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Design, Fabrication and Evaluation of a Plantain Roaster

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ABSTRACT

Roasted plantain *(boli)* is a delicacy in Nigeria. The conventional method of processing this food is crude, stressful and unhygienic. In this work, an electric roaster capable of roasting twenty-one plantain fingers per batch was designed, fabricated and tested. The roaster had two electric heating elements (one at the top and the other at the base of the roaster) supplying power at the rate of 2.4 kW. In addition, moisture release pipe and a temperature regulator were incorporated. The roaster was used to produce plantain, product was compared with roasted plantain prepared using the conventional method to test acceptability. At a $p < 0.05$ significance level, it was observed that the samples had no significant difference in appearance, aroma, texture and overall acceptability. However, sample at the upper layer of the roaster was significantly different from the other samples in taste. Generally, sample roasted in the lower part of the roaster was most preferred.

Keywords: Plantain, roaster, design, fabrication, quality.

Introduction

Plantain (*Musa paradisiaca*) is a staple food in the developing world. Plantain contains about 52.9% moisture content, 0.8% protein, 0.1% fat, 25.5% carbohydrate, 0.3% fibre and 0.63% ash (INIBAP, 2003). Analysis of the ripe fruit of *Musa paradisiaca* shows it contains sugar, gum, malic, gallic, and pectic acids, albumen, and lignin (Henriette, 2010).

The fruit is consumed raw or processed by boiling, drying, grinding, frying, or roasting before consumption. Such processing makes the crop palatable for human consumption and helps to extend the shelf life of the crop. In addition, varieties of products, which are more convenient to transport and consume, are provided.

Roasting is a food processing method that uses heated air to alter the eating quality of foods to cause some desirable physical and chemical changes and to enhance food flavour. During roasting, the characteristic flavour is developed (Norman and Hotchkiss, 2006). This desirable qualities developed in the food product are factors that increase the market value of the product and enhance its use as raw material for both small and large scale processors. A secondary purpose of roasting is preservation by destruction of microorganisms and reduction of the water activity at the surface of the food. High temperature used in roasting causes complex changes to the component of the food at the surface. These changes enhance eating quality and retain moisture in the bulk of the food. In contrast with dehydration, where the aim is to remove as much water as possible with minimal changes in the sensory quality, in roasting the heat-induced changes at the surface of the food and retention of moisture in the interior of the food product are desirable quality characteristics. The equipment used in the process of roasting is called a roaster or grill. It is usually similar to an oven in design.

Over the years, roasted plantain *(boli)* enjoyed by many has been processed using unhygienic method.

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In Nigeria, this roasted product is processed in open roaster exposing it to dust, lead and other contaminants. This unhealthy habit should be corrected. Also, using a roaster to process a food product for which it was not intended could lead to ineffective roasting, energy wastage, and could even damage the food product or the machine (Fellows, 2000).

The objective of upgrading an indigenous system is to achieve a more sanitary and hygienic system, as well as a system for achieving technical efficiency in terms of time, energy, labour and material use while focusing on improved product quality. Therefore, a roasting machine specifically for plantain was design, fabricated and tested.

Methodology

Design of heat requirements

Quantity of heat needed to satisfactorily roast plantain was calculated using equation 1.

$$H = mC_p(\Delta T) \qquad (1)$$

Where H is quantity of heat required (J), m is mass of plantain at maximum loading. C_p is specific heat capacity of plantain. ΔT is difference in temperature between the tropical ambient and that of roasting.

Mass (m) for different varieties of plantain was weighed and determined to be 120 g on average. For a maximum loading of 7 pieces of plantain per roasting grid on 3 grids is 21 pieces. Thus, mass is 2.52 kg.

