Design and construction of a mechanized charcoal-fueled corn roaster

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Abstract: The economic situation in most developing countries has left farmers and processors operating at small scale and under unhygienic environment. The productivity is often too low to justify labour and time investment. With respect to the challenges particularly associated with roasting of corn, a roaster was designed, constructed and its performance evaluated. The mechanized charcoal fueled corn roaster consists of a frame, roasting unit, charcoal tray, air blowing unit and a power transmission system. The functional efficiency of the machine at different roasting temperatures of 100°C, 130°C and 150°C ranged between 88% and 94%, while the roasting capacity and roasting time ranged between 40 and 54 fresh corns per hour in 22 and 30 min, respectively. The developed roaster can effectively address the need of rural dwellers as well as small and medium scale processors, which would subsequently contribute to economic empowerment and alleviation of food insecurity in areas where this food product is frequently consumed.

Keywords: corn roaster, corn, design and construction, food security

Citation: Sobowale, S. S., O. B. Oluwole, O. P. Olatidoye, O. A. Eweje, A. T. Olayanju, and O. A. Adebo. 2020. Design and construction of a mechanized charcoal-fueled corn roaster. Agricultural Engineering International: CIGR Journal, 22 (4):93-101.

1 Introduction

Maize (*Zea mays*), also known as corn is the fourth most important cereal crop ranking after rice, wheat, oat and barley. While the United States is the largest producer of this crop with 42% of the world's production, Nigeria and South Africa are the leading producers of this crop in Africa with about 8 million tons, constituting 6.5% of the world's production (Food and Agriculture Organization Statistics [FAOSTAT], 2019). It serves as a staple and vital source of carbohydrate, protein, iron, vitamin B and minerals as well as a source of raw materials in the food industry (Ndirika, 1995; Aremu et al., 2015). It is thus an important source of food for both urban and rural dwellers. With increasing population and consequent increase in the use of corn, the market demand for the grain is increasing, making its production vital in Africa (Aremu et al., 2015). As with other food crops, processing is needed to transform corn into forms that can readily be consumed and such processing

Received date: 2019-08-30 **Accepted date:** 2020-05-25
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techniques include boiling, extrusion, cooking, germination, fermentation and roasting (Suri and Tanumihardjo, 2016).

Roasting is the process by which agricultural products are exposed to dry heat in an oven or over a fire for the purpose of removing moisture and cooking of the products for consumption (Heldman and Hartelr, 1997; Sobowale and Adebiyi et al., 2017a). As such, the quality of the roasted product thus depends on the effectiveness of the roasting process. Particularly, roasting is a significant form of processing operation (Fellows, 2000), as roasted corn is generally adjudged as being more palatable, with enriched flavors and taste. While roasted corn is a desired form in which it is consumed by both young and old in parts of Africa, the roasting process is being done traditionally which is highly labor intensive and unhygienic. It is an intricate and tedious process, with little output and productivity to justify the time and effort invested into it (Ayatse et al., 1983; Oke, 2013). Over time, the roasting processes become so strenuous, that the operator tires out before the corn is completely roasted. Few corn cobs are thus roasted in long hours making consumers to wait, while some eventually lose interest. The process is usually done by women and children, under uncomfortable conditions. This results in profuse sweating and relative discomfort due to contact and long-term exposure emanating from the burning charcoal (Mato and Onajin-Obembe, 2008). Health risks may arise due to contact and exposure to direct heat emitted from the charcoal which may probably have damaging effects to the skin and organs; and may lead to low productivity. To thus address these impending challenges, there is therefore a need to come up with equipment which reduces human labor and ensures maximum roasting efficiency by designing and constructing a mechanized charcoal-fueled corn roaster. The constructed roaster is envisaged to deliver the desired and safe roasted corn for its intended consumers and contribute to alleviation of food insecurity.

2 Materials and methods

2.1 Materials

The white fresh corn (*Zea mays*) samples were obtained from local markets in Abeokuta (7.158N, 3.358E), Ogun State, Nigeria. The samples were cleaned to remove debris and foreign materials. Other materials used in the construction of the machine were angle iron, stainless steel plate, insulator (slag wood), electric motor, fan and shaft with journal bearing, slider crank, pulley, metal grills, electric gear box, digital temperature controller and temperature probe (K- type).

