Development of a twin screw extruder

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Abstract: The aim of this study was to design, construct a multi-purpose twin screw extruder and evaluate its performance. All parts of the extruder were constructed using locally available materials and was made suitable for both batch and continuous production. The extruder essentially consists of the hopper, barrel, variable screw speed and temperature control, electrical motor and replaceable dies to give different sizes and shapes in the final products. It could also handle feed materials of different rheology. Performance evaluation of the extruder was done using cocoyam flour, varying feed moisture content (FMC) and screw speed (SS). Both the FMC and SS were observed to significantly affect all performance indicators (expansion ratio, residence time, throughput and functional efficiency) of the extrusion process. The availability and efficient access to this equipment would encourage the development of locally made extruded products. Through effective utilization, it is expected that the extruder would expand the production and processing of extruded foods.

Keywords: extrusion, twin screw extruder, design, performance evaluation, cocoyam

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1 Introduction

Extrusion is one of the major processes used in manufacturing of various food products. It is a thermo-mechanical process in which heat and mass transfer, pressure changes and shear are combined to produce effects such as kneading, cooking, drying, melting, texturizing, conveying, pounding and forming (Cheng and Friis, 2010). The extrusion process is typically done using an extruder and the same equipment with slight modifications which may be used for obtaining different products, signifying its key importance and potential wide spread application in the food industry. Extrusion has been used in the manufacture of foods including but not limited to pet foods, acceptable snacks, baby foods, noodles, instant beverages and pasta.

According to Senanayake and Clarke (1999), the screw type extruders (single and twin) are distinct as they offer the possibility for continuous processing and better mixing ability. Nonetheless, their operating principles are quite similar (Fellows, 2000). Although the importance and potential application of extrusion in the food industry is known, most available food extruders in the market are either too expensive and/or not readily available for potential food processors in underdeveloped nations. This has substantially resulted in less and hindered growth of extrusion technology in these countries. Twin screw extruders are known for its numerous applications for food extrusion. However, its high cost, sophisticated constructional features, high maintenance needs and subsequent inaccessibility are major barriers to its availability for food processing in these nations.

Attempts made towards the provision of an appropriate equipment for extrusion in developing nations are relatively few, not readily available or their costs are quite high. This may be because the design and construction of this equipment has not been fully engineered and due to the relative complexities of extrusion (Mielnik, 1991; Yamsaengsung and Noomuang, 2010). While the relatively cheaper single screw extruder

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could be applicable in developing nations, it lacks certain technical requirements including the capacity to handle various feed types (oily, sticky, viscous or wet materials). To thus address this prevailing challenge, this study was aimed at designing and constructing a twin-screw extruder that would facilitate the production of acceptable extruded foods in less developed and developing nations._

Cocoyam flour was particularly selected for the testing and evaluating the equipment. This was towards improving the utilization of the crop, and positioning it as a potential source for extruded food products. Additionally, it is one of the most common crop in West Africa, with Nigeria being the largest exporter of the produce (FAOSTAT, 2016).

2 Materials and methods

This section describes the materials used, the methods applied, calculations used and factors considered in developing the twin screw extruder.

2.1 Design consideration

The extruder designed in this study was guided by challenges associated with the construction of a twin screw extruder reported by Senanayake and Clarke (1999) and Yamsaengsung and Noomuang (2010). Other pertinent considerations were basic engineering principles, innovation and possible constraints. Hence, factors that governed the design and subsequent selection of materials for the extruder were (i) variable screw speed, (ii) incorporation of various dies, (iii) adjustable barrel temperature, (iv) hygiene, (v) ease of cleaning, (vi) low labor and maintenance cost, (vi) availability of raw materials for construction, (vii) safety, (viii) costs, (ix) ease of automation, (x) thermal compatibility, (xi) simplicity of fabrication and dismantling, (xii) resistance to corrosion, rust and wear, (xi) rigidity, strength and reliability.