Specific heat (c_p) of plantain was calculated using Singh and Heldman (2003) model (Equation 2).

$$C_p = 1.424x_c + 1.549x_p + 1.675x_f + 0.837x_a + 4.187x_w \qquad (2)$$

Where x_c is the mass fraction of carbohydrate in the food product

x_p is the mass fraction of protein in the food product

x_f is the mass fraction of fat in the food product

x_a is the mass fraction of ash in the food product

x_w is the mass fraction of water in the food product

For ripe plantain, on the average, $x_c = 0.312$, $x_p = 0.012$, $x_f = 0.004$, $x_a = 0.01$, $x_w = 0.662$

For unripe, $x_c = 0.305$, $x_p = 0.013$, $x_f = 0.001$, $x_a = 0.007$, $x_w = 0.674$ (Morton 1987)

Substituting these values, C_p ripe plantain is 3.25 kJ/kg°K and unripe is 3.28 kJ/kg°K.

$$\Delta t = t_{final} - t_{reference} \qquad (3)$$

$\{t_{reference}$ = tropical ambient temperature of 30°C$\}$

$\Delta t = 200 - 30 = 170°C$

Therefore,

H for ripe is 1.39 x 10^3 kJ and H for unripe is 1.41 x 10^3 kJ. If roasting duration is fixed for 15 min, power required is 1.55 kW for ripe, and 1.56 kW for unripe.

Heat losses through the walls

Fourier's first law of heat transfer was used to calculate heat loss through the walls. This heat loss was assumed to take place at a steady state, and considering that the roaster has already been heated to 200°C, while the outside is at the tropical ambient temperature of 30°C.

Fourier's law:

$$q = -kA\frac{\Delta T}{\Delta x} \qquad (4)$$

$$\Delta T = -q\,\frac{\Delta T}{kA} \qquad (5)$$

$$\Delta T_{s1} = -q\,\frac{\Delta x_{s1}}{k_{s1}A} \qquad (6)$$

$$\Delta T_{w} = -q\,\frac{\Delta x_{w}}{k_{w}A} \qquad (7)$$

$$\Delta T_{s2} = -q\,\frac{\Delta x_{s2}}{k_{s2}A} \qquad (8)$$

where

q is rate of heat flow (W)

Δ_{xs} is thickness of mild steel (m)

Δ_{xw} is thickness of fibre wool (m)
k_s is thermal conductivity of mild steel (W/m°C)
k_w is thermal conductivity of fibre wool insulation (W/m°C)
A is area of the wall (m^2)
T_2 is temperature of the roaster (°C)
T_1 is temperature of the surrounding environment (°C)
ΔT_w is temperature difference along the fibre wool thickness (°C)
ΔT_s is temperature difference along the mild steel thickness (°C)

$$\Delta T = T_1 - T_2 = \Delta T_{s1} + \Delta T_w + \Delta T_{s2} \tag{9}$$

Substituting equations 6, 7 & 8 into 9

$$T_1 - T_2 = -\left(\frac{q\Delta x_{s1}}{k_{s1}A} + \frac{q\Delta x_w}{k_w A} + \frac{q\Delta x_{s2}}{k_{s2}A}\right) \tag{10}$$

$$T_1 - T_2 = -q\left(\frac{\Delta x_{s1}}{Ak_{s1}} + \frac{\Delta x_w}{Ak_w} + \frac{\Delta x_{s2}}{Ak_{s2}}\right) \tag{11}$$

$$T_2 - T_1 = q\left(\frac{\Delta x_{s1}}{Ak_{s1}} + \frac{\Delta x_w}{Ak_w} + \frac{\Delta x_{s2}}{Ak_{s2}}\right) \tag{12}$$

