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Design Development and Construction of Solar Powered Fresh Juice Extracting Machine

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Abstract:
One of the greatest problems of fruit farmers in Nigeria is their inability to process and add value to their produce. This results from the paucity of processing and preservation facilities or the prohibitive cost of imported ones, especially for low-income farmers who produce the bulk of the commodity. It therefore becomes imperative to design, develop and construct low-cost, durable, efficient and environmentally friendly machines to meet the needs of both the urban and, more importantly, the rural farmers with a view to improving their income and also making their produce available and affordable all year round. The machine components include feeding hoppers, a top cover, an auger conveyor housed in a cylindrical barrel, a juice sieve, a juice collector, a waste outlet, a transmission belt, a main frame, pulleys, bearings, 3hp DC motor, a control panel, a solar panel, 20Ah charger controller 100Ah Solar battery, breaker and control switch.

Keywords: *Solar power, juice extracting machine*

1. Introduction

The agricultural potentials of Nigeria that have been exploited in the pre-independence and post-independence periods prior to 1975 gave it a leadership position internationally in the production and exportation of agricultural products (Ndubisi et al., 2015). Furthermore, the agricultural sector accounted for 50% of the GDP and employed about 72% of the labour force on average between 1960 and 1970 (CBN, 2004; Fasanya et al., 2013).

In developed countries like the USA, Germany, France, Italy, Canada and the United Kingdom, among others, the productivity of the agricultural sector is always on the increase. These achievements result from the level of mechanization of their agricultural activities. However, mechanization has been very slow and sometimes difficult in Nigeria because of the high cost of imported machines and equipment and the lack of indigenously designed, developed and technologically advanced agricultural machines and tools (Ekerete, 2020).

From the foregoing, it has become imperative to conceptualize, develop, design and produce low-cost, durable and efficient machines to meet the growing needs of the food processing industry and the mechanization needs of the agricultural sector in Nigeria.

1.1. Statement of the Problem

Fruits are seasonal products in Nigeria and, therefore, cannot be available at affordable prices in sufficient quantity all year round because of the difficulty of processing, storage and preservation. The major problem is the high perishing rate of fresh fruits, especially in sub-Saharan region (Olaniyan, 2016).

Many agricultural products in Sub-Saharan Africa, including Nigeria, are allowed to be wasted due to the inability or lack of equipment and machinery to properly process and store them, thereby inflicting serious economic and financial loss on the farmers and the continent in general. Based on the context above, this study seeks to design, develop and construct a solar-powered fresh juice-extracting machine.

1.2. Justification

Although successes have been recorded so far in the design and development of juice extractors, emphasis has always been on machines that rely on electricity as a source of power, which makes their application and utilization limited to places where such power is available and also the machines used mostly involve fruits that contain a large quantity of liquid. Therefore, the need to work on the possibility of designing a machine that can extract juice from both soft and hard fruits without solely relying on electric power, which restricts its usage, becomes very necessary.

1.3. Objectives of the Study

The major objective of this study is to design, develop, construct and carry out a performance evaluation of a motorized solar-powered fresh juice-extracting machine. Specifically, the study sought to:

- Carryout the design analysis of the juice extractor
- Construct/fabricate the machine components and assemble them
- Determine the optimum operating capacity of the machine (Extraction speed (5) and feed rate (F)).
- Evaluation of the performance of the extractor (Juice yield, Extraction efficiency and extraction losses).
- Evaluate the production capacity of the juice-extracting machine.

1.4. Research Questions

The research was guided by the following research questions:

- What appropriate design analysis is considered suitable for an excellent juice-extracting machine?
- How can the various components of the juice-extracting machine be constructed/fabricated and assembled?
- How can the optimum operating capacity of the machine be determined?
- What will be the performance of the machine in terms of yield efficiency and extraction losses?
- What will be the production rate of the juice-extracting machine materials and methods?

1.5. Research Design

The study adopted the research and development (R&D) design.

1.6. Area of the Study

The study was carried out at the Department of Mechanical Production Technology Education Welding Workshop, College of Technical and Vocational Education Kaduna Polytechnic, Nigeria.

1.7. Material Selection

The following factors were considered in the selection of the materials for construction/fabrication:

- Physical properties such as density, size and shape
- Mechanical properties which include strength, toughness, Stiffness, Fatigue hardness and wear resistance.
- Chemical properties which include resistance to oxidation and all forms of corrosion
- Availability of materials: All the materials used were selected based on their availability in the market
- Cost of Materials: Materials used are available at a cheaper cost all over the country.
- Cost of Maintenance: All replaceable parts were not welded to the machine frame to allow for easy replacement in case of any damage or spoilage.
- Strength of Materials: To avoid operational failure, the strength of the materials used was ascertained.
- Durability and Hygiene: - Since the machine is food processing equipment, most of the parts were produced using stainless steel to enhance the durability of the machine and control oxidation.

