Development of a plantain slicing device

S. O. Obayopo · K. A. Taiwo · O. K. Owolarafe ·
S. A. Adio

Revised: 20 November 2011 / Accepted: 6 February 2012 / Published online: 17 February 2012
© Association of Food Scientists & Technologists (India) 2012

Abstract Plantains are usually processed after harvesting in order to increase its shelf life. However, the human cost of such processing is enormous and impacts negatively on the economic benefits derivable from plantain production. Therefore, the development of appropriate, low-cost, easy to operate and maintain plantain slicer is long overdue. This paper presents the design, construction and performance evaluation of a highly efficient device that simulates the traditional method of cutting plantain pulp transversely. The machine achieves, respectively, 90.7% and 92.6% efficiency, when used to make a 5 mm cut in moderately ripe and unripe matured plantain pulps. Furthermore, efficiency based on the rate of slices production per time was measured to be 90% and 91%, respectively, for moderately ripe and unripe matured plantain pulps. This design apart from increasing the shelf life of plantains will increase the economic benefits for local plantain processors.

Keywords Plantain slicer · Cutting · Shelf life · Processing · Low-cost · Efficiency

S. O. Obayopo (✉) · S. A. Adio
Department of Mechanical Engineering, Faculty of Technology,
Obafemi Awolowo University,
Ife-Ibadan highway,
Ile-Ife, Nigeria
e-mail: sirajolanre@yahoo.com

K. A. Taiwo
Department of Food Science and Engineering,
Faculty of Technology, Obafemi Awolowo University,
Ife-Ibadan highway,
Ile-Ife, Nigeria

O. K. Owolarafe
Department of Agricultural Engineering, Faculty of Technology,
Obafemi Awolowo University,
Ife-Ibadan highway,
Ile-Ife, Nigeria

Introduction

Plantain (*Musa Paradisiaca L.*) is a crop which is generally grown in the tropical and temperate region of the world, and is a good source of vitamins and dietary fibre. The mature fruit, i.e. the plantain bunch, has valuable economic and nutritional importance, and is the main part of the fruit. A bunch consists of several ‘fingers’ (several plantains that are attached in a single bunch), each having a length in the range of 2.5–12 in., and width of between 0.75 to 2 in. (CRFG 1997). Individual plantain fruit has a protective outer layer with a freshly edible inner part which is cooked by boiling, steaming, baking, roasting or frying and may be processed into plantain chips (Asoegwu et al. 1998).

The production of the genus of musa (plantains and bananas) hits over one hundred million tons (100 million tons) in year 2005 (FAO 2007). Presently, it is grown in over 130 countries of the tropical and sub-tropical countries of the world (Sharrock and Frison 1999), with India as the world leading producer of bananas. In sub-Saharan Africa, Uganda is the leading producer of plantain, followed by Nigeria, Ghana, Rwanda, Cote de Ivory and Cameroon (FAO 2008). However, apart from these African countries, the production of plantains and bananas cut across the tropical region of the continent (CRFG 1997). In Nigeria, for agro-climate reasons, plantain cultivation is concentrated in the southern region of the country. This crop also serves as source of income for rural farmers and substantial foreign exchange can be earned from export.

According to FAO (1999), 69.4% of plantain and other cooking bananas are used for human consumption while 8.0% are used for animal feed. Post-harvest losses and transformed quantities in the world are 11.5% and 11%, respectively.

Because of the high perishability of the plantain fruit and the inadequacy and relative ineffectiveness of handling, processing and storage facilities in most African countries that produce the crop, there is a continuous loss of about 35–100% of the production in this region (Asoegwu et al. 1998). This post-harvest loss reduces the income derivable from the crop production by the farmers.

Processing of plantain for food is arguably, the most common post-harvesting operation of a staple food for consumption. However, there are several approaches to this, often depend on cultural heritage of producing countries. Boiling or steaming, roasting, boiling and pounding, frying, drying etc., are some of the ways of processing plantain as staple food. Plantain chips making, an art of frying round slices of un-ripened and slightly ripened plantain pulp in vegetable oil is the most popular plantain product in Nigeria and neighbouring countries, and is a quick alternative to other snacks. Each slice is usually well cut, making it easily packaged for commercialization than “ekpekere”; another variation of plantain chips which is made from frying of a longitudinally sliced un-ripened plantain chips. In addition, it serves as ‘fast-food’ for offices and road workers in the urban areas, especially at lunch time. It has attracted quite a number of small-scale business owners as a major business enterprise.

