Development of single screw extruder for the production of pineapple pomace fish feed

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Abstract: Mechanisms to support fish food production are constantly evolving with increasing available technologies. However, extruders for fish feed production with pineapple pomace are based on complex operating conditions and present difficulties in confirming design parameters. This paper aims at developing and testing single screw extruder capable of producing fish feed. The design theory of single-screw extruder geometry has led to the construction and discussion of the capabilities of current design techniques for the production of fish feed. The machine identifies clear speeds that are suitable for screws that use pineapple pomace based as internal materials. The performance of the extruder is greatly affected by the increase in die size and pomace. Regression equations of dependences were created for all these two significant criteria and costs per kilogram of processed feed mash were calculated. Optimum efficiency (87%) occurred at die size (8 mm) and pineapple pomace inclusion (16%). The results of this study provide an opportunity to give the extruder design a new level of versatility.

Keywords: complex operating conditions, construct, design theory, screw, die size

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1 Introduction

Agro-waste has become an attractive ingredient in the extrusion industry in a recent year. The use of less expensive ingredients in fish feed formulations is gaining the attention of researchers lately (Smith et al., 2010; Garza de Yta et al., 2012). The beneficial effects of dietary fruit pomace have been demonstrated by several authors (Olosunde, 2010; Kumar et al., 2010; Azevedo et al., 2011). In large scale juice processing, about 65% of the pineapple is extracted as juice, while the remaining 35% is the by-product called pineapple pomace. Pomace generated from juice processing constitutes a disposal problem and environmental pollution and there is no processing equipment designed in addressing this problem through the utilization of this by-product. Pineapple pomace is rich in nutrients, functional and phytochemical compounds (Selani et al., 2014). In view of this, pineapple pomace has become a focus of interest as a source of a functional feed ingredient. One of the established technologies of processing pineapple pomace in animal feed is the extrusion process.

Extrusion is one of the bulk deformation processes used in the manufacturing of various products. The extrusion

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process is simple and involves forcing feed mash through a die to produce a continuous length of constant cross-section corresponding to the shape of the die opening (Pawar et al., 2014). Extrusion technology becomes widely used in the agri-food processing industry, where it is known as extrusion-cooking (Moscicki and Zuilichem, 2011). The design of equipment for the process has not been fully developed, including information from the extrusion point pressure and influence of moisture content (Karkle et al., 2012). However, due to the importance of extrusion to manufacturing engineering, it is expedient to carry out research that could help to fully understand the underlying science and engineering of the process.

The last decade has seen the transformation of fish feed production from a technology used in research centers or laboratories for the development of prototypes to actual production techniques. Fish feed machine manufacturing producers have shifted attention to the development of equipment that will allow the use of agro-waste materials with production speed and precision at a constantly higher level of efficiency. The introduction of agro-waste is changing the way of manufacturing and designing products and at the same time obliges us to reconsider the process machinery with which to realize this production.

The development of extruders has evolved recently yielding quality products, new flavour generation, and sterilisation. Numerous studies have focused on the extrusion processing techniques that will improve certain physicochemical properties of pomace based food products, such as potato based snacks (Bastos-Cardoso et al., 2007), barley-tomato pomace (Karkle et al., 2012) and carrot pomace (Alam and Kumar, 2014). Therefore, this paper focuses on the development, design, and evaluation of the pineapple pomace based extruder.

2 Methodology

The single-screw extruder (SE 2014; UI, Ibadan, Nigeria) was designed in search of a simple technology that is easy to use and easy to manufacture, and is a motorized device that can process formulated fish feed into extrudates using locally available material. The results of the preliminary study material were used for the design calculations (Oduntan and Bamgboye, 2015).

2.1 Bulk density

The bulk densities of wet pineapple pomace, dried pineapple pomace, and cassava flour were determined according to the recommendations of ASABE S269.4 (ASABE *Standards*, 2003). A container was filled with pomace using a funnel without compacting the contents. The material was leveled with the top of the container and weighed. The mash density was obtained from the ratios of the measured masses of samples in the container to the volume of the container. For each run, five measurements were taken to obtain the averages and standard deviations.

2.2 Coefficient of sliding friction and static angle of repose

The coefficient of sliding friction of the samples was determined on four different clean dried surfaces (polished wood, mild steel, galvanized steel, and stainless steel) at different ratios of tinned candles and manioc flour. The inclined plane was raised slightly, and the inclination angle at which the specimen began to slide was read by the protractor with a sensitivity of one degree. The tangent of the angle was recorded as a coefficient of friction.

