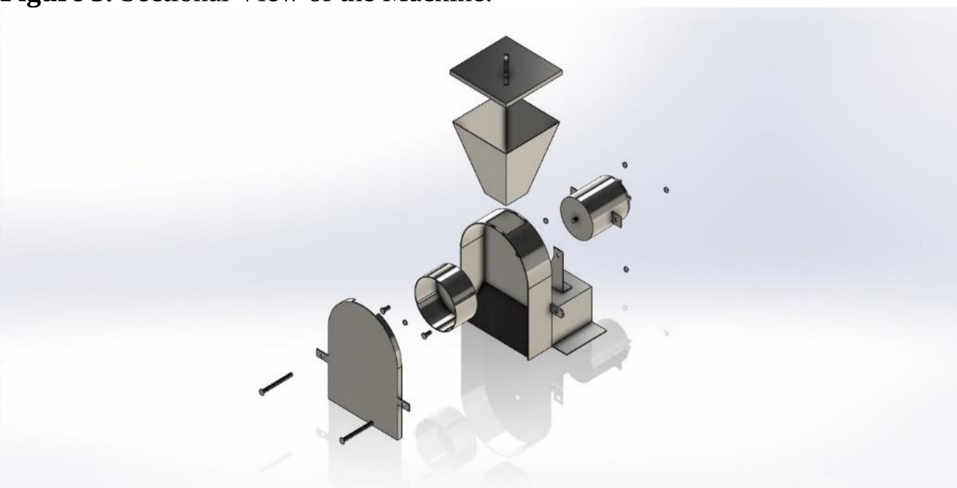

Figure 4. Exploded View of the Machine.

4. *Fabrication of Gyratory Bladed Drum:* The drum is made from stainless steel which is fabricated in form of an open drum with dimensions Diameter 140 mm and Depth 60 mm. Four grooves were made at points equidistant around the circumference of the drum. The stainless sheet was bent round and welded to the already cut-out base to form the grinding drum, and the edges was grinded to give it a consistent shape and to check for integrity of the weld. A hole was drilled in the centre of the drum and a nut was welded to fix the disc on the electric motor.
5. *Assemblage of the Machine Components:* The machine's electric motor was mounted behind the grinding compartment on top of the machine base and connected to the grinding disc through its threaded shaft.
   Final additions such as (grinding, body filling, painting) were conducted where necessary on the machine for enhanced aesthetics.

RESULTS

The testing of the machine was conducted at the Central Mechanical Workshop, Federal University of Technology, Akure (FUTA). The grinding machine was assessed under no load condition to check for faults, fine tuning and to ensure it is in proper working order. Having ascertained the condition of the machine, a series of five tests was conducted with the machine. Five batches of ripe plantain with different quantity were grinded to evaluate its performance efficiency. Table 1 presents the results of these tests.

Table 1. Showing the results gotten when conducting test samples.

Test	Number of Plantains	Mass of Unpeeled Plantain (g)	Mass of Peeled Plantain (Input) (g)	Mass of Grinded Plantain (Output) (g)	Mass Loss (g)	Mass Loss (%)
1	1	193	137	66	71	51.82
2	2	316	220	137	83	37.73
3	3	524	371	308	63	16.98
4	4	571	385	325	60	15.58
5	5	830	549	487	62	11.29

The weight of the samples (unpeeled, peeled, grinded) was taken with a weighing balance and recorded. The machine took a time of 3 seconds to grind five plantains during the last test and lesser for previous test.

Performance Evaluation of the Grinding Machine

The experimental results reveal several important aspects of the plantain grinding machine performance across all tests, there was a substantial mass loss during the grinding process. The two outliers recorded were recorded during Test 1 and 2. During test 3-5, there was a more consistent mass loss ranging from 16.98% - 11.29%. As the number of plantains processed increased, there was a clear trend of decreasing percentage mass loss. This suggests that the machine operates more efficiently with larger quantities.

The efficiency of the grinding process varies significantly with the quantity of plantains processed. It was observed that:

1. For a single plantain (Test 1), the efficiency is quite low, with only 48.18% of the input mass being successfully ground and collected.
2. As the quantity increases, the efficiency improves dramatically, reaching 88.71% for five plantains (Test 5).

This indicates that the machine is designed to operate more efficiently with larger quantities, which is an important consideration for its practical application. The tests demonstrate the machine's ability to manage varying quantities of plantains, from a single plantain to a batch of five. The significant improvement in efficiency with larger quantities suggests that the machine is better suited for processing multiple plantains rather than individual ones.

Efficiency of The Grinding Machine

When calculating the overall efficiency of the machine, we combined operational and motor efficiency. We used the average efficiency from our tests as the operational efficiency and estimated mechanical based on standard values for similar machines.

Operational Efficiency (η_operation) = (weight of Input/weight of Output) × 100

Operational Efficiency (average from tests) = (48.18% + 62.27% + 83.02% + 84.42% + 88.71%) / 5
= 73.32%

Estimated Motor Efficiency = 80% (typical D.C motor efficiency)
Overall Efficiency = Operational Efficiency × Motor Efficiency

= 0.7332 × 0.80
= 0.5866 or 58.66%

CONCLUSION

The usefulness of plantain is numerous, it can be processed into chips, flour or in this case: plantain cake (Dodo Ikire). However, the traditional method of producing plantain cake pulp is tedious, time consuming and unhealthy. In this research work, a gyratory bladed grinding machine for plantain processing was successfully designed and fabricated. Tests were conducted to analyse its performance and output. Results from these tests indicates a grinding efficiency of 73.32%, and a processing capacity of 196g/s. This meets the requirements of both small and medium scale plantain cake processing industries. It can be scaled easily for large scale production needs. The grinded pulp was of uniform texture and thickness. Due to its low cost of production and, it will be suitable for use in Nigeria and other plantain producing countries in sub-Saharan Africa where mechanized solutions are not readily available. The machine is easy to operate, maintain and its environmental and user friendly.

The results indicate that while the machine performs well with larger quantities, there is significant room for improvement, especially when processing smaller amounts of plantains. The design should be optimized to maintain high efficiency across all batch sizes.

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