Fourier's law derivation:

$$q_{loss} = \frac{T_2 - T_1}{\left(\frac{\Delta x_{s1}}{k_s A} + \frac{\Delta x_w}{k_w A} + \frac{\Delta x_{s2}}{k_s A}\right)} \tag{13}$$

$$q_{loss} = \frac{473 - 303}{\left(\frac{0.0015}{48 \times 0.25} + \frac{0.05}{0.042 \times 0.25} + \frac{0.0015}{48 \times 0.25}\right)} \tag{14}$$

$$q_{loss} = 35.70W$$

Total heat requirement for ripe = $Q = q_{loss} + H_{ripe}$ (15)

$$Q_{ripe} = 1.583 \text{ kW}$$

Total heat requirement for unripe =

$$Q = q_{loss} + H_{green} \tag{16}$$

$$Q_{unripe} = 1.597 \text{ kW}$$

Heat transfer rate

The major source of heat transfer in this system is the convective heat transfer from a set of copper heating elements with thermal conductivity of 401 W/m°K (Toledo, 2000). According to Newton's law of cooling,

$$q = hA(T_s - T_\infty) \tag{17}$$

$$N_{NU} = \frac{hd_c}{k} = a(N_{Ra})^m \tag{18}$$

$$N_{Ra} = N_{Gr} \times N_{pr} \tag{19}$$

$$(N_{pr}) = {\mu c_p}/{k} \tag{20}$$

$$N_{Gr} = \frac{d_c^3 \rho^2 g \beta \Delta T}{\mu^2} \tag{21}$$

$$T_f = \frac{T_s + T_\infty}{2} \tag{22}$$

Where
q is rate of heat transfer (W)
H is convective heat transfer coefficient (W/m^2°C)
A is surface area of the solid (m^2)
T_s is surface temperature of the solid plate (°C)
T_∞ is temperature of the fluid far away from the plate surface (°C)
a and m are constant

N_{NU} is Nusselt number (dimensionless)

N_{Ra} is Rayleigh number (dimensionless)
N_{pr} is Prandtl number (dimensionless)
N_{Gr} is Grashof number (dimensionless)
μ is velocity of fluid (m/s)
C_p is specific heat (kJ/kg °C)
K is thermal conductivity of fluid (W/m °C)
d_c is characteristic dimension (m)
ρ is density (Kg/m^3)
g is acceleration due to gravity
β is coefficient of volumetric expansion (K^{-1})
ΔT is temperature difference between wall and the surrounding bulk (°C)
μ is viscosity (Pa s)
T_f is film temperature (°C)

$$T_f = \frac{200 + 30}{2} = 115°C$$

For dry air at 115°C,

$r = 0.8815\ kg/m^3, g = 9.81 m/s^2, \beta = 2.585 \times 10^{-3} K^{-1}$

$\mu = 22.3365 \times 10^{-6}\ Ns/m^2, k_{air} = 0.03168 W/(m°K)$

The prandtl number for dry air at atmospheric pressure and at the parameters specified is 0.71 (Singh and Heldman, 2003).

For copper plate:

$d_c = 0.2m, \Delta T = 20 - 30 = 170°C$

From equation (20)

$$N_{Gr} = \frac{0.2^3 \times 0.8815^2 \times 9.81 \times (2.585 \times 10^{-3}) \times 170}{(22.335 \times 10^{-6})^2}$$

$$N_{Gr} = 5.37 \times 10^7 \qquad (23)$$

From equation (19)

$N_{Gr} = 5.37 \times 10^7, N_{pr} = 0.71$
$N_{Ra} = 5.37 \times 10^7 \times 0.71$

$$N_{Ra} = 3.8 \times 10^7 \qquad (24)$$

For the heating element on the roof

For horizontal plate facing down at:
$N_{Ra} = 3.8 \times 10^7$:

$a = 0.27, m = 0.25, K_{air} = 0.03168 W/(m°K)$,
$d_c = 0.05m$ (Singh and Heldman, 2003).

Substituting into equation (18)

$$N_{NU} = \frac{h \times 0.05}{0.03168} = 0.27\ (3.8 \times 10^7)0.2^5$$

$$h = \frac{21.199 \times 0.03168}{0.05}$$

$$h = 13.43 W/m^2 °K \qquad (25)$$

For the design having a 500 × 500 mm plate for heating, using equation (17)

$A = 0.05 \times 0.5 = 0.25m^2, T_s, 200°C, T_\infty = 30°C$
$h = 13.43 W/m^2 °K$
$q = 13.43 \times 0.25 \times (200 - 30)$

$$q = 570.78W \qquad (26)$$

For the heating element on the floor

For horizontal plate facing up at $N_{Ra} = 3.8 \times 10^7$:

$a = 0.15, m = 0.333, k_{air} = 0.03168 W/(m°K)$,
$d_c = 0.05m$ (Singh and Heldman, 2003).

