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Design, Fabrication and Performance Evaluation of Dried Plantain (*Musa Paradisiaca*) Grinding Machine from Locally Sourced Materials

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ABSTRACT
Plantain (*Musa paradisiaca*) is a major staple food crop of the humid tropics and a significant source of food and income in Nigeria, yet post-harvest losses remain high with an estimated 20–40% of production due to the perishability of the fresh fruit and the inadequacy of local processing infrastructure. Conversion of unripe plantain into shelf-stable flour is the most practical route to loss reduction, but the critical size-reduction operation is still performed largely by laborious traditional methods or with expensive, imported general-purpose mills that are poorly suited to the hard texture of dried plantain chips. This study reports the design, fabrication and performance evaluation of a dedicated dried plantain grinding machine constructed entirely from locally sourced materials. The machine comprises a tapered stainless-steel feed hopper, an impact–attrition grinding chamber lined with a removable perforated screen, a balanced medium-carbon steel rotor and beater assembly, a stainless-steel discharge chute and a mild-steel angle-iron frame, driven by a 2 hp single-phase electric motor through a belt-and-pulley transmission. Fabrication employed standard workshop processes of marking out, cutting, forming, machining, welding, drilling, assembly and finishing, followed by no-load and load testing. In replicated performance tests with dried unripe plantain chips at approximately 10% moisture content (wet basis), a 5.20 kg batch was milled in a mean time of 4.25 min, yielding 4.78 kg of flour. These figures correspond to a throughput capacity of 74.29 kg/h, a milling (recovery) efficiency of 91.92% and a material loss of 8.08%, while approximately 85% of the product passed a 500 µm sieve and the flour retained its natural creamy-white colour with no evidence of thermal damage. The machine is simple to operate, easily dismantled for cleaning, and considerably cheaper than comparable imported mills. It therefore offers a viable, affordable and hygienic solution for small- and medium-scale plantain flour production, with direct application to post-harvest loss reduction and value addition in developing economies.

Keywords:
Plantain Flour,
Grinding Machine,
Size Reduction,
Hammer Mill,
Post-Harvest Losses,
Local Content Development,
Milling Efficiency.

INTRODUCTION

Plantain (*Musa paradisiaca*) is one of the most important staple food crops of the humid tropics and occupies a central place in the food economy of West and Central Africa. Global production runs into tens of millions of tonnes annually, with African countries notably Cameroon, Ghana, Uganda, Nigeria and Côte d'Ivoire accounting for a substantial share of output (FAO, 2021). Nigeria is among the world's largest producers, with most of its output coming from smallholder farmers in the southern rain-forest belt. The crop is valued for its high content of carbohydrates, dietary fibre, potassium and vitamins A, B6 and C, and it provides food and income for millions of rural and urban households (Adeniji et al., 2010).

Plantain is consumed at every stage of ripeness, and the stage largely dictates the mode of preparation. Unripe (green) plantain is firm and starchy and is boiled and eaten with stews, or sliced thinly and fried into crisp chips. Ripe (yellow) plantain, with its balance of starch and sugar, is fried into the sweet golden pieces known locally as *dodo* or roasted whole over coals as *bole*. Overripe fruit, soft and sugar-rich, is mashed into pancakes, fritters and other traditional dishes. Among these forms, powdered plantain flour is the most versatile and nutrient-dense product. Unlike the fresh fruit, which must be consumed within days of ripening, the flour is shelf-stable for six months or more, is light and inexpensive to package and transport, and can be reconstituted or incorporated into foods throughout the year, independent of the harvest season. Its versatility derives from its functional properties: it is rich in resistant starch and dietary fibre, exhibits good water-absorption and swelling capacity, is naturally gluten-free, and possesses a comparatively low glycaemic index (Falade and Oyeyinka, 2015). It consequently serves simultaneously as a traditional staple (reconstituted into *amala* or plantain *fufu*), a bakery and confectionery ingredient and wheat-flour substitute, a base for gluten-free and diabetic-diet formulations. Also, it is a component of weaning foods and breakfast cereals, a soup thickener and coating batter, a constituent of composite-flour programmes, an industrial feedstock for starch and fermentation products. Furthermore, through its milling residues it can be used as a livestock feed component. This breadth of end uses makes plantain flour the single most valuable value-added product obtainable from this fruit and the strongest justification for mechanising its production.