2.2 Design calculations

Sequel to design computations for extruders and machines provided in the literature (Senanayake and Clarke, 1999; Harold et al., 2005; Khurmi and Gupta, 2005; Singh and Heldman, 2008; Sobowale et al., 2016a; Sobowale et al., 2016b), Equations (1)-(16) were used to compute the parameters for the components of the twin screw extruder.

$$L_b = \frac{L}{D} \times d \quad (1)$$

$$Y_{\max} = P_o b^3 / 192EI \quad (2)$$

$$P_t = P_s + V_d \Delta P \quad (3)$$

$$N_p = \frac{P_s}{\rho N^3 D^4 L} \quad (4)$$

$$N_r = \frac{D_2}{D_1} \quad (5)$$

$$N_1 D_1 = N_2 D_2 \quad (6)$$

$$B_l = \pi D_2 N_2 \quad (7)$$

$$\varepsilon = 10D / 100 \quad (8)$$

$$\delta_f = 0.1 - 0.3 D_b / 100 \quad (9)$$

$$\theta_s = \theta_b + 2.8^o \quad (10)$$

$$W_s = W_b - 0.003mm \quad (11)$$

$$W_p = M_p \quad (12)$$

$$V = \pi \Delta r^2 h \quad (13)$$

$$D_s = \sqrt[3]{16T / \pi r} \quad (14)$$

$$D_b = \sqrt{\frac{m}{2.3 N H_m G}} \quad (15)$$

$$C_{req} = f_d F_{ax} \left[\frac{60 L_f N}{10^6} \right]^{3/10} \quad (16)$$

where, L_b is the length of barrel (mm); L is screw length (mm); D is the screw diameter (mm); $Y_{\max}$ is the beam height (mm); P_o is the initial pitch circle diameter (mm); b is the beam thickness (mm); E is the flight width (mm); I is the beam face length (mm); P_t is the total power consumption (kW); P_s is the portion of the power consumption for viscous dissipation associated with shear of the feed (kW); V_d is the speed diameter (mm); ΔP is the pressure difference (N mm^{-2}); N_p is the screw power number (rpm); ρ is the extrudate density (kg/m^3); N is the screw speed (rpm); N_r is the speed ratio (rpm); D_2 is the diameter of the driven pulley (mm); D_1 is the diameter of the driving pulley (mm); N_1 is the speed of the driving pulley (rpm); N_2 is the speed of the driven pulley (rpm), B_1 is the barrel length (mm); ε is the flight width (%); δ_f is the radial flight clearance (%); D_b is the inside diameter of the extruder barrel (mm); θ_s is the helix angle at the root of the screw (degree (^{o})); θ_b is the helix angle at the root of the bolt (degree (^{o})); W_s is the channel width at the root of the screw (mm); W_b is the channel width at the root of the bolt (mm); W_p is the weight of the pulley (N); M_p is the mass of the pulley (kg); g is acceleration due to gravity (9.81 m s^{-2}); V is the volume of the hopper (m^3); π is 3.142; Δr is the change in shaft radius (mm); h is the height of the shaft (mm); D_s is the diameter of the shaft (mm); T is the permissible shear stress of the shaft (Nm); m is the mass flow rate (kg/hr); H_m the channel depth of metering (mm); G is the specific gravity (no unit); C_{req} is the dynamic bearing capacity of thrust bearing (kN); f_d is the factor for sense of rotation (no unit); F_{ax} is the thrust pressure from the extruder (kN), and L_f is the bearing life duration (hr).

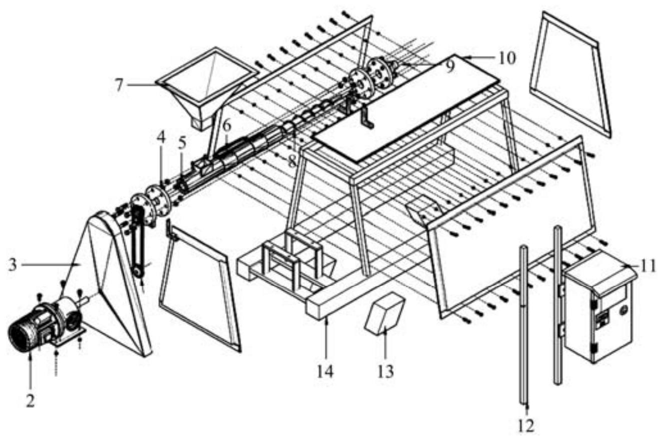
Some values obtained from the design calculations and other major parameters are presented in Table 1.