The static angle of repose of the samples was determined using a cylindrical container open at both ends and arranged on a flat surface (Aviara et al., 2012). It was filled with patterns from above. The cylinder was then raised gradually, allowing the sample to flow and form a pile. The angle of repose was calculated from the measurements of the vertical depth and the propagation radius of the sample. This was repeated five times.

2.3 Extrusion machine main parts

2.3.1 The hopper

The following values of properties of pineapple pomace were used:

Pineapple Pomace bulk density, r = 427±46 kg m^{-3}

Maximum coefficient of friction on mild steel, m = 0.763

Hence, for free flow, the following relationship between the angle of inclination q and the

coefficient of friction (Amol et al., 2015) prevails:

$\tan q > m$;

Therefore, $q > \tan^{-1}(0.763)$ or 37°

The design angle was chosen to be 45°, about twenty - percent above the calculated value. As expected, the angle of repose of powder increases when the powder contains a lot of docking (Bhattacharya, 2013).

2.3.2 Worm shaft of the extruder

The worm shaft is the main component of the extruder and is loaded with weights of material to be machined, roller, bearings and screw threads. In operation, the worm shaft transports the material (in this case mash) for extrusion. To protect against bending and torsional stresses, therefore, the shaft diameter was determined from the equation given by Olaniyan et al. (2017) as:

$$d_s = 16T / (0.27\pi\delta_0) \tag{1}$$

Where, d_s is diameter of the screw shaft (mm), T is the Torque transmitted by the shaft of extruder (55.93 Nm), δ_0 is the yield stress for mild steel (200 N mm^{-2}).

hence, d_s = 44.407mm.

Therefore, a mild steel shaft with a diameter of 40 mm is available, which was used to build the screw.

2.3.3 Screw worm

The worm shaft is essentially a conical worm conveyor, reducing the volume displacement from the end of the cylinder to the discharge end. In this way, the mash was printed on the pressure through which the mash was cooked while being propelled by the screwing operation (Savoire et al., 2013). The screw thread system was calculated using the expression in Equation 2 below as:

$$U_n = a + (n-1)d \tag{2}$$

Where, U_n is the screw depth at the discharge end (mm), a is the screw depth at the feed end, n is the number of screw turns, d is the common difference between the next successive screw depths (mm).

The predetermined varied values are $U_n = a = 5$ mm and $n = 17$, depending on the availability of tools and materials. As a result, the calculated depth of the shaft was d = -0.18 mm. Thus, the screw depth from the feed end to the discharge end of the cylinder would be constantly reduced by 0.18 mm. Therefore, compression in the extruder is achieved by reducing the pitch of the screw over its entire length.

$$\text{Compression Ratio} = V_1/V_2 = 3.06{:}1 \tag{3}$$

Where, V_1 is volume of the first pitch (mm^3) and V_2 *is* volume of the last pitch (mm^3).

2.3.4 Quantity of materials transferred

The load that can be lifted by the screw was determined from the equations given by Stosic et al. (2011) as:

$$W_e = T\left[\frac{d_s / 2\tan\theta + (\mu / \cos\alpha)}{1 - \mu\tan\theta\cos\alpha}\right] \tag{4}$$

$$\alpha = \tan^{-1}(\tan\theta_n \cos\alpha) \tag{5}$$

Where, W_e is the load that can be lifted by the screw (kN), T is the Torque transmitted by the screw shaft (Nm), d_s is the screw diameter (mm), μ is the coefficient of friction, θ_n is the screw (lift) angle, α is the screw tapering angle.

Predetermined and determined values for the design T = 53.93 Nm, d_s = 40 mm, θ= 2°, μ = 0.15, and θ_n = 20°; Thus, calculated values of the load that can be lifted by the screw, α and the screw tapering angle, W_e were 84.21 kN and 19.99° respectively.

Therefore, 8.50 kg of mash can be processed at a time approximately.

2.3.5 Pressure to be developed by the screw thread and the barrel

The pressing area (Stosic et al., 2011) and the pressure developed by the screw worm were determined by Equations 6 and 7 respectively as:

$$A_p = \pi D_m n h \tag{6}$$

$$P_r = W_e / A_p \tag{7}$$

Where, P_r is the pressure developed by the screw thread (N mm^{-2}), A_p is the pressing area (mm^2), h is the screw depth at the maximum pressure (discharge end).