Substituting into equation (18)

$$N_{NU} = \frac{h \times 0.05}{0.03168} = 0.15\ (3.8 \times 10^7)^{0.333}$$

$$h = 31.77 W/(m^2 °K) \qquad (27)$$

Recall and substituting these values (17)
$A = 0.5 \times 0.5 = 0.25m^2, T, 200°C, T_\infty = 30°C$,

$h = 31.77 W/(m^2 °K)$

$q = 31.77 \times 0.25 \times (200 - 30)$

$$q = 1350.23W \qquad (28)$$

Therefore, total convective heat transfer of plates is the addition of heat transfer rates of the two plates.

$q_{plate} = 570.78 + 1350.23$

$$q_{plate} = 1921.01W \qquad (29)$$

The heat transfer rate of 1921.01W would suffice to roast plantain, as compared to 1582.7W (ripe) and 1596.98W (green) which was the calculated energy requirement needed to roast the plantain, taking into consideration the heat losses through the walls. Therefore, a set of two heating elements having a power rating of 1200W each was selected. The excess energy would take care of other negligible heat losses and voltage drops that can reduce the heat supply. The elements were placed at both the top and bottom parts of the equipment.

Description of the roaster

The roaster has a square shape of 608 x 608 x 608 x 608 mm dimension (Figure 1). Four rectangular shapes 20 x 140 mm were used as stand. The sides of the roaster were stuffed with fibre wool (50 mm thickness) to prevent heat loss. Inner chamber of the roaster has stainless steel roasting grid (25 x 25 mm) hanging on three layers (Figure 2). The chamber is heated by two 1.2 kW heating elements suspended on the top and bottom of the inner compartment. Also incorporated was moisture escape outlet, thermocopple and switch (Plate 1). Detail cost of constructional materials as at October 2010 is presented as Table 1.

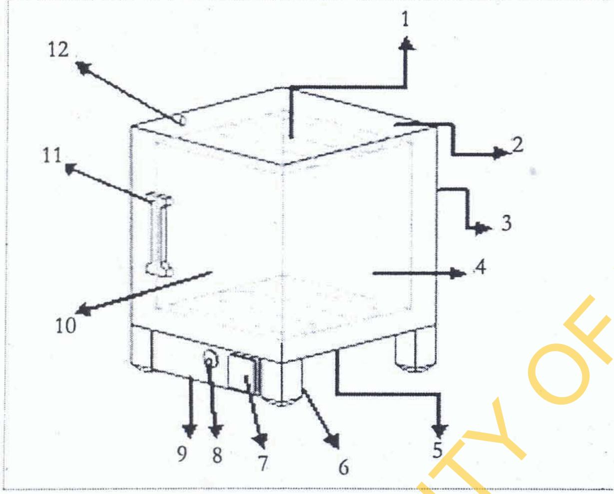

Fig. 1: Isometric view of roaster

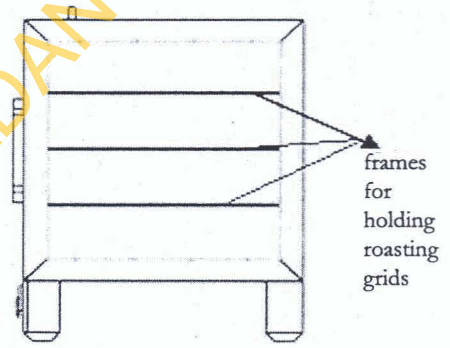

Fig. 2: Front view of roaster

1 – Heating element
2 – Roof
3 – Back
4 – Side
5 – Base
6 – Stand
7 – Temperature regulator control
8 – Switch
9 – Holding board for electrical equipment
10 – Door
11 – Door handle
12 – Moisture release pipe