Slicing is a cutting process for size reduction of fruits and vegetables. It involves pushing or forcing a thin, sharp knife to shear through the material intended to be sliced (Owolarafe et al. 2007). This results in minimal deformation and rupture of the fruits cell wall. Presently, the traditional method of slicing plantain with a kitchen knife on a wooden plate is still very much in use, due to the fact that patented plantain slicers like “Robot–Couple” models are not readily available for immediate use of plantain chips producers. Nevertheless, as the plantain chips industry attract more investments depicted by the increase in the rate of packaged brands that are being sold on Nigerian roads, markets, stores, fast food joints and supermarkets, the need for a simple, affordable, easy to maintain slicing device cannot be overestimated.

Agricultural materials commonly subjected to cutting could be classified as: (i). Non-fibrous, liquid cell materials having uniform properties in all direction at the time of cutting, (ii). Fibrous materials with high tensile strength fibers oriented in a common direction with comparatively low-strength materials bonding the fibers together. In the first case, the comprehensive stress applied by the cutting tool to the cell will cause pressure in the cell wall at the point of contact with the cutting tool. This point is subjected to: (i) High shear stress due to the applied compressive stress in one direction. (ii) Tensile stress due to addition of bending stresses at the point of indentation to

the hydrostatic stress. (iii) Movement of the tool in a direction parallel to its edge and perpendicular to the direction of the compressive force applied (slicing action) which can further add to the shear stress applied to the cell wall at the point of contact.

The development of an appropriate plantain slicer, simulating the laborious and time consuming traditional method of cutting plantain with a knife which is highly prevalent in Nigeria and most West African countries is attempted in this work. The objective of this work was to develop a simple motorised plantain slicer for small scale plantain chips producers.

Materials and methods

Component parts of the machine

The machine is a simple device, used in making a transverse cutting of plantain pulp into uniform sizes. The machine consists mainly of the following parts as shown in Fig. 1:

- (i) *Slicing unit*: The primary purpose of this unit is to slice the pulp of plantain to desired thickness and discharge it through the discharge opening into a collecting container. It is made up of the following.
 - a. *Cutting disc housing*: This disc housing was cut out from a mild steel plate of 3 mm thickness and 240 mm diameter. A center hole of 25 mm diameter was made to allow holding of this disc with a shaft. This housing serves as the cutting blade compartment (Fig. 1d). It also has a covering unit (Fig. 1e) that keeps the cutting disc in place and consists of an output opening for the processed plantain pulp. An opening and leading edge was made on this covering plate to guide the plantain pulp towards the cutting blade.
 - b. *Cutting disc*: The cutting disc (Fig. 1f) was fabricated from a stainless steel plate with dimensions as 4 mm×4 mm, held in position by a permanent joint, with 5 mm space between the cutting disc housing and the cutting disc. The size of the cutting disc was based on the traditional thickness of the available plantain chips in the market.
 - c. *Shaft*: The shaft (Fig. 1c) used was of 25 mm diameter and 610 mm long. 100 mm to one of the ends of the shaft was supported by a deep groove ball bearing and was connected to the pulley which rotates the shaft mechanically, while the other end fastened to the slicing unit was also supported by a deep groove ball bearing, 100 mm before the end of the shaft.

Fig. 1 Different parts of the plantain slicing device: **a** Housing, **b** Housing cover, **c** Shaft, **d** Cutting disc housing, **e** Cutting disc cover, **f** Cutting disc, **g** Driven pulley

- (ii) *Frame*: The frame (Fig. 1a) acts as the support for other parts of the machine. The frame was made to a rectangular box form using angle iron and mild steel plate. The dimensions are shown in the description in Fig 1a. An additional top covering (Fig. 1b) is added for safety of users from rotating parts of the machine and to make the machine compact for mobility. The electric motor stand was also incorporated to this unit.
- (iii) *Electric motor*: Electric motor was used to drive the driven pulley (Fig. 1g), and to provide the required shaft speed for the slicing operation. An electric motor

stand with four slots holes for pre-tensioning of belt by adjustment of center distance between the driving and driven pulleys is also provided.

- (iv) *Bearing*: The bearing specification are bore diameter, $d=25$ mm, Outside diameter, $D=47$ mm and the width, $B=12$ mm, based on design calculations and manufacturer specification for the dynamic load on shaft (SKF 1977).

The orthographic projection and the exploded view of the machine are presented in Figs. 2 and 3, respectively. Figure 4 shows the assembly of the machine.