Despite its economic and nutritional importance, plantain is highly perishable. The fresh fruit has a moisture content of typically 60–65% (wet basis), rendering it susceptible to rapid ripening, microbial spoilage and mechanical damage during handling and storage; post-harvest losses in developing countries are estimated at 20–40% of production, largely because of inadequate storage, processing and preservation infrastructure. The most effective loss-reduction strategy is the conversion of unripe plantain into dried chips typically sliced 2–10 mm thick and dried at 55–70 °C to 8–12% moisture content which are subsequently milled into flour (Adeniji et al., 2010). The dried chips are hard and brittle, with hardness increasing as moisture falls, and this vitreous texture defines the loading conditions of any machine intended to grind them.

Size reduction is the critical and most energy-intensive operation in flour production, and it largely determines the fineness, colour and functional properties of the product. The principal comminution mechanisms are compression, impact, attrition and cutting. Hard, brittle materials such as dried plantain chips respond best to impact and attrition, which explains the dominance of hammer (beater) mills and burr mills for dried starchy crops (McCabe et al., 2005). The energy of comminution is described by the classical laws of Rittinger, Kick and Bond, which together with the physical properties of the feed guide the selection of mill type, rotor speed and motor power (Perry and Green, 2008). For rotary impact mills, beater tip speeds of 15–50 m/s are typical for food materials, the screen aperture controls the maximum discharged particle size, and the beater-to-screen clearance governs the intensity of attrition.

In many rural communities, however, milling is still carried out with the mortar and pestle which is a method that is slow, laborious, unhygienic and incapable of producing flour of uniform particle size. Where mechanised milling exists, processors rely on general-purpose burr mills or hammer mills designed for grains. Burr mills reduce material by attrition between grooved plates, but the plates wear rapidly on hard dry chips, metal contamination results as they wear, and throughput is low. Hammer mills with rotors carrying beaters at high speed inside a screen-lined chamber are robust, simple to maintain and well suited to hard, brittle feeds, and locally fabricated laboratory- and small-scale versions have been demonstrated for milling agricultural products (Nasir, 2005; Ajaka and Adesina, 2014). Commercial machines of either type, however, are generally imported, expensive, energy-demanding and not optimised for dried plantain; their capital and maintenance costs place them beyond the reach of small- and medium-scale processors (Ukhurebor and Adekunle, 2018).

Reports on plantain-specific processing machinery have concentrated largely on slicing and drying equipment, with comparatively few purpose-built mills for dried plantain chips. Operators report rapid wear of grinding elements, inconsistent fineness and product discolouration from overheating. The literature therefore reveals a clear gap: a purpose-designed, low-cost, locally fabricated machine that grinds dried plantain chips efficiently into flour of acceptable fineness while preserving product hygiene and quality. The design lessons from previous work are that impact grinding against a perforated screen offers the best combination of simplicity, robustness and fineness control for hard dried chips. Also, the feed hopper must be tapered for gravity flow and stainless steel or coated surfaces used wherever the product contacts the machine. Furthermore, the frame must be rigid enough to absorb the vibration of a high-speed rotor.

The aim of the present study was therefore to design, fabricate and evaluate the performance of a dried plantain grinding machine using locally available materials. The specific objectives were: (i) to prepare a detailed design of the machine, including its assembly and component views; (ii) to select locally available materials for the components on the basis of strength, food safety, wear and corrosion resistance, cost and availability; (iii) to determine the principal design parameters, including hopper capacity, shaft diameter, pulley and belt sizes, speed ratio and motor power; (iv) to fabricate and assemble the feed hopper, grinding chamber, rotor shaft, discharge chute, supporting frame and drive system; (v) to evaluate the fabricated machine with dried plantain chips in terms of throughput capacity, milling efficiency, material loss and product fineness.