2.2 Methods

2.2.1 Design consideration

In developing and fabricating the mechanized charcoal fueled corn roaster, the following were vital factors that were considered:

(I) Material selection – use of readily available locally sourced materials for the fabrication of the equipment was carefully analyzed as well as selection consideration was based on engineering properties such as strength, hardness, ductility, machinability and dimensional stability at high temperature (creep).

(II) Rigidity and strength - the frame of the corn roaster was rigid enough to withstand the loads of various components being supported. This helps to reduce vibration effects during operation.

(III) Operational cost - materials used in the fabrication of the roaster are selected such that the production cost and the marketability of the machine is guaranteed.

(IV) Resistance to corrosion and rust - Since the roaster is a food processing machine, product contact surfaces, that is, all the surfaces exposed to direct contact with the product will be basically made of stainless materials that are less vulnerable to oxidation so as to prevent rust and corrosion. The materials were corrosion proof to the product, non-toxic, and confer no physiological and organoleptic difference. The materials were temperature proof, suitable for surface treatment, shaping and welding ability. The austenitic chrome-nickel or chrome-nickel-molybdenum stainless steels used for the construction of equipment and machining in the food industry, was considered.

2.2.2 Design calculations

Design calculation was necessary to determine reliable parameters by which the system would achieve safe and reliable operations while ensuring the design objective (Singh and Heldman, 1993; Sobowale et al., 2016). Further to earlier stated design considerations, basic corn roasting techniques and effective simulation of the process guided the design computations. Accordingly, relevant parameters to ensure a safe and reliable system and operation while achieving the design objective were considered. Considerations were given to the different shapes of machine components including a frame that will accommodate the blower, motor, chains, sprockets, roasting chamber and charcoal chamber and a roasting unit with appropriate lengths and diameters of corn cobs. Others included in the design were volumes of the roasting and charcoal chamber, speed of the shaft, the charcoal tray, air blowing unit and power transmission system. Based on the above consideration, Equations 1 - 18 were used to compute the parameters for the components of the roaster (Hannah and Stephens 1980; Khumi and Gupta, 2004; Oke et al., 2013; Sobowale et al., 2016; Sobowale and Adebiyi et al., 2017a; and Sobowale and Adebo et al., 2017).