Fig. 2 Orthographic projection of the machine

Design for power requirement

The required rotational force F_c , to drive the shaft was obtained using the relation below (Hall et al. 1983)

$$F_c = \frac{2m}{D} \left(\frac{\pi DN}{60} \right)^2 \quad (1)$$

Where

- m mass of the cutting disc
- D diameter of the cutting disc
- N speed of the shaft

Using the above relation, using a speed of 400 rpm (assumed in practice based ruptured strength of unripe plantain) based on the work of Asoegwu et al. 1998. The cutting disc mass and diameter are 1.0 kg and 240 mm, respectively.

The value of F_c obtained was 210.55 N.

The equivalent torque of 25.27 Nm was obtained from the calculated centrifugal force above, using equation (Hall et al. 1983).

$$T = F_c \frac{D}{2} \quad (2)$$

Hence, the power required to drive the shaft of the machine was calculated using the relation below (Hall et al. 1983)

$$P = \frac{2\pi NT}{60} \quad (3)$$

The power requirement was then found to be 1056.35 W (1.42 hp)

From this calculation, a motor of 1.5 hp was chosen for the design.

Design for shaft strength

The shaft is made of mild steel and is being supported on two rolling elements bearings and at both ends of the shaft will be attached the driven pulley and the cutting disc. The cutting disc will hold the cutting blade. Snap rings were used to restrain axial movement of the rolling element and key way has been machined such that it holds the pulley in position. The analysis of the total loading condition of the shaft is shown in Fig. 5.

The properties of the selected shaft material are:

Allowable shear stress, $S_c = 4 \times 10^6 \text{ N/m}^2$ (for shaft with a keyway incorporated)

Length of shaft $L_s = 610 \text{ mm} = 0.61 \text{ m}$

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Housing	Mild Steel
2	1	Housing Top cover	Stainless Steel
3	1	Cutting Disc Housing	Stainless Steel
4	1	Shaft	Mild Steel
5	1	Cutting Disc	Stainless Steel
6	1	Driven Pulley	Alluminium
7	1	Cutting Disc Housing Cover	Stainless Steel
8	1	Cutting Blade	Stainless Steel
9	2	Bearing Assembly	CNS 02 4645-B 71905 Single row angular contact ball bearings
10	1	Electric Motor	Motor Assembly - Custom
11	1	V-Belt	A Belt
12	1	Driver Pulley	Mild Steel
13	6	ANSI B18.22.1 - 1/4 - narrow - Type A	Plain Washer (Inch)Type A and B
14	6	ANSI B18.21.1 - 0.25	Helical Spring Lock Washers
15	3	ANSI B18.3 - 1/4-28 UNF - 0.75	Hexagon Socket Head Cap Screw
16	3	ANSI B18.2.2 - 1/4 - 28	Hex Nuts (Inch Series) Hex Nut

Fig. 3 Exploded view of the plantain slicing device

For a rotating shaft with gradually applied load, the bending fatigue factor,

K_b 1.5 and the torsional fatigue factor

K_t 1.0 (Hall et al. 1983)

Fig. 4 Assembly of the machine

The maximum bending moment, M_b on the shaft is 57.265 Nm and the maximum torsional force of the shaft M_t is calculated using (Hall et al. 1983).

$$M_t = \frac{60P}{2\pi N} \quad (4)$$

which gives $M_t = 26.71$ Nm

$P = 1119$ and $N = 400$.

The required shaft diameter is determined using the formula (Hall et al. 1983).

$$d^3 = \frac{16}{\pi S_3} \sqrt{[(K_b M_b)^2 + (K_t M_t)^2]} \quad (5)$$

Therefore, the minimum diameter for the shaft should be 22.5 mm.

The bearing bore available close to this shaft diameter based on manufacturing standards is 25 mm (S.K.F. 1977).

Therefore, 25 mm shaft is chosen for the design.

Design for feed rate

The required thickness of the plantain slice is 5 mm and it is expected to be produced at every half of a revolution of the cutting disc. i.e. thickness of sliced plantain/

Fig. 5 Shaft loading, shear force diagram (SFD) and bending moment diagram (BMD) Maximum Bending Moment, $M_b=57.265$ Nm (absolute)

revolution=10 mm/rev. The speed of the cutting disc is 400 rpm=6.667 rev/s. The feed rate is calculated as follows:

$$\begin{aligned} \text{Feed Rate} &= \text{thickness of plantain/revolution (mm/rev)} \\ &\quad \times \text{speed of cutting disc (rev/s)}. \quad (6) \\ &= 6.667 \text{ rev/sec} \times 10 \text{ mm/rev} \\ &= 66.67 \text{ mm/sec} = 4000 \text{ mm/min} \end{aligned}$$

Therefore, the size of the plantain pulp to be sliced (in inches/minute) is 157.5.