Substituting π = 3.142, D_m = 40 mm, n = 17, h = 2.12 mm and W_e = 84.21 kN;

hence, A_p = 4526.62 mm^2; P_r = 18.6 N mm^{-2}.

Therefore, *a* calculated pressure of 18.6MPa would be available for extrusion process during the operation.

2.3.6 The pressure of the barrel

The pressure that can be withstood by the barrel was determined by the equation given by Adetola et al. (2014) as:

$$P_b = 2t\delta_a / D_i \tag{8}$$

Where, P_b is the pressure to be withstood by the barrel (N mm^{-2}), t is thickness of the barrel (mm), δ_a is allowable stress (= 0.27δ_o), δ_o is the yield stress of mild steel (N mm^{-2}), D_i is the inside diameter of the barrel (mm).

Substituting t = 25 mm, δ_o = 200 N mm^{-2}, and D_i = 40 mm; hence, δ_a = 54 N mm^{-2} , P_b= 67.50 N mm^{-2} or 67.50 MPa.

This means that the pressure that the barrel can withstand (67.50 MPa) is greater than the theoretical pressure developed by the screw worm (18.60 MPa) and the experimental pressure (8.69 MPa). Therefore, the barrel will withstand the extrusion pressure without bursting.

2.3.7 Volumetric capacity of extruder

The theoretical volumetric capacity of the extruder was determined using a modified form of the equation given by Zareiforoush et al. (2010) as:

$$Q_t = \pi / 4(D_{sf}^{\ 2} - d_{ss}^{\ 2}) P_S N_s \tag{9}$$

Where, Q_t is theoretical volumetric capacity (m^3 s^{-1}), D_{sf} is diameter of the screw flight (m), d_{ss} is base diameter of the screw shaft (m), P_s is screw pitch (m), N_s is rotational speed (rpm).

Substituting D_{sf} = d_s = 40 mm, d_{ss} = 35 mm, P_s = 40 mm, N_s = 225 rpm into Equation 9;

hence, Q_t= 2.649x10^{-3} m^3 s^{-1}.

$$\text{Mass flow rate } (M_{fr}) = \rho_{ss} Q_t \tag{10}$$

Where ρ_{ss} is the specific weight of pineapple pomace and cassava flour at 26% moisture content.

Substituting ρ_{ss}= 469 kg m^{-3} into Equation 10.

M_{fr}= (469) (2.649x10^{-3}) (3.6) ton hr^{-1}

M_{fr} = 4.473 ton hr^{-1}.

2.3.8 Power requirement

The power required to drive the extruder was calculated using a modified Equation 11 from Oduntan et al. (2012) as:

$$P_e = 4.5 Q_t l_s \rho g F \tag{11}$$

Where, P_e is the power required to drive the extruder (kW), Q_t is the volumetric capacity of the worm shaft (m^3 h^{-1}), l_s is length of screw shaft (mm), g is the acceleration due to gravity (m s^{-2}), F is the material factor

Substituting =2.649x10^{-3} m^3 h^{-1}, l_s = 500 mm, g = 9.81 m s^{-2}, and F = 0.4 into Equation 11.

hence, P_e = 5.847 kW.

The power of the electric motor to drive the extruder was estimated using the Equation 12 given by Oduntan et al. (2012) below as:

$$P_m = P_e / \eta \tag{12}$$

where, P_m is the power of the electric motor (kW) and η is the drive efficiency (%). Given that η = 75% or 0.75; hence, P_m= 7.796 kW or 10.45 hp. The speed of electric motor spin at moderate shear cook extruder is between 10-25 rpm (Frame, 2012).

2.4 Discharge efficiency

The performance of the extruder in producing extruded products was evaluated on the basis of the quantity of recovered at constant speed of the shaft and the die size. The dozing of the mash at different blend (pomace: cassava: water) ratio were kept constant at 10 kg per batch (Oduntan et al., 2014). The weight of the extruded product in a time frame of 10 minutes was determined. The performance of the machine was measured in terms of its discharge efficiency n_d which was expressed as

$$n_d = (m_a/m_b)\ 100\% \tag{13}$$

Where m_a is the mass of extruded product (kg); m_b is the mass of mash introduced into the machine (kg). It is a measure of effectiveness of the screw; some losses may be due to moisture migration.

