KAMPALA INTERNATIONAL UNIVERSITY
KIU
Journal of Science, Engineering and Technology

KJSET Research Article

Development of a fundamental model for pelleting efficiency of an innovative hybrid fish feed processing system

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Paper history:
Received 05 April 2025
Accepted in revised form 21 May5 2025

Keywords
Feed rate; Die size; Orifice; Hybrid fish feed Pelletizing machine; Pelleting Efficiency Model; Floatability.

Abstract

The development of a fundamental model for predicting pelleting efficiency at variable feed rates and number of orifices was central to optimizing the performance of an innovative hybrid fish feed processing system. The system was designed for simplicity, quality, and precision in fish feed production. Machine parameters, derived from comprehensive design and parametric analysis, were used to establish input variables for the pelleting efficiency model, including feed rate and number of orifices. With a constant driving force of 713.38 N from a 3 hp electric motor, the system demonstrated pelleting efficiencies of 55 %, 70 %, and 88 % for 15, 20, and 25 orifices, respectively. At a fixed die orifice, increasing the feed rate from 10 to 20 mm/rev at interval of 5 mm/rev resulted in efficiencies of 60 %, 80 %, and 110 %. Evaluation of the combined effect of the factors predicted an optimum efficiency of 86.9 % at optimal settings of 20mm/rev and 15 orifices. The model's experimental validation, conducted under optimized conditions, showed that the 20-orifice die produced a higher pelleting efficiency (97%) but with reduced pellet floatability, whereas the 15-orifice die yielded an efficiency of 86.21 % and better floatability. The prediction error of 0.69% validated the model's accuracy at 99 %. In addition, an introduction of cassava starch constituent improved pellet floatability and surface finish. This study therefore, highlights the potential of the developed model to enhance pelleting performance, balancing efficiency and pellet quality, and providing a robust foundation for optimizing fish feed production processes.

Nomenclature and units

η_{PE}	Pelleting Efficiency, *%*
F_D	Driving force, *N*
P_A	Auger pressure, *N/m²*
F_R	Feed rate, *mm/s*
B_S	Barrel size, *mm*
N_R	Number of orifices
D_S	Die size, *mm*
ρ_F	Feed density, *Kg/m³*

1.0 Introduction

The pelleting process involves the forced passage of moist, powdered, or mashed feed through holes in a die, where the feed is subjected to heat, moisture, and pressure. This process homogenizes the feed ingredients, leading to the formation of pellets. Regupath *et al.* (2019) explored various pelletizer types used in fisheries feed production, identifying two primary designs: the revolving die/roller pelletizer and the screw pelletizer. Romallosa & Cabarles (2018) designed a pellet mill based on the revolving roller/die mechanism, which incorporates essential components such as a feed hopper, pelleting chamber, pellet roll, die plate, discharge chute, and frame. In this design, screw conveyors are used to transport the powdered feed to the pelleting die.

In the context of indigenous and adaptable feed production mechanization, several studies have contributed to advancing pelletizer designs. Okolie *et al.* (2019) described a pelletizing machine that integrates a hopper, screw conveyor, barrel, dies, drive system, and heater. Chukwuneke *et al*. (2019) observed that many stand-alone pelletizing machines share common components, including the frame, electric motor, pulley, hopper, screw conveyor, barrel, dies, and drive system. Similar findings were reported by Orisaleye *et al.* (2009), Ojomo *et al.* (2010), Abubakre *et al.* (2014), Odesola *et al*. (2016), and Regupath *et al.* (2019). However, some of these machines are distinguished by unique features, such as the integration of alternate manual and mechanical drivers.

In contrast, Nwaokocha and Akinyemi (2008) developed a laboratory-scale pelleting machine that uses a screw conveyor to push the ground feed through the die. Muo *et al.* (2018) fabricated an electrically powered fish feed pelleting machine driven by three electric motors (3, 1.8, and 0.7 Hp). These motor powered the screw conveyor, hopper, and extrusion cutter respectively, highlighting the versatility of the electric-powered screw conveyors systems in feed pelleting operations.

Other researchers, such as Ojomo *et al.* (2010), focused on evaluating the performance of fish feed pelletizing machines. Their study revealed that increasing the moisture content by 1% resulted in a significant 20% improvement in pelleting efficiency. Abubakre *et al.* (2014) proposed a model specifically designed for the pelletizing component of feed pelletizers, while Okolie *et al.* (2019) developed a fish feed pelletizing machine tailored for small-scale farmers.