$$V_o = L_o \times B_o \times T_o \quad (1)$$

$$V_1 = L_1 \times B_1 \times T_1 \quad (2)$$

$$M_o = \rho V_o \quad (3)$$

$$V_{Ro} = L_{Ro} \times B_{Ro} \times T_{Ro} \quad (4)$$

$$V_{R1} = L_{R1} \times B_{R1} \times T_{R1} \quad (5)$$

$$V_{Co} = L_{Co} \times B_{Co} \times T_{Co} \quad (6)$$

$$V_H = \frac{\pi d^2 h}{4} \times 160 \quad (7)$$

$$V_{hh} = \frac{\pi d_{hh}^2 h_{hh}}{4} \times 160 \quad (8)$$

$$V_{RC} = V_{Ro} - (V_{R1} + V_H + V_{hh}) \quad (9)$$

$$M_{RC} = \rho_{ss} V_{Ro} \quad (10)$$

$$V_{C1} = L_{C1} \times B_{C1} \times T_{C1} \quad (11)$$

$$V_{CC} = V_{C0} - V_{C1} \quad (12)$$

$$M_{CC} = \rho_{sm} V_{CC} \quad (13)$$

$$T_1 / T_2 = exp^{(\mu\theta)} \quad (14)$$

$$P_{(w)} = (T_1 - T_2) V_b \quad (15)$$

$$L_{10} = (C / P_c)^P \quad (16)$$

$$P = XF_r + YF_a \quad (17)$$

$$N_a = \frac{N_e \times D_e}{D_a} \quad (18)$$

where: θ is the angle of lap, μ is the coefficient of friction, ρ is the density of angle bar (7.82 × 10^{-6} kg mm^{-3}), ρ_{sm} is the density of stainless steel (7.82 × 10^{-6} kg mm^{-3}), ρ_{ss} is the density of stainless steel (7.85 × 10^{-6} kg mm^{-3}), B_0 is the breadth of outer long brace (mm), B_1 is the breadth of inner long braze (mm), B_{C0} is the breadth of outer charcoal chamber (mm), B_{C1} is the breadth of inner charcoal chamber (mm), B_{R0} is the breadth of the outer roasting chamber (mm), B_{R1} is the breadth of the inner volume of the roasting chamber (mm), C is the basic dynamic load rating (N), d is the diameter of hole (mm), D_a – diameter of multiple-grooved pulley fitted to speed reducer worm gear shaft, D_e – diameter of pulley fitted to electric motor, d_{hh}– diameter of hanger hole (mm), F_a is the axial radial bearing (N), F_r is the actual radial bearing load (N), h is the height of hole (mm), h_{hh} is the height of hole (mm), L_{10} is the basic rating life in millions of revolution, L_0 is the length of outer long braze (mm), L_1 is the length of inner long braze (mm), L_{C0} is the length of outer charcoal chamber (mm), L_{C1} is the length of inner charcoal chamber (mm), L_{R0} is the length of outer roasting chamber (mm), L_{R1} is the length of inner roasting chamber (mm) P is the exponent for the life equation, M_{CC} – mass of charcoal chamber (kg), M_0 – mass of long braze (kg), M_{RC} is the mass of roasting chamber (kg), N_a is the speed of reducer worm gear shaft (rpm), N_e is the speed of electric motor (rpm), $P_{(w)}$ is the power transmitted (W), P_c is the equivalent dynamic bearing load (N), T_0 is the thickness of outer long braze (mm), T_1 (Equation 2) is the thickness of inner long braze (mm), T_1 (Equation 6) is the tension in slack side of the chain (N), T_2 is the tension at tight side of the chain (N), T_{C0} is the thickness of outer charcoal chamber (mm), T_{C1} is the thickness of inner charcoal chamber (mm), T_{R0} is the thickness of outer roasting chamber (mm), T_{R1} is the thickness of inner roasting chamber (mm) V_b is the speed of the driver (m s^{-1}), V_0 is the outer volume of long braze (mm^3), V_1 is the inner volume of long braze (mm^3), V_{C0} is the volume of outer charcoal chamber (mm^3), V_{CC} is the total volume of charcoal chamber (mm^3), V_{C1} is the volume of inner charcoal chamber (mm^3), V_H is the volume of roaster frame holes (mm^3), V_{hh} is the volume of hanger holes (mm^3), V_{R0} is the outer volume of roasting chamber (mm^3), V_{R1} is the inner volume of roasting chamber (mm^3), V_{RC} is the total volume of roasting chamber (mm^3), X is the radial load factor for the bearing (N), Y is the axial load factor for the bearing (N). Subsequent data obtained from the computed calculations from Equation 1-18 is presented in Table 1.

2.2.3 Sensory evaluation of roasted corn

Prior to the sensory evaluation test, ethical clearance was obtained and informed consent of the sensory panelists was sought and obtained. Twenty trained panelists were asked to rank each of the samples. A 9-point Hedonic scale for food preference (Sobowale and Adebiyi et al., 2017b; Sobowale et al., 2017) was used to evaluate the roasted corn in terms of color, aroma, sweetness, taste and overall acceptability. Each panelist was requested to assess each coded sample and recorded differences in each of the samples.

2.3 Construction and description of the roasting machine

The constructed equipment consisted of (a) frame, (b) roasting unit, (c) charcoal tray, (d) air blowing unit and (e) power transmission system. The pictorial, isometric, exploded and orthographic views of the fabricated corn roaster are depicted in Figures 1 to 4 and the fabrication of these parts is described below:

2.3.1 Frame

As shown in Figure 3, the frame comprises of the machine structure, which gives support for the entire machine. It was made of an angle iron of 2.5 mm and of cast iron sheet of 5 mm thickness and is rectangular in shape. The frame's length, breadth and height were 85, 90 and 46 mm, respectively. The frame is fitted with four supporting rolling tyres which act as its stand. Three equidistant openings of 65 mm diameter are made lengthwise on the longer side of the frame and 35 mm on the opposite side. The hot charcoal chamber is filled into the space formed by the frame and mesh assembly, up to the desired depth. The temperature of the charcoal chamber is maintained by supplying air to the bulk with the help of air blowing unit present beneath the frame.