2. Components of the Juice Extractor

2.1. Extracting Compartment

The extracting compartment of the machine comprises the cylindrical barrel, which houses a screw conveyor, and the pulley with bearing. The screw shaft is supported by the bearings at both ends, as shown in figure 1. The auger (Screw) conveyor and the barrel were both fabricated from stainless and the pulley fabricated from mild steel is mounted on the screw shaft made of (Stainless Steel with the main function of transmitting the rotary power (Torgue) from Dc motor to the juice extracting machine through the V-belt connection. The V-belt provides a means of changing speed.

Figure 1: Extracting Compartment

2.2. The Frame and Stand

The frame and the stand, fabricated from an angle iron bar, are the parts of the machine that provide support for both the juice extractor motor, as shown in figure 2. The frame also provides rigidity when the machine is in operation.

Figure 2: Frame and Stand

2.3. The Outlet Compartment

The outlet compartment comprises two major outlets: The juice outlet and the cake outlet. The juice outlets are perforations drilled below the cylindrical barrel, unto which a sieve made of stainless steel for juice collection is attached. The cake outlet is joined to the posterior end of the barrel, and the two outlets are designed to discharge the extracted fruit juice and the fruit residue (or fruit cake) simultaneously.

Figure 3: Outlet Compartment

2.4. The Power Unit

The power unit consists of a solar panel, a 3hp single-phase electric motor with belts and pulleys and a gearbox arrangement for speed variation. The motor powers the machine via v-belts, pulleys and gearbox arrangement and is mounted on a seating located at the tool frame. The belt receives power from a pulley mounted on the motor shaft.

Figure 4: Power Unit

Figure 5: Solar Panel

2.5. Design Theories

Power Requirement of the Chopping Unit.

Power required for splitting the fruits can be calculated using the equation given by Hannah and Hilkier (1988) as:

$P_c = F_c \times V$

Where:

P, = Power (watts)

F_e = Centrifugal Force (N)

V = Velocity of the shaft with blades

The average shear force for orange was assumed to be 90N.

Assuming the Centrifugal force of the shaft to be greater than the sheer force (F_S) by 25%.

25% of 90N = 22.5N

Therefore, Fs = 90 + 22.5 = 112.5N

2.6. Peripheral Speed of the Shaft with Blades

A shaft is a rotating member, usually of a circular cross-section (either solid or hollow), transmitting power. It is supported by bearings and supports gears, sprockets, wheels, rotors, etc., and it is subjected to torsion and transverse or axial loads, acting singly or in combination. The peripheral speeds of the shaft and blade are given by Bhandari (2004) as:

$V = \frac{\pi D n}{60}$

Where:

D = Diameter of Blades

n = Speed of Shaft with blades

Figure 6: Design of Blades and Shaft

2.7. Design of the Number of Blades on the Shaft

The number of blades on the shaft is determined using the expression adapted from Adebayo et al. (2014) as:

$S_n = 2 \times \frac{1s}{St}$

Where:

S_n = The number of blades on the shaft

1_s = Length of the shaft with blades

S_t = The desired thickness of lump (Spacing of Blades)

2.8. Volume of the Feed Hoppers

The feed hoppers are trapezoidal in shape to accommodate enough fruits and gradually introduce portions of the fruits by gravity into the chopping and extracting compartments. The volume of the hopper can be calculated using the expression below:

$$\left\{ V = (\tfrac{1}{2}A + 8)\ D \times C \right\}$$

Where:
V = Volume of hopper
D = Height of Hopper
C = Width of Upper End
A = Upper Length of Hopper
B = Lower Length

2.9. Design of the Screw Conveyor of the Extraction Unit

The screw conveyor is the main component of the extraction unit and its shaft is acted upon by weights of the pulley and screw thread. In operation, the screw conveyors convey, crush, press and squeeze the chopped fruit lumps for juice extraction. Therefore, to safeguard against bending and torsional stresses, the diameter of the shaft was determined from the equation given by Khurmi and Gupta (2008) as:

$$d_3{}^3 = \frac{16}{\pi \beta o}\ (k_b\ m_b)^2 + (k_t\ m_t)^2$$

Where:
d = Diameter of the shaft in m
β_0 = Allowable shear stress (55 x 106 N/m² for shaft without keyway)
K_b = Combined shock and fatigue factor applied to bending moment
K_t = 1.5 and K_t = 1.0 (for the load applied gradually)
M_0 = maximum bending moment kNm
M_t = Maximum torsional moment kNm