2.5 Cost analysis

The machine Instrumentation is the major part of the capital investment which actually includes not only the parts but also all auxilires for a complete system. Machine costs may be calculated from the purchased machine parts. Operating costs generally include those costs that are incurred as a direct result of the machine being used. These costs vary as machine use varies.

Operating labor is usually the second largest direct expense item on the manufacturing expense. Almost all plants are operated on a shift-work basis (even batch plants), with typically operators per shift position with five 8-hour shifts a week. More shift positions are needed when handling highly tonnage production and using more mechanical equipment. Operating labor can be estimated by multiplying number of operators per shift. The following technique used to estimate number of operating labors for chemical processing plants is given by Chen et al. (2014)

$$N_{OL}=(6.29 + 31.7 + 0.23N_{np})^{0.5} \quad (14)$$

Where, N_{OL} is the number of operators per shift, N_{np} = number of non-particulate processing steps (mixer, grinder, dryer and coater). In general, the number of processing steps that involve handling particulate solids is not always taken into account in determining the number of operators per shift.

2.6 Statistical analysis

The data obtained was analyzed using Fisher's test for ANOVA and response surface methodology (RSM).

3 Results and discussion

3.1 Machine description

The side and plan views of the equipment are shown in Figure 1. The extrusion machine is local manufactured and it consists of the following main parts:

3.2 Main frame

The main frame is a base supporting the feed unit, extrusion unit and main electric power motor. It was made of iron steel L-sections with 2000 mm length, 1050 mm width and 98 mm height (Figure 1).

3.3 Feed unit: Feed unit consists of feed hopper and feed screw.

Feed hopper: This serves as a container for the ration prepared before extrusion stage. It was constructed of iron sheet metal (2 mm thickness), with 300 mm length, 280 mm width and 160 mm height. Maximum capacity of feed hopper is 5 kg. A gate is located at the bottom of the hopper to allow for the free flow of ration to flow to the extrusion unit (Figure 1).

Feed screw: A screw was fixed in the bottom of the feed hopper to transmit ration from feed unit to extrusion unit. The feed screw dimensions of 500 mm length, 40 mm diameter and 25 mm pitch; feed screw is powered by an electrical variable speed motor by means of two gears and sprocket.

3.4 Extrusion unit: This unit is responsible for compressing and cooking of the ration before the forming zone.

Extruder single screw: It has a main shaft of dimensions 850 mm length and 50 mm diameter (Table 1). It is mounted on the machine from one end; on which all extrusion units were assembled. The units consist of a tapered screw, whose depth decreases consistently from the feed end to the discharge end of the barrel. A pulley having diameter of 280 mm was used to transmit the power from main motor to the main shaft by three (V) belts. The last part of extruder cylinder is die-house, with dimensions of 160 mm length, 50 mm diameter and 2 mm thickness. On the surface of the die there are six holes on die surface having diameter of 4 mm, 6 mm and 8mm.

Table 1 Machine parameters

Nos.	Description	Dimension
1	Hopper angle	45°
2	Shaft diameter	40 mm
3	Screw depth	-0.18 mm
4	Compression ratio	3:1
5	Load that can be lifted by the Screw	8.59
6	Pressure developed by the Screw Thread	18.6 Mpa
7	Pressure of the Barrel	67.50 Mpa
8	Volumetric capacity	2.649×10^{-3} m^3 s^{-1}
9	Power Requirement	7.796 kW