Belt and pulley selection

The belt and pulley system are necessary for power transmission from the electric motor to the shaft. It consists of the driving pulley (small pulley), driven pulley (big pulley) and a belt to transmit the drive from the driving pulley to the driven pulley. Thus, the selection of the above components involved calculating the size of the driving and the driven pulley necessary to achieve the required speed reduction from 1440 rpm to 400 rpm. Pre-tensioning by adjustment of center distance was used for the belt tensioning.

(a) *Belt*: The plantain slicer is considered a light duty machine with service factor of 1.0 (Fenner and Co Ltd. 1973). Therefore, the design power requirement

of the plantain slicer is calculated to be 056.35 W, obtained by using the equation

$$\text{Design Power} = \text{Running Power} \times \text{Service Factor}. \quad (7)$$

The intersecting point of the design power and the speed of the faster shaft (1440 rpm) depicts that transmission of the power from electric motor is in A – section with 1 groove pulley.

(b) *Size of the driving pulley*: From standard pulley selection table (Fenner & Co Ltd. 1973), the recommended minimum standard pulley diameter for the chosen electric motor is 67 mm. Therefore, the

Table 1 Number of Slices per 60 s of machine running time

No of replications	Number of slices (ripe)	Number of slices (unripe)
1	760	720
2	720	760
3	720	720
4	720	760
5	760	720
6	640	680
Average	720	727

Table 2 Conformity of slice with the standard thickness (5 mm)

TEST	RIPE		UNRIPE	
	No of slices that conform with standard thickness	No of slices that do not conform	No of slices that conform with standard thickness	No of slices that do not conform
1	720	40	640	80
2	640	80	720	80
3	640	80	680	40
4	680	40	720	40
5	720	40	640	80
6	520	120	640	40
Average	653.3	66.7	673.3	60

diameter of driven pulley is 240 mm, as obtained from (Hall et al. 1983)

$$N_1 d = N_2 D \quad (8)$$

(c) *Pitch length of the belt:* The minimum and maximum distance between pulley centers are 215 mm and 614, respectively (Shigley and Mischke 2004). This was obtained using the formula:

$$\begin{aligned} c_{\min} &\geq 0.7(d_1 + d_2) \\ c_{\max} &\leq 2(d_1 + d_2) \end{aligned} \quad (9)$$

Using 300 mm as the center distance, the calculated pitch length of belt (Shigley and Mischke 2001) is 1110 mm, as obtained from

$$L = 2C + \frac{\pi}{2}(D + d) + \frac{(D - d)^2}{4C} \quad (10)$$

Table 3 Materials for fabrication of the components and estimated cost

Materials	Components used for	Amount in NGN Naira (#)
Mild steel Sheet	Housing, Housing top cover, Cutting disc housing, Cutting disc, Cutting disc housing cover	4, 300
Stainless steel sheet	Cutting blade	400
Mild Steel Rod	Shaft	3,600
Angle iron	House frame	800
	Bearings	3,200
	Electrodes	300
	Bolts and Nuts	300
	Belt	400
	Pulley	700
Accessories	Electric motor	7,400
	Workmanship	2,500
Total		23,900 ^a

^a This amount is equivalent to \$154

The catalogue code of A-section that conforms with the pitch length of the belt calculated was 240A1100, indicating that the standard pitch length of the belt is 1100 mm.

(d) *The initial tension of the belt:* The tension of the belt is necessary for the appropriate transmission of the power, thereby preventing the unwanted slippage of the belt, as this will affect the power output due to fluctuation of speed. Power transmitted, P, between the two shafts is related to the belt tension and its linear velocity according to the following (Hall et al. 1983)

$$P = (T_1 - T_2)v, \quad (11)$$

where T_1 = tension of belt at the tight side and T_2 = tension of belt at the slack side. The factor $v=5.05$ m/s, is the velocity, and is obtained using the expression (Hall et al. 1983):

$$v = \frac{\pi d N}{60} \quad (12)$$

$$\frac{T_1 - mv^2}{T_2 - mv^2} = e^{\mu\alpha/\sin\frac{\theta}{2}} \quad (13)$$

m linear density of belt

μ coefficient of friction between the belt and pulley=0.3 (Hall et al. 1983)

θ groove angle for V belt=40°

α angle of wrap

T_1 and T_2 were obtained as 393.2 N and 171.6 N, respectively by solving Eqs. 11, 12 and 13.

With 1.5 hp motor selected, the actual driving power (from Eq. 11) is 1119 W.