Performance evaluation

The roaster was first heated to 200°C while empty and the time it took to get to that temperature was recorded. Efficiency of the temperature regulation control and the electric switch was also observed through its regular tripping off and switching back on of the heating element. Effectiveness of the heat sensor was determined by measuring the temperature of the roasting chamber with a thermometer and comparing this temperature with that given by the temperature regulation control. Also monitored were efficiency of the insulation and moisture outlet opening. The temperature drop during loading, and the time it took to recover and get back to the roasting temperature was also noted as an indicator of the roasting power of the heating elements.

Roasting efficiency was determined by using the machine to produce roasted plantain *(boli)*. Using Morton (1987) classification guide, ripe mature plantain fruits sourced from Bodija market in Ibadan, Oyo State was used for the study. Twenty-one peeled plantain fingers were loaded and roasted at 200°C. After roasting for 15 minutes, the plantains were removed and coded. The coded samples were subjected to sensory evaluation using *boli* produced from the same set of ripe plantains as reference. The existing traditional roasting facility used consists of burning charcoal under a surface covered with wire mesh in an open air. *Boli* produced and reference sample were subjected to sensory evaluation. Coded samples were served to a 25-member trained panelist positioned in partitioned booths. Aroma, texture, taste and overall acceptability of the roasted plantain were evaluated under amber light while appearance was under bright illumination. A 9-point hedonic scale was used where 9 was like extremely, 8 like very much, 7 like moderately, 6 like slightly, 5 neither like nor dislike, 4 dislike slightly, 3 dislike moderately, 2 dislike very much, 1 dislike extremely. One-way Analysis of Variance (ANOVA) analyzed the data.

Results and Discussion

The roaster took 32 min to reach the desired temperature of 200°C from an ambient temperature of 30°C, which is about 5.3°C rise in temperature per min. Temperature regulator functioned properly; electricity tripped off on attainment of set temperature and on when temperature dropped. Errors of ± 3°C were recorded between the roaster temperature and external device used for temperature monitoring. Similar observation was reported by Akinoso, Olayanju and Bankole (2008) for a palm kernel roaster. When chamber temperature was 200°C, external surface temperature was 45°C, an evidence of good insulation. The exhaust pipe was moist, suggesting moisture escape through the channel. Loading of the roaster with 21 fingers of plantain dropped temperature by 20°C. This observation might be due to plantain's surface trying to attain temperature equilibrium with the surrounding air since the initial temperature of plantain was lower (30°C) than that of heated air in the roasting chamber (200°C).

Mean preference scores of sensory attributes of the plantain is presented as Table 2. Statistical analysis of the data shows that there was no significant difference ($p < 0.05$) in all the samples in terms of appearance. This observation may be associated to closeness in roasting temperature range. Reference sample was the most preferred in appearance, followed by the sample in the lower layer of the roaster, while the sample roasted in the upper layer of the roaster was the least preferred in appearance. This could be as a result of its being a little burnt at the top since the sample was directly exposed to the heating element at the roof of the heating chamber. Therefore, noticeable change in colour could be associated to non-enzymatic browning reactions. Caramelization and Maillard reactions are non-enzymatic browning promoted by heating (McGee, 2004).

The aroma of the sample in the lower layer of the roaster was the most preferred, followed by that from the market. This could be because of the similarity in the position of the major heat source of the two samples (i.e. from beneath, with wire gauze/roasting grid between the sample and the heat source). The sample at the middle layer of the roaster was least preferred in aroma and this could be associated to distance from heating elements like the other samples, and thus not having its flavour fully expressed. Dry roasting of plantain changes the chemistry of protein in the food and its flavour (FAO, 2003). In all, there was also no significant difference ($p < 0.05$) in all the samples as regards their aroma (Table 2).