Table 1 Some design parameter values and geometric details of the roaster

Parameter	Value
Tension in slack side of chain (N)	330
Tension in the tight side of belt (N)	450
Velocity of crank (m s^{-1})	28
Power required (W)	962
Length of slider (mm)	83
Diameter of shaft (mm)	18
Factor of safety	2
Bearing design life (rpm)	1.0×10^7
Bearing design load (N)	550
Basic working life (hr)	15.2×10^7
Speed reducer worm gear shaft (rpm)	1.5×10^3
V_0 (mm^3)	351, 900
V_1 (mm^3)	126, 876
M_0 (kg)	0.99
V_{R0} (mm^3)	255, 024
V_{R1} (mm^3)	37, 184
V_H (mm^3)	15, 710
V_{hh} (mm^3)	62.84
V_{RC} (mm^3)	202, 067
M_{RC} (kg)	158.62
V_{C0} (mm^3)	139,440
V_R (mm^3)	89, 600
V_{CC}(mm^3)	49, 840
M_{CC} (kg)	0.39
N_a(rpm)	1, 516

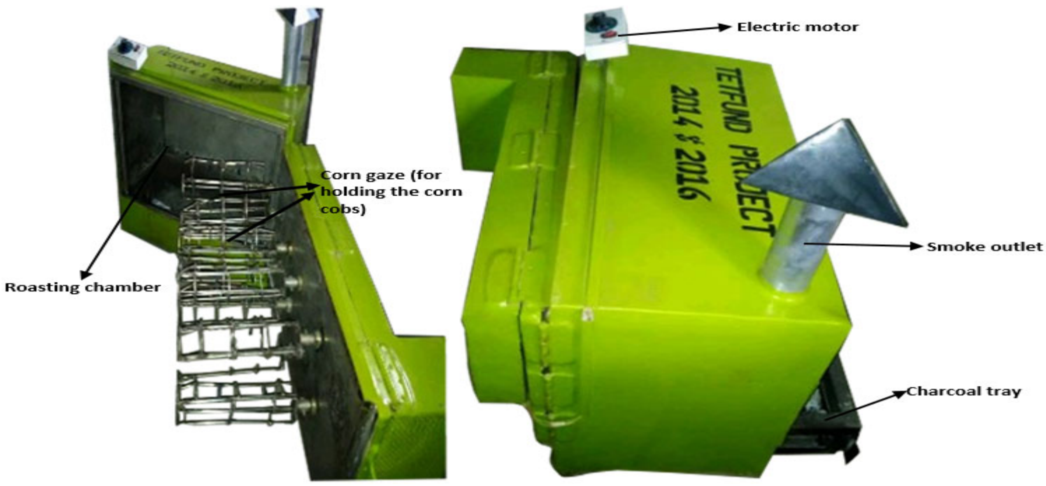

Figure 1 Pictorial view of the charcoal-fueled corn roaster

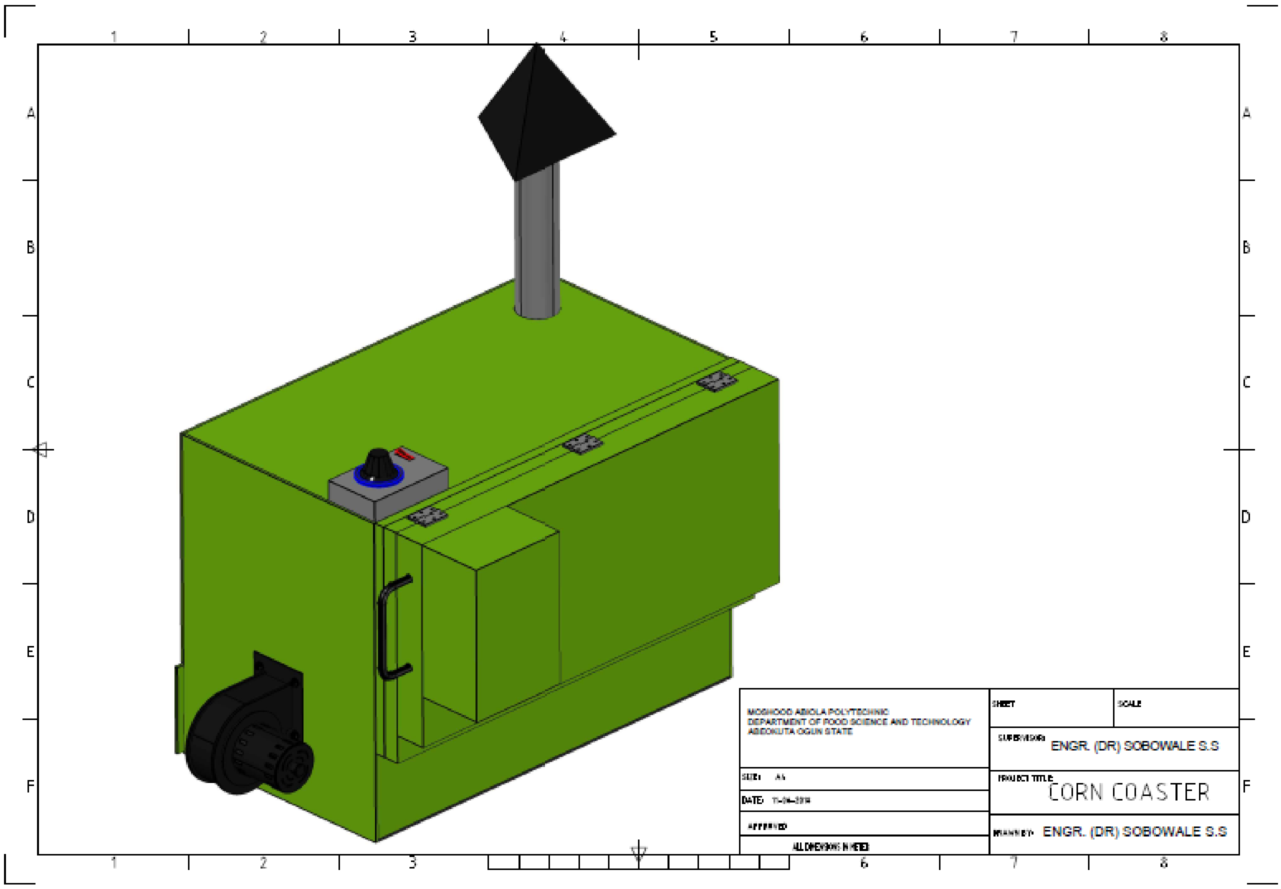

Figure 2 Isometric view of mechanized charcoal-fuelled corn roaster

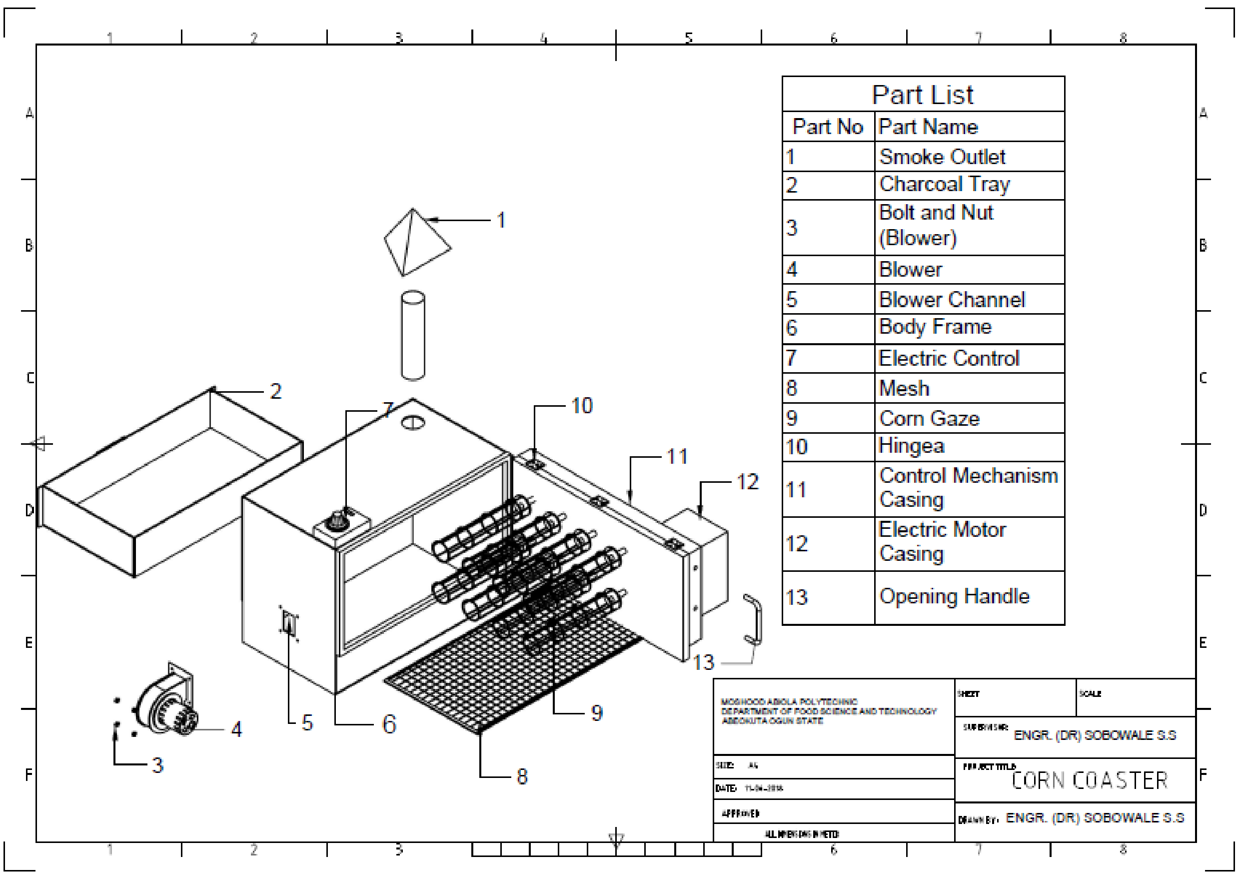

Figure 3 Exploded view of mechanized charcoal-fuelled corn roaster

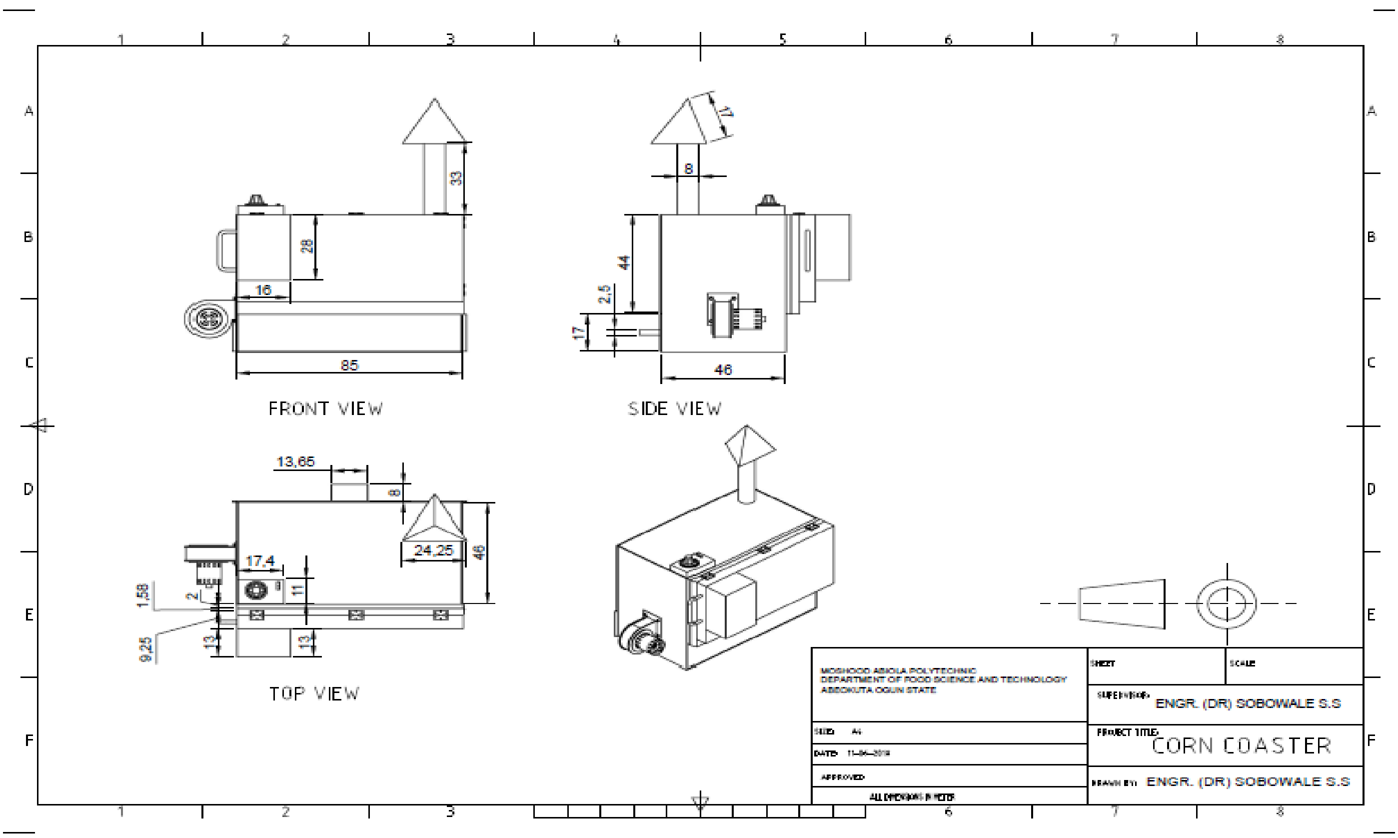

Figure 4 Orthographic view of mechanized charcoal-fuelled corn roaster

2.3.2 Roasting unit

The roasting unit is identical to a conical frustum in shape and made of stainless-steel sheet of 3 mm thickness. The length and major and minor diameters of the roasting unit are 84, 69 and 44 mm, respectively. Three