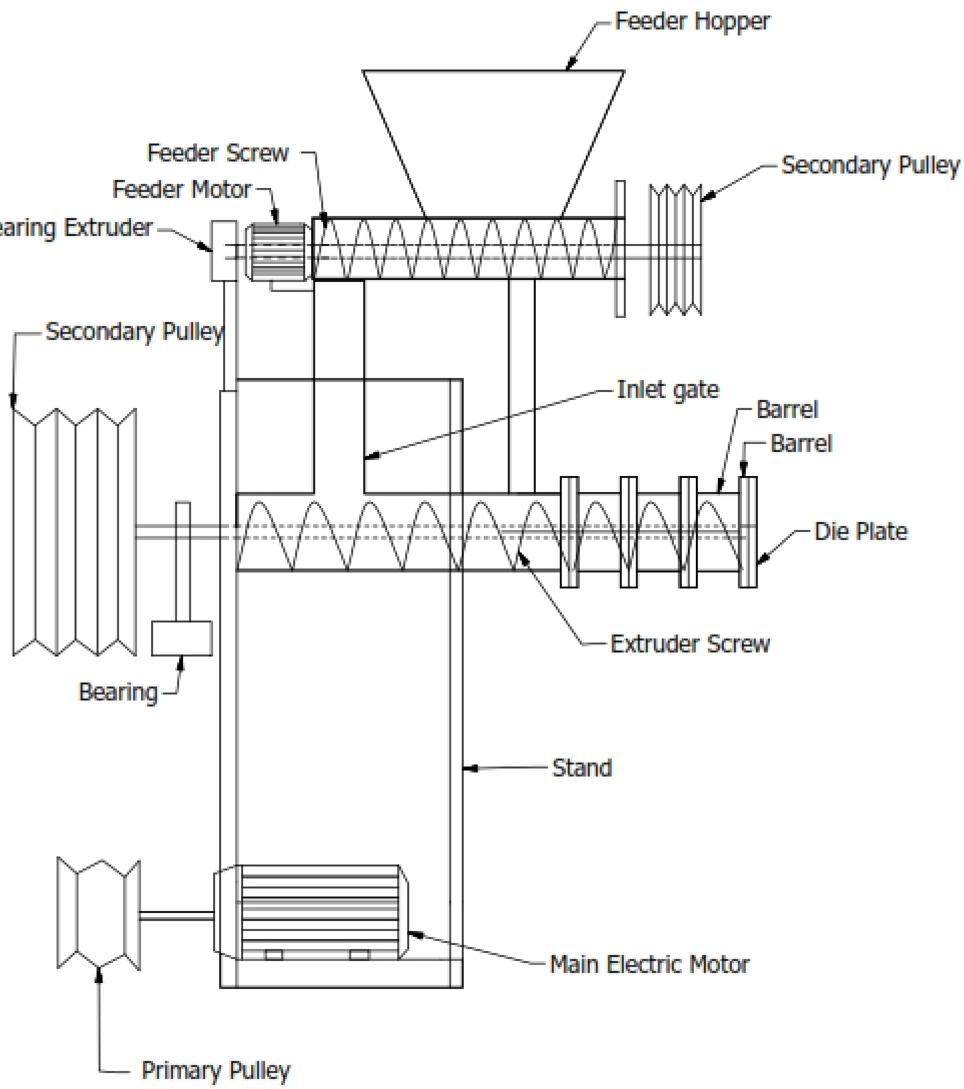

Figure 1 Side view drawing of extruder machine

Each hole consists of die hole entry: The entry is of conical shape to help ration to flow easily inside the effective hole

Die effective hole thickness: It is a straight distance which press and form ration through the hole to get the final product (pellets). Dimensions of entry and effective hole thickness can be changed to adapt the experimental ration treatment to control specification of the obtained extrudates.

3.5 Power transmission and electric control

Main motor: The machine is powered by a 4.0 kW electrical gear motor through a pulley (diameter of 120 mm) and 3 (V) belts.

Feeder motor: It has electric/mechanical gear motor with step pulley to vary shaft speed, output power 1.5 kW and 18 A. It is operated by a V -belt to change feed rate. Motor shaft speed ranged from 28 rpm to 160 rpm.

3.6 Efficiency of the Machine

Analysis of variance (ANOVA) values for the quadratic regression model obtained from D-optimal employed in the machine efficiency are listed in Table 2. On the basis of the experimental values, statistical testing was carried out using Fisher's test for ANOVA. The statistical significance of the second-order equation revealed that the regression is statistically significant ($P < 0.0001$); however, the lack of fit is not statistically significant at a 99% confidence level. Table 2 depicts the significance of the regression coefficients and ANOVA for the regression model, respectively. The results indicate that P-value less than 0.05 indicate model terms are significant. In this case, pineapple pomace, die size are significant model terms. The model's F value of 9.13 in these tables implies that the model is significant for machine efficiency. The fit of the models was controlled by the coefficient of determination R^2. Based on the ANOVA results, the models report a high R^2 value of 89.00% for extrusion point pressure of pomace. Also, an acceptable agreement with the adjusted determination coefficient is necessary. In this study, the Adj-R^2 value of 63.35% was found. The values of R^2 and Adj-R^2 are close to 1.0, which is very high and advocates a high correlation between the observed values and the predicted values.