While alternative methods, such as gravity-based and roller conveyor systems, are also used to convey powdered feed to the die, this research focuses on the screw conveyor (auger) system, which is central to the choice of mechanism for the hybrid fish feed processing system under investigation.

In a more recent study, Kadurumba & Igbo (2020) introduced an innovative fish feed pelleting machine, testing it under various conditions by adjusting motor speed and moisture content. The tests were repeated at five different moisture contents (7%, 9%, 11%, 13%, and 15%) and with three die diameters (3 mm, 4 mm, and 6 mm). The results revealed high pelleting efficiency, ranging from 92.1% to 94.0%. Notably, an optimum pelleting efficiency (85.7%) was achieved with a feed mixture at a die hole diameter of 4 mm, die speed of 95 rpm, and 11% moisture content. These highlighted the critical role of optimized operational parameters in enhancing machine performance (Edeh *et al*., 2022).

This study therefore, underscores the importance of refining the pelleting systems parameters to improve feed quality and processing efficiency. The development of a fundamental model for pelleting efficiency in an innovative hybrid fish feed processing system, as proposed in this study, aims to further optimize these parameters, with a particular focus on the screw conveyor system, to meet the growing demand for efficient, sustainable feed production both small-scale and commercial producers.

2.0 Materials and Methods

On the integrated hybrid fish feed processing machine developed by Nnadi (2024), pelletizing operation is preceded by mixing and conditioning of feed input ingredients. The pelletizing unit consists of a hopper, screw conveyor, barrel, dies, drives system and heater. The feed meal from the homogenization unit is fed into the hopper that leads to the pelletizing chamber equipped with the screw shaft that propels the feed (Fig. 2.1). A prime mover powers the pulley and belt system that drives the shaft.

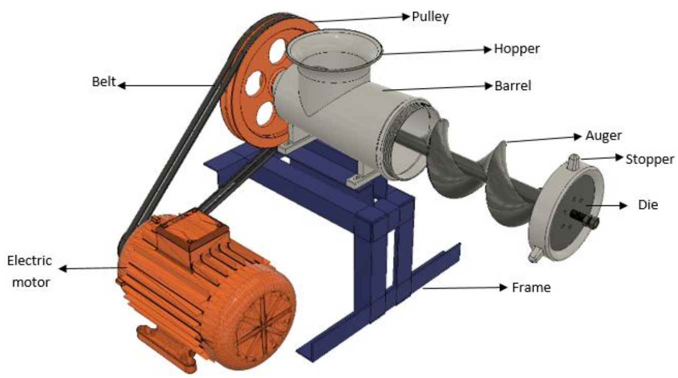

Figure 2.1 Pelletizing Unit

This study is centered on the fish-feed pelletizing unit. The design of the unit significantly influences the quality and floatability characteristics of the final feed products. This feature of the floating nature of feed is enhanced at the point of drying through moisture content reduction of the feed. Thus, a suitable number of orifices is chosen on the die to achieve floatability after adequate drying. The die is a plate (made from 10 mm thick mild steel plate) placed at the terminal of the screw conveyor and is made of various number of apertures (8mm and below drilled onto them) through which the material is extruded to form pellets. These dies of different sizes are designed to be replaceable so as to meet the demand variation in product granules. Other materials utilized in facilitating the process include:

(i) a threaded cover that secures the die to the end surface of the pelletizing barrel.
(ii) A 3hp electric motor as the prime mover that powers the screw conveyor inside the barrel for continuous pelleting through belt-pulley arrangement
(iii) A V-belt for the transfer of motion
(iv) A tapered barrel that encloses the auger.
(v) The solid shaft auger that transports the ingredients to the die and utilizes the friction between the barrel and screw to convey the ingredients. A pulley and belt drive the auger
(vi) Three robust spikes incorporated into a threaded stopper to hold the die plate in place securely.