MATERIALS AND METHODS

Materials

Materials were selected against seven criteria: mechanical strength, suitability for food processing, endurance to wear, resistance to corrosion, availability in the local market, ease of fabrication, and affordability. Stainless steel sheet (1.5–2.0 mm) was used for all contact surfaces since it is corrosion-resistant, non-toxic, easy to clean and does not contaminate or discolour the flour. Mild steel sheet (2–3 mm) was used to form the outer casing of the grinding chamber and the guards, while mild steel angle bar (50 mm × 50 mm × 5 mm) formed the supporting frame that carries the chamber, shaft bearings and motor as well as providing the rigidity needed to absorb rotor vibration. The rotor shaft was machined from Ø25–30 mm medium-carbon steel bright round bar, whose combination of strength, toughness and machinability enables it to transmit the drive torque and resist the combined bending and torsional stresses. Mild steel flat bars (50 mm × 6 mm) welded to the shaft serve as the beaters/conveyors that effect impact grinding and convey the stock through the chamber. A removable perforated screen fitted in the lower part of the chamber controls product fineness. The prime mover is a 2 hp, 1440 rpm single-phase electric motor driving the rotor through a V-belt and pulley transmission, which steps the speed to the grinding value and cushions the motor against shock loads with the shaft running in two pillow-block ball bearings. M10–M12 bolts, nuts and washers fasten the bearings, motor, hopper and chamber covers and permit dismantling for cleaning and maintenance. Consumables comprised E6013 (gauge 12) mild-steel electrodes, hacksaw blades, cutting and grinding discs and emery cloth, with body filler and primer/gloss paint applied to external mild-steel surfaces for corrosion protection and finish.

Equipment and Tools

Fabrication employed an arc welding machine and accessories for joining frame members, hopper seams, chamber and brackets while a centre lathe was used for turning the rotor shaft, facing, chamfering and machining the pulley and bearing seats. A bench and portable drilling machines were used to drill bolt holes in the frame, chamber and motor base with an angle grinder that undertakes cutting, weld dressing and edge finishing. With a hacksaw and guillotine, angle bars, flat bars and sheet were cut to marked sizes while a bending/rolling machine with folding bars was used for forming the hopper taper and rolling the chamber shell. Marking-out and inspection were carried out using a steel rule, tape measure, try square, scriber, punch and spirit level, with a vernier calliper and micrometer screw gauge for precise shaft, bore and clearance measurements. Also, bench vice, clamps, files, hammers and spanners served the fitting and assembly operations while personal protective equipment used includes welding shield, gloves, ear plugs, nose masks and safety boots.

Machine Description and Operating Principle

The machine consists of five functional units, shown in the design views of Figures 4–6: (i) the feed hopper (Figure 1) as a tapered stainless-steel container mounted above the grinding chamber, through which chips flow by gravity into the milling zone; (ii) the rotor/shaft and beater–conveyor assembly, whose flat-bar beaters, rotating at high speed, shatter the chips by impact against the chamber wall and screen; (iii) the grinding chamber in figure 2a and 2b as the heart of the machine houses the rotor and lined in its lower part with the removable perforated screen that controls fineness. (iv) The discharge chute (Figure 3), through which milled flour leaves the chamber under gravity into a collecting receptacle; and (v) the supporting frame and drive system, comprising the angle-iron stand, the electric motor and the guarded belt-and-pulley transmission.

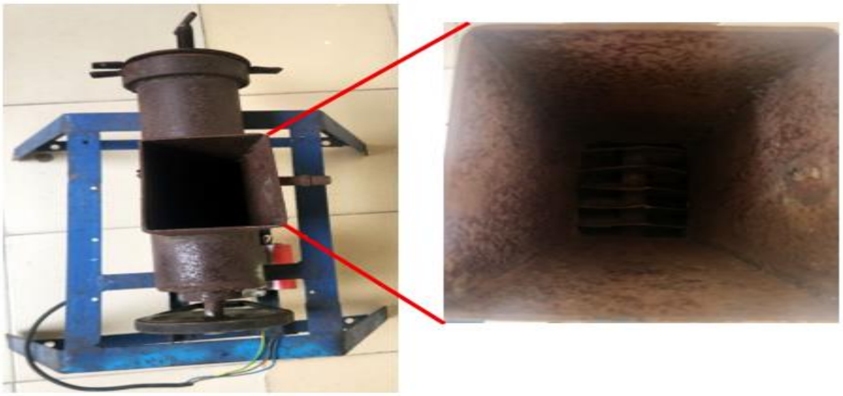

Figure 1: Design views showing the feed hopper, shaft and beater–conveyor assembly

(a) (b)

Figure 2. Design views of the grinding chamber when (a) open and (b) closed

Figure 3: Front design view showing the discharge side of the machine and supporting frame

In operation, the motor is switched on and allowed to attain full speed before dried plantain chips are fed steadily through the hopper. Within the chamber the chips are struck repeatedly by the rotating beaters and hurled against the chamber wall and screen, breaking progressively into finer particles. Particles fine enough to pass the screen apertures fall into the discharge chute and are collected as flour; oversize particles are retained and milled further, so the screen aperture sets the upper bound of the product particle size.