Table 2 ANOVA Regression coefficient of second order polynomial and their significance for efficiency

Source	Value	dF	F Value	*p*-value (Prob> F)
Model		2	9.13	0.0214
x_1		1	14.00	0.0134
x_2		1	15.06	0.0166
x_1^2		1	1.40	0.2893
x_2		1	2.19	0.1986
R^2	0.8900			
Adjusted R^2	0.6335			
STD. Dev.	2.36			

The efficiency ranges from 70.8% to 87% with a ratio of maximum to minimum is 1.23. Figure 2 shows 3-D graph of the effect of pomace inclusion and die size on the extruder efficiency. It indicates an increase of the efficiency according to the size of the die in the extruder in all predetermined the levels of inclusion rate of pineapple pomace. The die hole is related to the materials flow in the barrel, increasing die holes' diameter results in higher efficiency. Therefore, maximum efficiency occurred when the operating die size falls between 7mm to 8mm within pineapple pomace inclusion range of 14% to 16% (Figure 2). The following relationship has been developed for the variations of efficiency with die size and pineapple pomace inclusion:

$$Y_{eff} = 79.80 + 4.15x_1 + 3.53x_2 - 0.70x_1x_2 - 1.84x_1^2 + 2.39x_2^2 \qquad R^2 = 0.89 \qquad (15)$$

where, Y_{eff} is machine efficiency in %; x_1 is pomace inclusion in %; x_2 is die size in mm.

The coefficient of pomace inclusions ratio (x_1) and the die size (x_2) were positive as indicated in Equation 14. As a result, an increase in the pomace inclusion ratio and the die size would lead to increased machine efficiency. A unit increase in pomace inclusion will lead to an increase in the efficiency by 4.15%. It was established that change in die size from 4mm to 6mm increase the efficiency with a rate of 3.53%. The relationship between the pomace inclusion ratio and the die size are significant model conditions. In this case, the analysis of variance showed that the efficiency is largely dependent on the linear conditions of die size and pomace inclusion (p <0.05).

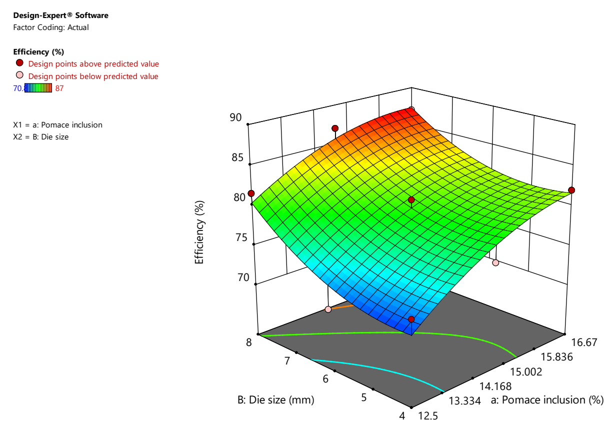

Figure 2 Three-dimension graph for machine efficiency over the pomace inclusion and die size

3.7 Economic

The total investment cost on the extruder was 3,837 USD (1 USD = 367 Naira). This extruder was used to produce extrudates for farmers as a public service activity and available for students' research work of the University. Based on this activity, it was derived that the extruder can be used to produce 50 tons of feed per year. In general, 235±3.2 kg of extrudates were obtained from daily production. The average market prices of good quality extruded feed 0.95 USD. It was calculated that two labours will be required for operations. The labour cost for machine operation was approximately 25 USD per batch and the annual maintenance cost was estimated to be 1% of the total investment cost. With the gross income from the production of fish feed from this machine, it would take about four to five years to recover the money back.

To expand the extruder, we built two units of this dryer at Fexod Fedek Ventures, Ibadan, Nigeria. The extruder is used to produce fish for a fish farmer. For users, the extruders are satisfied with the performance of the extruder.

4 Conclusions

An extrusion powered by 4.0 kW gear electric motor with a compression ratio of 3:1 was developed with a throughput of 26.1 kg h^{-1} and efficiency of 87%. The improved screw and die size configuration results in considerable good extrudates and increase efficiency. The extrudates were a high quality product compared to the high quality imported.

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