Figure 7: Screw Conveyor Unit

2.10. Design of the Load That Can Be Lifted by the Auger

The load that can be lifted by the screw is determined from the equation given by Hall et al. (2002) as:

$$We = T\ \frac{\frac{Dm\tan\theta}{2} + \frac{\mu}{\cos\propto}}{(1-\theta\cos\propto)}$$

$$\propto = \tan^{-1}(\tan\theta n \cos\theta)$$

Where:
W_e = Load that can be lifted by the screw (k W)
T = Torque transmitted by the screw shaft
D_m = Mean thread diameter
μ= Coefficient of Friction
θn= Thread (lift) angle
$\propto$= Tapering Angle

2.11. Design of the Pressing Area and Pressure Developed by the Anger

The pressing area and the pressure developed by the auger were determined from equations (3.7) and (3.8), respectively, given by Hall et al. (2002) as:

$$A_p = \pi Dmnh$$

$$P_r = \frac{We}{Ap}$$

Where:
P_r = Pressure developed by the auger
H = screw depth at the maximum pressure (discharged end)

n = Number of Threads

2.12. Design of the Pressure on the Barrel

The pressure to be withstood by the barrel was determined from the equation (Ryder, 1985):

$P_b = \frac{2t\delta a}{Dt}$

Where:
Pb = Pressure on the barrel
t = Thickness of the barrel
Di = The inside diameter of the barrel
δa =Allowable stress, and (6a = 0.27(0))
δo = The yield stress for stainless steel

2.13. Design of the First Pitch of the Decreasing Pitch Auger

Auger fighting design considerations and nomenclature are presented in EP389.1 (ASAE, 1993). This engineering practice states that the pitch of the flighting should be between 0.9 and 1.5 times the outside diameter of the flighting. Therefore, the first pitch of the decreasing pitch auger is given by equation (10) (ASAE, 1993) as:

P_s = 1.4Ds7

Where:
P_s and D_s are, respectively, the pitch and outside diameter of the auger.

2.14. Design of the Pitch of the Decreasing Pitch Auger

The auger was designed to have pitches of decreasing order. In the determination of the pitches, the Iteration method was used. A value was assumed for the pitch (P (x)) in order to obtain a value for the inlet velocity (v) and then evaluate the remaining six pitches using iteration.

The summation of the seven pitches must not be greater than the total length of the auger (0.7m). The auger was designed using a method by Jones and Kisher (1995) in Gbabp et al. (2013) as:

$P(Xn0) = \frac{4vDsL}{\frac{\pi}{4}(Ds2 - ds2)N}$

Where:
P (Xn) = n^{th} pitch (m)
v = inlet velocity of fruit (m/s)
D_s = outside diameter of auger (110mm)
d_s = inner diameter of auger (40mm)
L = Length of auger (700mm)
N = speed in rev/min of the screw shaft (365rpm)

2.15. Design of the Theoretical Capacity of the Extractor

The theoretical capacity of the extractor was determined using a modified form of the equation given by Onvualu et al. (2006) as:

$= 60 \times \frac{\pi}{4} (D_s^2 - d_s^2) P_s N_s \varphi$

Where:
Q_e = theoretical capacity of the extractor in kg/hr
D_s = diameter of the screw of auger m
d_s = base diameter of the screw shaft in m
P_s = pitch of auger in m
N_s = rotational speed of auger in rpm
φ= filling factor

2.16. Design of the Volumetric Capacity of the Machine

The volumetric capacity of the machine is given by Onwuala et al. (2006) as:

$Q_{vc} = \frac{Qs}{p}$

Where:
Q_e = the theoretical capacity of the extractor
P = the density of fruit in kg/m^3

2.17. Design of the Power Requirement for Extraction

The power requirement of the machine for extraction can be calculated using the equation adapted from Hall et al. (2002) as:

$P_e = 4.5 \times Q_{vc} \times I_s \times p \times g \times F$

Where:
P_e = Power Requirement for extraction
Q_{vc} = Volumetric Capacity
I_s = Length of Screw Shaft

p = Density of the material
g = acceleration due to gravity
F = the material factor

Therefore, the total power equipment is the sum of the power required for chopping and that required for extraction

$P_t = P_c + P_e$

Where:

P_t is the total power requirement of the machine.

The power of the electric motor to drive the system can be estimated from the equation given by Onwuala et al. (2006) as:

$P_m = \frac{Pt}{\vartheta}$

Where:

P_m = Power of the prime mover and
n = the drive efficiency

3. Results

The result of the research is a functional solar-powered juice extractor for fresh pineapple fruits, orange fruits and ginger, which has been tested. See figure 8 below.