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

Parameters	Value
Extruder barrel inside diameter	65.2 mm
Extruder barrel outside diameter	90 mm
Extruder nominal screw diameter	65 mm
Extruder nominal screw length	1898 mm
Screw shank length	250 mm
Screw length of feed/solid conveying section	340 mm
Screw length of transition/kneading section	790 mm
Screw length of the mixing/metering section	518 mm
Screw channel depth at the feed/solid conveying section	27 mm
Screw channel depth at the mixing/metering section	2.72 mm
Screw root helix angle at tapered transition/kneading section	25^o
Screw root helix angle at shallow mixing/metering section	30^o
Flight width	5.6 mm
Radial flight clearance between the screw and the barrel	0.2 mm
Cylindrical hopper diameter	294 mm
Cylindrical hopper height	300 mm
Drive motor size	5 hp
Operating pressure	700 bar
Diameter of driven pulley	0.0735 m
Weight of pulley	14.715 N
Volume of hopper	4.125×10^3 m^3
Torque	4.95 N m
Diameter of shaft	24 mm
Diameter of barrel	71 mm
Thrust bearing	15.14 kN

2.3 Design of extruder components

The extruder comprises of a barrel within which tapered rotatable screws are mounted, for transporting and shearing the feed inside the extruder. The screw conveys the feed by viscous drag against the barrel which is divided into three functional longitudinal sections, i.e. a feeding/conveying section, a transition/kneading section and a metering/mixing/texturizing section. Sequel to obtaining the values which guided the design, the design of a 50 kg h^{-1} output extruder was also considered. In line with this, the following assumptions were made: (i) a steady state laminar flow conditions and uniform mass flow rate, (ii) inertial and gravitational forces are neglected when compared to friction forces and pressure, (iii) constant pressure gradient in the channel cross-section, i.e. no consideration of the effects of normal stress is necessary, (iv) hydro-dynamically fully developed flow in every cross-section of the channel with one direction of shear perpendicular to the axis of the channel, (v) constant density (incompressibility), heat transfer and thermal diffusivity of the extrudate, (vi) isothermal flow, i.e. all particles of the extrudate have the same temperature, (vii) screw axial length L to diameter D (L/D ratio) of 25/1 (estimated using a Vernier caliper), (viii) length of feed/solid conveying section is 20.63% of screw length (estimated using a meter rule and expressed as %), (ix) length of metering section is 31.43% of screw length (estimated using a meter rule and expressed as %), (x) compression ratio is assumed to be 8:1 and (xi) channel depth of metering section H_m = 2.72 mm. Parameters (x) and (xi) were obtained from the literature (Harper, 1979; Harper, 1981; Harper, 1992). Subsequently, the different components shown in Figure 1 were fixed and joined together to form the extruder (Figure 2 and 3).



1. Chain drive 2. electric motor 3. Safety guard 4.Flange 5. Barrel 6. Heater 7. Hopper 8. Screw 9. Die holder 10. Tray 11. Control unit 12. Control unit stand 13. Base support 14. Chases