identical roasting units snug fit in the holes made in the frame of the roaster without using nuts and bolts. This is easily removed when needed. The roasting unit is attached with the exhaust stainless pipe (Figure 3) i.e., smoke outlet which has length of 33 mm and 8 mm diameter. To ensure effective heat distribution and to prevent loss of same, a slag wool insulator was used.

2.3.3 Charcoal trays

The charcoal trays (Figure 3) are made from stainless steel of 2 mm thickness to accommodate hot charcoal that are used for corn roasting conveniently and the air flow from the fan, produced by an air blowing unit. The inner and outer dimensions of the tray are 80 × 40 × 28 mm and 83 × 42 × 40 mm, respectively. A metal grill was attached to the tray as a means of separating the corn from the glowing charcoal. Two trays were constructed for roasting operation on the pattern of air flow duct.

2.3.4 Air blowing unit

The air blowing unit (Figure 3) consists of a metallic fan which is made from a sheet metal and a shaft supported by a journal bearing. The sheet metal serves as the fan blade while the housing is made to aspirate air and build up pressure toward the discharge end. These are rotated with the help of motor with chain-sprocket mechanism. The fan is made of aluminum and has four blades, with thickness and diameter of 2 and 18 mm, respectively. The fan is fixed in an inverted direction, at a distance of 16 mm beneath the mesh assembly, rotating with the help of a set of machine parts of bearing with gear teeth, chain, motor and wheels. The wind generated from the rotation of the fan is forced onto the bed of charcoal chamber from beneath, thus providing the heat to the roasting unit.

2.3.5 Power transmission system

The rotary motion of the fan was achieved through a 1 HP motor with chain and sprocket mechanism (Figure 3). The chain has a length of 85 mm with a spacing of 15 mm between consecutive links. The transmission system also comprises of two sprockets, a smaller one of 18 mm diameter with 10 ‘teeth’ and the larger one of 180 mm diameter with 44 ‘teeth’. Both sprockets are aligned horizontally and the chain runs over them. The smaller sprocket is integrated with the fan hub and a motor is provided on the larger sprocket for its rotation.

2.4 Operation of the corn roaster

About 2 kg of prepared hot charcoal was fed into the charcoal trays and twenty pieces of about 1 kg corn cobs were immediately fit into the stainless grills. At this point, the digital temperature controller was set at at different temperatures of 100ºC, 130ºC and 150ºC to monitor the temperature in the roasting chamber and regulate the heat generated from the hot charcoal through the rotation of the fan and hence maintain the intensity of the heat. While