Results and discussion

Average number of slices produced Six experimental replications were carried out on the slicing device, each experiment was conducted for 60 s and the numbers of slices for the duration were recorded. Matured ripe and unripe plantains were used with moisture content of 75% and 64% respectively. Table 1 gives the result of the cutting of the plantain pulp slices.

Average dimensions of slices The requirement of the design was to produce 5 ± 0.5 mm plantain slices, which is the distance between the blade and the cutting disc. Thus, slices with thickness of between 4.5 mm to 5 mm are acceptable. Each test was analyzed for conformity with the standard thickness, using a vernier-caliper. The variation in thickness as reported in Table 2 was due to inconsistent feeding of the plantain which was done manually. The average number of slices that fell in acceptable range was 653 and 673, corresponding respectively to 90.7% and 92.6% of the total inputs of ripe and unripe plantains.

Efficiency of the slicer Efficiency of the plantain slicer was determined based on the average number of slices produced. The average efficiency, η , of the slicer was estimated to be 90% for ripe plantain and 91% for the unripe plantain samples and these values were obtained using the formula,

$$\eta = \frac{N_a}{N_i} \times 100\%, \quad (14)$$

where N_a is the actual number sliced per minute and N_i is the ideal number of slices per minute.

Cost estimation

Table 3 gives the cost for the development of the prototype of the plantain slicing device. The cost estimate of the prototype includes the cost of workmanship and the estimation was based on the current cost of the materials used for the fabrication of the prototype machine. The cost estimate was \$154 for the prototype, while an average imported slicer depending on the designer cost between \$220–815. This shows that the present design will definitely satisfy the need of the increasing local plantain chips producer.

Conclusion

A prototype device for slicing cuts of small thicknesses (5 ± 0.5 mm) of plantain pulp was developed in this study. The device is low-cost, works on simple design mechanism, easy to operate, and is fabricated from materials that are available locally. A preliminary evaluation of the machine in terms of efficiency and cost indicates that it has a high potential in substituting the traditional manual cutting of plantain for processing. Furthermore, the device has a very high efficiency of 90%, when cutting through ripe plantain, and 91% for unripe plantain. Due to its low-cost, it will be suitable for use in Nigeria and other plantain producing countries in sub-Saharan Africa, where patented mechanized plantain slicing machine is not readily available, or where available, the costs are prohibitive.

References

- Asoegwu SN, Nwandikom GI, Nwammuo OP (1998) Some mechanical properties of plantain fruit. *Int Agrophysics* 12:67–77
- CRFG (1997) Banana Fruit Fact. <http://www.crfg.org/pubs/ff/banana.html>. Accessed 10 June 2010
- FAO (1999) FAOSTAT: Platin: Post harvest operation. Food and Agricultural Organization of the United Nations. http://www.fao.org/fileadmin/user_upload/inpho/docs/Post_Harvest_Compendium_-_Plantain.pdf. Accessed 04 November 2011
- FAO (2007) FAOSTAT: core production data. Food and Agriculture Organization of the United Nations, Rome, <http://faostat.fao.org/site/340/default.aspx>. Accessed 10 June 2010
- FAO (2008) FAOSTAT: Overview of World Banana Production and Trade. Food and Agriculture Organization of the United Nations. <http://www.fao.org/docrep/007/y5102e/y5102e04.htm>. Accessed 12 June 2010
- Fenner JH & Co Ltd. (1973) Fenner drives product catalogue. http://www.fennerdrives.com/about_fenner_drives/catalogs.aspx. Accessed 12 June 2010
- Hall AS, Hollowenko AR, Laughlin HG (1983) Schaum's outline series of theory and problems of machine design. McGraw-Hill Publishers Incorporated, New York, pp 113–121
- Owolarafe OK, Muritala OA, Ogunsina BS (2007) Development of an okra slicing device. *J Food Sci Tech Mysore India* 44(4):426–429
- Sharrock S, Frison E (1999) Musa Production around the world-trends, varieties and regional importance in: INIBAP annual report 1998. INIBAP: Montpellier (FRA), 42–47
- Shigley JE, Mischke CR (2001) Mechanical engineering design. McGraw Hill Book Co, New York, pp 1069–1075
- Shigley JE, Mischke CR (2004) Standard handbook of machine design. McGraw Hill Book Co, pp 14–23
- SKF (1977) Bearing maintenance and replacement guide, p 56–57. <http://www.ien.com/uploadedfiles/ien/Blog/SKFBearingInstallationAndMaintenance.pdf>. Accessed 12 June 2010