Figure 1 Exploded view of the extruder showing parts

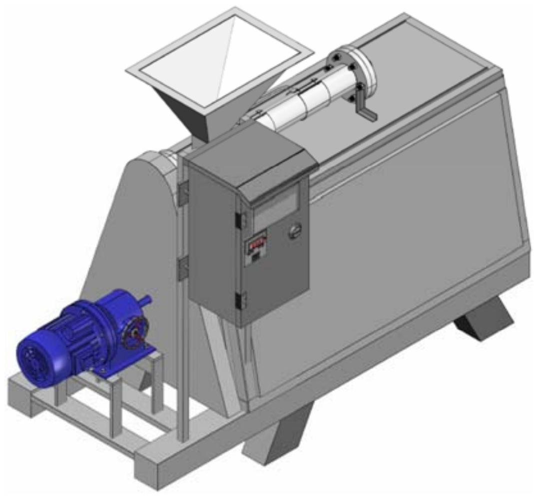


Figure 2 A 3D diagram of the constructed extruder

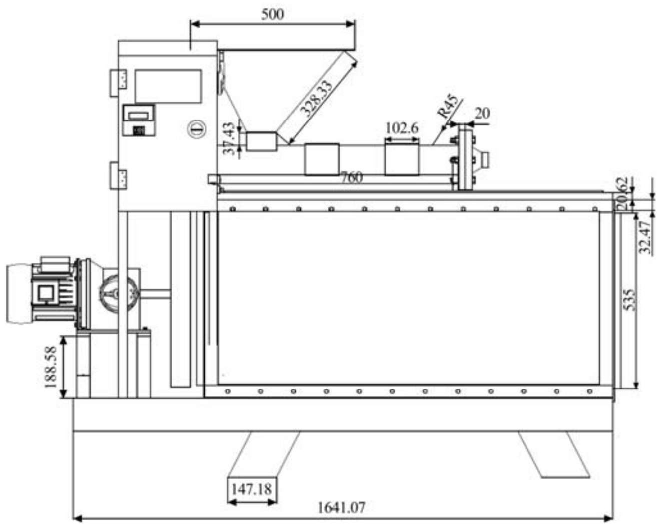


Figure 3 Front view of the extruder

2.4 Performance evaluation

The cocoyam (*Xanthosoma sagittifolium*) tubers were purchased from a local market in Sagamu, Ogun State, Nigeria. Flours were subsequently produced as depicted in Figure 4. Performance evaluations were done with cocoyam flour at feed moisture contents (*FMC*s) of (42.5% and 52.5%), screw speed (*SS*) of 600 and 800 rpm and a barrel temperature of 55°C. Performance indicators evaluated included residence time (*RT*) (Iwe et al., 2001), expansion ratio (*ER*) (Fan et al., 1996), throughput and functional efficiency (Equations (17) and (18)) (Senanayake and Clarke, 1999; Sobowale et al., 2016b).

$$\epsilon = \frac{M_o}{M_f} \times 100 \quad (17)$$

$$T_p = \frac{M_o}{RT} \quad (18)$$

where, ϵ is the efficiency of the machine (%); M_f is the mass of the feed sample (g); M_o is the mass of extruded sample obtained (g); T_p is the throughput (g s^{-1}) and *RT* is the residence time (s).

All performance tests were done in triplicates and difference among the means were separated using Duncan multiple range test (DMRT) at 5% confidence level on SPSS 22 (IBM Statistics, USA).

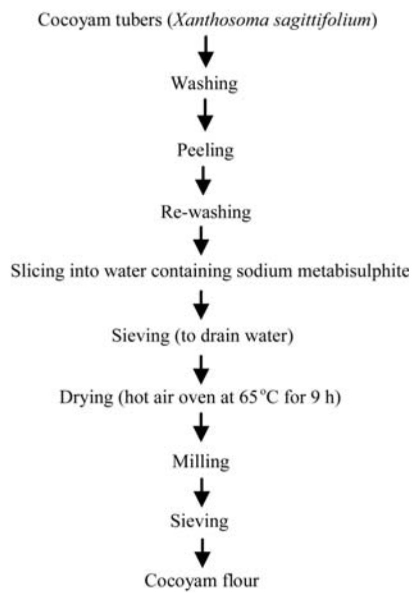


Figure 4 Flow chart for the production of cocoyam flour

3 Results and discussion

This section describes the performance of the developed extruding machine relative to the parameters varied.

3.1 Machine performance

The constructed extruder performed satisfactorily, with products expanding fairly well. No major difficulty was encountered during the operation except for the discoloration of the cocoyam extrudate at elevated temperatures, resulting in an unacceptable product. This eventually influenced the barrel temperature and *FMC* selected and suggests that cold extrusion is more suitable for the cocoyam extrudate. Tests on the equipment also revealed its capability as a multipurpose extruding machine producing different extruded product of different shapes and sizes, by incorporating a replaceable die unit of different shapes into the machine. Cleaning and maintenance was simple, quick with no mechanical breakdown experienced throughout.

3.2 Residence time

As observed in Table 2, increasing *SS* generally led to decreasing *RT* of the cocoyam extrudate. This was in agreement with the study of Yağcı and Göğüş (2008). The *FMC* was observed to cause both a significant ($p≤0.05$) increase and decrease in the *RT* of the extrudates (Table 2). These observations thus suggest that *RT* is rather a function of different combination of factors including but not limited to *FMC*, *SS*, screw geometry, barrel temperature, composition and rheology of the feed (substrate). The relatively short *RT* values obtained in this study is also well desired, considering the need to retain and maintain heat labile nutrients, which could easily be destroyed at prolonged residence times.