Figure 8: Complete Assembly of the Solar Powered Extractor Machine

4. Discussion of Results

4.1. Juice Yield (j_y)

The results show that the optimum feed of the machine for both pineapple and orange fruits is (3.0 kg/min) and tat for ginger (3.5 kg/min), respectively. More juice was yielded from pineapple fruits, followed closely by orange fruits than ginger. This may be due to the fact that pineapple and orange fruit are more succulent in nature compared to ginger. As a result, more juice was extracted at each operating speed from pineapple and orange fruits with the aid of the fabricated juice extractor than obtained from ginger.

In general, the juice yield of the machine for all the fruits tested decreases as the machine operating speed increases and vice-versa. A similar observation was made by Adebayo et al. (2014), Badmus and Adeyemi (2004) and Olaniyan (2010) for other juice extractors. At high speeds, there is a reduction in juice extracted even from pineapple and orange despite the succulent nature of the fruits. This may be due to the losses arising from the vibrations of the machine at high operating speeds, causing splashing of juice to the walls of the machine, thus reducing the yield. This is in agreement with the observation of Adebayo et al. (2014). Hence, a controlled speed should be maintained when operating the machine for juice extraction from fruits to obtain a high yield of juice.

4.2. Extraction Efficiency

The juice extraction efficiencies of the machine are tested using pineapple, orange and ginger. It can be seen that the efficiency of extraction for pineapple and orange increased to a maximum value of 84% and 82%, respectively, at optimum operating speed 335rpm and optimum feed (3.0 kg/min), and then decreased at speeds beyond 335rpm. For ginger, the optimum speed is 476 rpm. This may be due to the fact that ginger, being harder and less succulent than pineapple and orange, is less efficient for juice extraction at low speeds. When a small quantity of water was added to the fruit during the extraction processes, it enhanced the ease of juice extraction, reduced the roughages and at the same time increased the quality of water added to the fruit during the extraction processes, it enhanced the ease of juice extraction. At high speeds, fruits were not completely grinded and that may be responsible for the reduction of yield of juice extracted compared to when the machine was run at a slow and steady speed. Thus, performance tests show that the optimum extraction efficiency of the motorized juice extractor depends on the nature of the fruit from which juice is to be extracted and the extraction speed of the machine. A similar observation was posited by Gbabo et al., (2013) and Ndubisi et al., (2013) for other juice extractors. The chopper has a role to play with regard to the sizes of fruits that pass down to the barrel where the fruit juice is finally extracted. The roughages increase with increasing speed, while there is a reduction in extraction time as the extraction speed increases.

4.3. Extraction Losses (E_L)

An increase in machine operating speed increases the extraction losses and vice versa. This may be because of losses arising from the splashing of the juice at the machine walls due to vibrations at high speeds. As a result, the volumes of juice extracted from all the fruits tested were minimal at the highest extraction speed of 632rpm. Just like pineapple fruits, juice from succulent fruits should be extracted at a controllable speed to avoid much splashing of the juice at the machine outlet. Provision should be made for an adjustable cone for the machine for the proper discharge of the residual wastes from fruits arising from the screw conveyor, thus reducing the volume of juice loss at high speeds.

5. Conclusions

- The design analysis of the fruit juice extraction machine was carried out and the machine was successfully constructed, assembled and tested.
- The optimum operating speed of the machine for juice extraction was found to be 335rpm for orange and pineapple fruits and 476rpm for ginger.
- The average juice extraction efficiency at optimum speed (S) and feed (F) for pineapple, orange and ginger were respectively 84%, 80% and 71%. Juice yield at optimum S and F for pineapple, orange and ginger were respectively 71%; Juice at optimum S and F for pineapple, orange and ginger were respectively 74%, 72% and 34%. Juice extraction losses for pineapple, orange and ginger were respectively 18%, 16% and 9% optimum Sand F.
- The production capacity of the developed juice extractor was found to be about 30litres/hour for orange, 32litres/hour for pineapple and 24litres/hour for ginger.
- With a machine cost of about ₦350,000 due to the escalation cost of materials in the market, it is affordable for small-scale farmers in rural communities.

6. Recommendations

- The length of the auger should be increased and should cover about 95% of the shaft for proper juicing and easy ejection of seeds.
- The perforation of the inner cylinder should be increased in order to allow the free flow of the extracted juice.
- A pulping machine should be incorporated to separate the juice from the fruit pulp, thereby avoiding blockages of the perforations.

7. Contributions to Knowledge

The following are some of the contributions of this work:

- The work has recast the drudgery of manual juice extraction methods and the expensive importation of fruit juice extracting machines to Nigeria.
- The work has established that the efficiency of extraction of a juice extractor depends on the speed of extraction S, (rpm), feed rate F (kg/min) and nature of the fruit.

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