the rotation of the fan was operated through 1 HP motor with chain and sprocket mechanism and forces blowing air onto the bed of charcoal chamber from beneath to increase the intensity of the hot charcoal. This provided hot air to the roasting chamber until the set temperature was reached. The corns were then rotating continuously until uniform roasted corn was obtained. At the completion of the roasting process, the corn was removed and the smoke generated from the charcoal chamber was discharged through the exhaust pipe.

2.5 Performance evaluation

After construction, performance evaluation tests were carried with the constructed roasting machine. The functional efficiency, roasting capacity and time were investigated. Fresh corns were roasted at different temperatures of 100ºC, 130ºC and 150ºC, while the initial weight and final weight after roasting were estimated. Using Equations 19 and 20 (Sobowale and Adebiyi et al., 2017a; Sobowale and Adebo et al., 2017), the following performance indicators were examined:

$$E = \left(M_o / M_f \right) \times 100 \quad (19)$$

$$C_R = \frac{Number\ of\ corns\ roasted}{Time\ taken\ to\ roast\ the\ corns(hr)} \quad (20)$$

Where, E is the functional efficiency of the machine (%); C_R is the roasting capacity (corn hr^{-1}); M_f is the mass of the fresh corn sample (kg); M_o is the mass of roasted corn sample obtained (kg).