Design Considerations

The design was guided by the physical and mechanical properties of dried plantain chips such as hardness, brittleness, bulk density of roughly 500–650 kg/m³ and milling moisture content of 8–12% wet basis. Other fabrication considerations includes hygienic design, with stainless steel on all product-contact surfaces, smooth internal finishes and easy dismantling for cleaning. Also, a rotor speed and beater tip speed adequate for effective impact grinding without excessive heat generation and a shaft diameter carrying a generous factor of safety against combined bending and torsion were determined from standard shaft design equations (Khurmi and Gupta, 2005). Furthermore, a belt-and-pulley ratio matching the motor speed to the required rotor speed was also taken into consideration. Meanwhile, the frame stability against vibration; operator safety through belt guard, enclosed chamber, stable stand as well as minimum cost consistent with functional and safety requirements were also considered.

Fabrication Procedure

Fabrication followed a fixed sequence guided by the dimensions in the design views. The isometric, orthographic and component views were first studied and every dimension extracted onto a cutting schedule. All materials were procured locally, inspected against specification and marked for their components. Profiles of the frame members, hopper flat pattern, chamber shell, end covers, discharge chute and beaters were marked out with rule, tape, try square, scriber and punch before being cut while the angle bars were cut with grinder and hacksaw, sheet blanks with guillotine and grinder before all edges were dressed. The frame members were set square, clamped, tack-welded, checked for level and squareness, then fully arc-welded, after which the bearing and motor-base holes were drilled. The folding machine was used to fold the stainless hopper pattern before being seam welded and dressed. The chamber shell was rolled to the design diameter and seam-welded prior to cutting of the end covers which were later drilled and fitted. Furthermore, the inlet and discharge openings were cut and the curved perforated screen was formed and secured in the lower chamber with provision for easy removal. To ensure torque stability, the shaft was faced, centre-drilled and turned on the lathe to its bearing as well as suitable for the beater-carrier and pulley seats before it was finished with emery cloth and keywayed for the pulley. Meanwhile, the flat-bar beaters were cut, drilled and mounted on the shaft in a balanced arrangement before the assembly was checked for static balance to minimise vibration. Likewise, the discharge chute was folded and welded from stainless sheet before being fitted below the screen. At assembly, the pillow-block bearings were bolted to the frame, the shaft mounted and checked for free rotation and alignment before the chamber was positioned around the rotor and bolted down. To complete this, the hopper was bolted to the inlet and the beater-to-screen radial clearance set and verified. To achieve the expected torque on the rotor, the motor was bolted to its slotted base while the pulleys were keyed and aligned with a straight edge providing the clearance for the V-belt to be fitted and tensioned by adjusting the motor position before installing the belt guard. For safety and minimal accidents, all welds were dressed, sharp edges removed, mild-steel surfaces filled, primed and painted while the stainless surfaces were polished and washed. Finally, to test the performance of the machine, it was run without load to check for abnormal noise, vibration, belt slip and bearing heating, and adjusted until it ran smoothly, before proceeding to load testing.

Performance Evaluation

The machine performance was evaluated with dried unripe plantain chips at approximately 10% moisture content (wet basis). For each test run, a weighed batch of chips was fed into the hopper with the machine at design speed, the milling time recorded with a stopwatch, and the discharged flour collected, weighed and subjected to sieve analysis with standard test sieves. Each test was replicated three times and mean values reported. The performance indices were computed from Equations (1) to (3) as:

$$C = \frac{M_e}{t} \qquad (1)$$

Where C is the throughput (milling) capacity (kg/h), *Me* is the mass of chips fed (kg) and t is the milling time (h);

$$\eta = \frac{M_o}{M_e} \times 100\% \qquad (2)$$

Where η is the milling (recovery) efficiency and *Mo* is the mass of flour recovered (kg)

$$\%Loss = \frac{M_e - M_o}{M_e} \times 100\% \qquad (3)$$

Which accounts for material retained in the machine and dust losses. Fineness was expressed as the percentage of product passing the 500 µm reference sieve.