Table 2 Result of extrusion parameters investigated

FMC, %	*SS*, rpm	*RT*, s	*ER*	T_p, g s^{-1}
42.5	600	$64^c±0.09$	$0.20^a±0.12$	7.04
52.5		$62^b±0.10$	$0.20^a±0.16$	7.03
42.5	700	$59^a±0.06$	$0.22^c±0.16$	7.90
52.5		$61^b±0.06$	$0.21^b±0.09$	7.35

Note: **FMC* – feed moisture content; **SS* – screw speed; *RT* – residence time; *ER* – expansion ratio; T_p – throughput. Means with no common letters within a column significantly differ ($p≤0.05$).

3.3 Expansion ratio

*ER*s are used to describe the degree of puffing of extrudates and are conventionally affected by *FMC* and *SS* as they influence modifications that affect expansion. As observed on Table 2, there was no significant ($p≤0.05$) difference in the *ER* of the extrudates at lesser *SS*, as compared to the difference at higher *SS*. Nonetheless, the *ER* values are relatively lower than those reported for other extrudates produced at higher temperatures: sorghum (Asare et al., 2010), rice-legume (Asare et al., 2012), water yam (Oke et al., 2013) and wheat-plantain (Sobowale et al., 2016c). Samples with lower expansion rate and longer *RT*s could also suggest that the resulting extrudate was well gelatinized. On the other hand, high *FMC*s may have also contributed to reduced elasticity of the dough causing a decrease in *ER*.

3.4 Throughput and functional efficiency

The throughput and functional efficiency as affected by *FMC* and *SS* of the extrudate is presented in Table 2 and Figure 5 respectively. As expected and observed with other investigated parameters, both the *FMC* and *SS* were observed to influence both parameters. The throughput was observed to reduce and increase with increasing *FMC* and *SS* respectively (Table 2). While the increase in *FMC* might have caused an increase in backflow and reduced viscosity, increasing *SS* led to increased rate of material conveyance in the extruder (Senanayake and Clarke, 1999; Yamsaengsung and Noomuang, 2010). Moisture and material losses occurring during the extrusion process might have also contributed to this observation. The functional efficiency (Figure 5) also followed the same trend with cocoyam extrudates obtained with *FMC* of 42.5% and *SS* of 700 rpm having the highest functional efficiency of 93%. Likewise, reduced *FMC* and increasing *SS* influenced the shear rate, affected the quantity of extrudate and subsequently the functional efficiency.

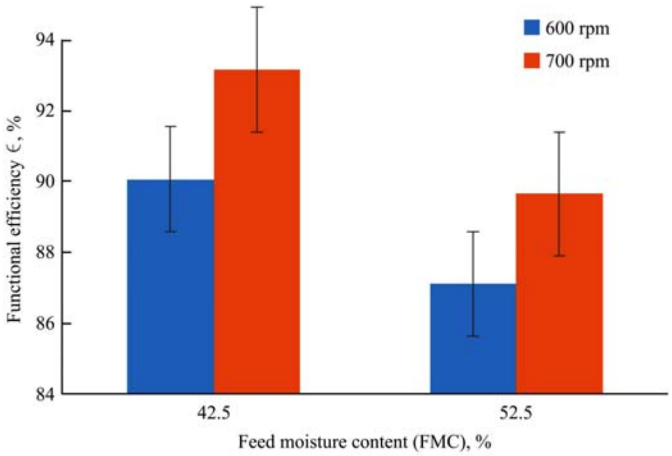


Figure 5 Effect of feed moisture content and screw speed on functional efficiency

4 Conclusion

A twin screw extruder was designed, constructed and evaluated. The extruder was constructed using locally available materials and can be easily operated. The extruder was used to produce an attractive and acceptable extrudate (from cocoyam flour) (Figure 6). The performance parameters of the extruder were largely influenced by the feed moisture content, screw speed and temperature. The equipment would be of significant importance to small, medium and large scale food processors for commercial and mass production of extruded products. Commercialization and consumption of subsequent extruded products would largely contribute to economic empowerment and alleviation of food insecurity plaguing developing nations.

Figure 6 Picture of the obtained cocoyam extrudates

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