3 Results and discussion

The details of the variables used to evaluate the performance of the roaster are given in Table 2, while the results of the tests at different roasting temperatures with the functional efficiency and roasting time are shown in Table 3.

Table 2 Details variables used in the performance of the roaster

Parameter	Values
Roasting temperature (ºC)	100, 130, 150
Performance indicators	Functional efficiency, roasting capacity and roasting time

Table 3 Performance of the corn roaster under different temperatures

No of corns	Roasting temp (ºC)	Functional efficiency (E)	Roasting time (min)	Roasting capacity (C_R) (corns hr^{-1})
20	100	88	30	40
20	130	90	26	46
20	150	94	22	54

The functional efficiency of the corn roaster at different roasting temperatures of 100ºC, 130ºC and 150ºC was 88, 90 and 94% with consecutive roasting times of 30, 26 and 22 min, respectively. The roasting capacity was given as 40, 46 and 54 fresh corn cobs hr^{-1}, respectively. Functional efficiency was generally observed to increase with rise in roasting temperatures, while the roasting time decreased. The increase in the roasting temperature encouraged the transfer of heat from the roaster to the corn kernels placed in the grills of the roasting units, thereby increasing the roasting efficiency. Nevertheless, the optimal functional efficiency of 94% was observed when 20 corns were roasted at 150ºC for a period of 22 min. This result is in agreement with earlier work carried out by Sobowale et al. (2016) on performance evaluation of *gari* roaster with a reported increase in functional efficiency at elevated temperature. In addition, it also validates initial observations and in tandem with results obtained by Awopetu and Aderibigbe (2017) and Ilori et al. (2014) on development of manually operated multi-purpose roasting machine and development and performance evaluation of a maize roaster, respectively. This relatively high percentages of functional efficiency showed that the machine performed satisfactorily. Therefore, as roasting temperature increases, the potential to undergo this biochemical reaction increases. This is in line with the works of Tairu et al. (2000) and Olaniyan (2012).

Consumer acceptability tests were conducted to evaluate their preferences in terms of color, aroma, sweetness, taste and overall acceptability of roasted corn samples and to know the level of acceptance based on the magnitude of their responses (likes and dislikes). The panelists thus used the corresponding sensory scores for each of the attributes as shown in Table 4. Results showed that there were significant differences (p<0.05) in all the samples investigated using one-way ANOVA. Corn roasted at temperature of 150°C, for a period of 22 min were generally the most preferred and accepted by the sensory panellists, while sample roasted at temperature of 100°C and time of 30 min were the least preferred.

Table 4 Sensory evaluation of roasted corn at different temperatures

Sample code	Color	Aroma	Sweetness	Taste	Overall acceptability
152	6.60^a	7.80^c	6.90^a	7.10^a	6.60^a
234	6.80^a	6.20^a	7.50^b	8.30^c	7.30^b
312	8.60^b	6.70^b	8.20^c	8.10^b	8.80^c

Note: Mean values with different subscripts within a column are significantly different (p < 0.05)

152 - corn roasted at 100°C; **234** - corn roasted at 130°C; **312** - corn roasted at 150°C.

4 Conclusion

A prototype mechanized charcoal-fuelled corn roaster was designed, constructed and evaluated in this study. The design concept was based on roasting principle and the materials of construction which were locally sourced. The equipment can be easily operated. The drudgery and tediousness associated with corn roasting can be effectively addressed using this equipment. The equipment would be of significant importance and viable alternative to local roasting methods which are commonly found among rural dwellers as well as small and medium scale processors in developing nations. The optimal functional efficiency of 94% was observed when 20 corns were roasted at 150°C for a period of 22 min. Commercialization and consumption of roasted corn products would largely contribute to economic empowerment and alleviation of food insecurity in African countries.

Acknowledgments

Funding provided by Nigerian government through the Tertiary Education Trust Fund (TETFUND) of the Federal Ministry of Education and Management of Moshood Abiola Polytechnic, Abeokuta, Nigeria to Dr. Sobowale Sunday Samuel, is duly acknowledged.

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