RESULTS AND DISCUSSION

Fabrication and No-Load Performance

The machine was successfully fabricated and assembled in full accordance with the design views. The stainless-steel tapered hopper, the grinding chamber with its removable perforated screen, the rotor shaft with its balanced beater assembly, the discharge chute, the angle-iron frame and the belt-driven transmission all fitted together as designed, and the completed machine matched the assembled design views. During no-load trials the machine ran smoothly, with no abnormal vibration, belt slip or undue bearing heating, confirming the adequacy of the shaft design, the static balancing of the beater assembly and the rigidity of the frame.

Milling Performance

Table 1 summarises the mean results of the replicated test runs. Applying Equation (1) to the measured feed mass of 5.20 kg and mean milling time of 4.25 min (0.0708 h) gives a throughput capacity C = 5.20/0.0708 = 74.29 kg/h. From Equation (2), the recovery of 4.78 kg of flour from 5.20 kg of feed corresponds to a milling efficiency η = (4.78/5.20) × 100 = 91.92%, and from Equation (3) the material loss is (5.20 − 4.78)/5.20 × 100 = 8.08%. Approximately 85% of the product passed the 500 μm sieve in a single pass.

Table 1. Mean Performance Test Results Of the Dried Plantain Grinding Machine (N = 3)

S/N	Performance Parameter	Mean Value
1	Mass of dried chips fed per batch (kg)	5.20
2	Mean milling time per batch (min)	4.25
3	Mass of flour recovered (kg)	4.78
4	Throughput capacity, C (kg/h)	74.29
5	Milling (recovery) efficiency, η (%)	91.92
6	Material loss (%)	8.08
7	Fineness – product passing 500 μm sieve (%)	≈ 85

Discussion

The measured throughput of 74.29 kg/h is adequate for small- and medium-scale processing, and the recovery efficiency of 91.92% compares favourably with values reported for locally fabricated hammer-type mills grinding dried starchy crops (Nasir, 2005; Ajaka and Adesina, 2014). The 8.08% loss was attributable mainly to fine dust escaping with air currents at the discharge and to a small quantity of material retained within the chamber and screen after each run. Based on this, both loss mechanisms can be reduced by improved sealing of the chamber and by fitting a cyclone or dust bag at the discharge. The fineness achieved with about 85% of the product passing the 500 μm sieve in a single pass is suitable for plantain-flour dough preparation and most bakery applications. When a finer flour is required, a finer screen can be fitted at some cost in throughput. The flour retained the characteristic creamy-white colour of unripe plantain with no visible browning, indicating that heat generation during the short milling times was insufficient to damage the product and this result attributed to the correct choice of rotor speed and beater-to-screen clearance. Operationally, the machine proved simple to be used with its screen, hopper and covers being easily dismantled for cleaning which satisfy the hygienic-design objective. It was also recorded that vibration and noise were within tolerable workshop limits, although hearing protection is recommended for prolonged operation. The total production cost was significantly lower than the price of comparable imported mills, confirming the economic attractiveness of local fabrication from locally sourced materials.

CONCLUSION

A dried plantain grinding machine was designed, fabricated from locally available materials and evaluated as a contribution to post-harvest loss reduction and small-scale plantain flour production. The machine comprising a tapered stainless-steel feed hopper, an impact-attrition grinding chamber with removable perforated screen, a balanced rotor and beater assembly and a discharge chute were all fabricated under workshop practice. Also, the rigid angle-iron frame and a belt-driven 2 hp single-phase motor were produced using standard workshop processes of marking out, cutting, forming, machining, welding, drilling and assembly. In replicated tests with dried unripe plantain chips, it achieved a throughput of 74.29 kg/h, a milling recovery efficiency of 91.92%, a material loss of 8.08% and good fineness (≈85% passing 500 μm), while the flour retained its natural colour. The machine is simple to operate, easy to clean and maintain, and considerably cheaper than imported alternatives; the aim and objectives of the study were therefore fully achieved, and the machine constitutes a viable, affordable solution for small- and medium-scale plantain flour processors.

The following recommendations arise from the work: a cyclone separator or dust-collection bag should be fitted at the discharge to recover fine dust, reduce losses and improve the working environment. Also, a petrol/diesel-engine or solar-powered variant should be developed for areas with unreliable electricity while interchangeable screens of different apertures should be supplied so that processors can select the fineness required for different end uses. In addition, full stainless-steel construction of the grinding chamber should be adopted in commercial versions to further enhance food safety and durability while further studies should evaluate the machine on other dried crops such as cassava chips, maize and dried yam to establish it as a multi-crop mill.

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