The analysis also showed that the sample in the lower layer of the roaster was the most preferred in terms of texture though there was also no significant difference between all the samples in terms of texture. The sample in the upper layer of the roaster was significantly different in taste from the other three samples (Table 2). This may be because of the burnt surface of the sample giving it a burnt and unpleasant taste. The sample in the lower layer of the roaster was rated the best in taste, followed by that in the middle layer and then the reference sample.

The samples were not significantly different in terms of the overall acceptability. This is suggesting cumulative marginal differences in appearance, aroma, texture and taste of *boli* produced using the designed roaster and conventional open roasting method. Thus, allaying the fear of consumers' acceptability. The sample roasted in the lower layer of the roaster was rated best in overall acceptability, followed by reference sample, then that roasted at the middle layer of the roaster and lastly the samples roasted in the upper part of the roaster. From these results, it is clear that the sample roasted on the lower roasting grid of the fabricated roaster is the most preferred and could be preferred to the ones processed locally.

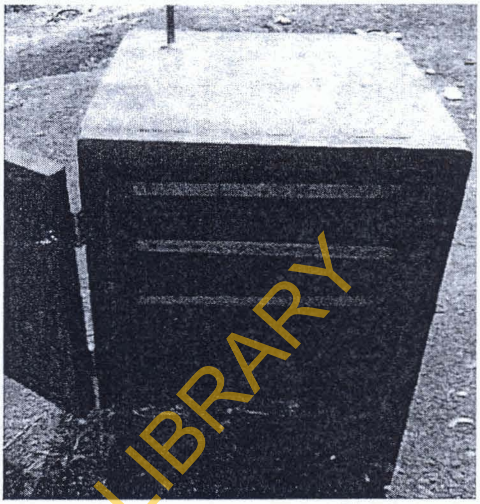

Plate 1: Complete assembly of the roaster

Table 1: Bill of engineering material for plantain roaster

S/N	Description	Quantity	Rate (₦)	Amount (₦)
1	2 x 1200 x 2400 mm mild steel	1	9,750	9,750
2	5 x 50 x 50 mm angle iron	1	1,500	4,500
3	2 x 1000 x 1000 mm stainless steel	1	6,000	6,000
4	Stainless steel electrodes	10	50	500
5	Mild steel electrode	55	20	1,100
6	Fibre wool		2,500	2,500
7	Wielding tools (cutting and grinding disks, blade, etc)	1 each		770
8	Heating elements	2	1,200	2,400
9	Temperature control	1	2,500	2,500
10	Thermocouple	1	500	500
11	Contactor	1	1,500	1,500
12	Switch	1	500	500
13	15 A plug	1	250	250
14	Wire	6 yards	150	900
15	Labour			7,800
	Total			**41,470**

Table 2: Sensory analysis of roasted plantain samples

Sample	Appearance	Aroma	Texture	Taste	Overall acceptability
Reference	7.67 ± 0.24^a	7.17 ± 0.19^a	7.07 ± 0.23^a	7.53 ± 0.22^a	7.53 ± 0.21^a
Upper layer	6.83 ± 0.25^a	7.07 ± 0.22^a	6.97 ± 0.32^a	6.77 ± 0.32^b	6.97 ± 0.26^a
Middle layer	7.07 ± 0.42^a	6.97 ± 0.28^a	7.20 ± 0.25^a	7.57 ± 0.21^a	7.40 ± 0.24^a
Lower layer	7.57 ± 0.25^a	7.20 ± 0.23^a	7.50 ± 0.24^a	7.70 ± 0.28^a	7.63 ± 0.26^a

Note: Higher values indicate higher preferences.

Attributes with the same superscript indicate that there is no significant difference ($p \leq 0.05$)

Conclusion

Equipment for producing roasted plantain was designed, fabricated and evaluated for performance. The roaster capacity is twenty-one fingers of plantain per batch in 45 min. Obtained product was similar in appearance, taste, texture and aroma to *boli* produced using conventional open roasting method. Use of transparent door was recommended for future design.

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