2.1 Design of the Pelleting Unit Hopper

The truncated hopper, with dimensions of length (a) = 60 mm, width (b) = 230 mm, and height (h) = 210 mm, allows for the volume ($V_{\mathbf{p}hop}$) calculation using the expression provided in equation 2.1:

$$V_{\mathbf{p}hop} = \frac{(a^2+b^2+ab)h}{3} \quad (2.1)$$

2.2 Design of the Pelleting Unit Barrel

The barrel was made from stainless steel, with a thermal conductivity of 50.2 W/mºC. The volume of the barrel is given by the expression in equation 2.2:

$$V_{pbal} = \pi r_{pbal}^2 h_{pbal} \quad (2.2)$$

Since the barrel is horizontally fitted, length = h_{pbal} = 230mm, radius (r_{pbal}) = 100mm

2.3 Design of the Pelleting Screw Conveyor (Auger)

The operating pressure of the barrel is given by the expression given in equation 2.3 (Kubota, 1995):

$$P_p = I_{pbal}/Z_{pbal} \quad (2.3)$$

Where; P_p = pressure I_{pbal} = constant (1 for horizontal auger), Z_{pbal} = Volumetric capacity of the barrel,

The trust force is given as follows;

$$W_{ptf} = P_p A_{ptf} \quad (2.4)$$

$$A_{ptf} = \pi\left(\frac{D_{ptf}^2 - d_{ptf}^2}{4}\right) \quad (2.5)$$

Where; W_{ptf} is the thrust force, A_{ptf} = area of the barrel, D_{ptf} = outer diameter of the barrel, d_{ptf} = inner diameter of the barrel

2.4 Determination of the Pelleting Pressure

The pelleting pressure is dependent on the diameter and number apertures of the dies. It can be expressed mathematically as in equation 2.6:

$$P_{pp} = W_{pp}/A_{pp} \quad (2.6)$$

Where; W_{pp} = thrust force, A_{pp} = total area of all the dies,

The total area of all the dies was obtained using equation 2.7:

$$A_{pp} = \frac{N_{pp}\pi D_{pp}^2}{4} \quad (2.7)$$

Where N_{pp} = number of dies (holes), D_{pp} = diameter of the die (hole)

Therefore, the extrusion pressure was derived as given in equation 2.8

$$P_{pp} = \frac{4W}{N_{pp}\pi D_{pp}^2} \quad (2.8)$$

Equations 2.1 through 2.8 were used to determine the physical, geometric and operational parameters of the pelleting machine required in the model development.

2.5 Pelletizing Unit Efficiency Model Development

The efficiency model was developed on the basis of some assumptions meant to simplify and reduce complexities of the number of parameters involved for manageability.

These assumptions include:

1) The feed particles and constituents are incompressible.
2) The bulk density of pellet is constant for any formulation with uniform distribution
3) Pressure is uniform and normal to the cross-sectional area.
4) Frictional resistance is negligible

The pelletizing efficiency, η_{PE} was therefore, modelled as a function of the driving force, F_D, auger pressure P_A, feed rate F_R, barrel size B_S, number of orifices N_R, die size D_S, and feed density ρ_F.

The mathematically expression is given in equation 2.9 and the dimensional parameters in Table 1.

$$\eta_{PE} = f|F_D, P_A, F_R, B_S, N_R, D_S, \rho_F| \quad (2.9)$$

Also rearranged as:

$$f_1|\eta_{PE}, F_D, P_A, F_R, B_S, N_R, D_S, \rho_F| = 0 \quad (2.10)$$

Since there are 3 fundamental dimensions and 8 variables (parameters) as shown in equation 2.10 and Table 1, there exist 5 pi-terms that can be written. Thus, the pi-terms is obtained as in equation 2.11

$$f_1|\pi_i| \quad \forall\, i = 1, 2, 3, 4, 5 \quad (2.11)$$

: **Table 1:** Parameters and Dimensions

S/N	Parameter	Symbol	Unit	Dimension
1	Pelleting Efficiency	η_{PE}	%	$M^0L^0T^0$
2	Driving force	F_D	N (kg.m/s^2)	MLT^{-2}
3	Auger pressure	P_A	N/m^2 (kg/ms^2)	$ML^{-1}T^{-2}$
4	Feed rate	F_R	mm/s	LT^{-1}
5	Barrel size	B_S	m	L
6	Number of orifices	N_R	-	$M^0L^0T^0$
7	Die size	D_S	mm	L
8	Feed density	ρ_F	Kg/m^3	ML^{-3}

Using the pi Buckingham theory, equation 2.11 is expanded to the following:

$$\pi_1 = |P_A{}^q . D_S{}^r . \rho_F{}^s . \eta_{PE}| \quad (2.12)$$

$$\pi_2 = |P_A{}^q . D_S{}^r . \rho_F{}^s . F_D| \quad (2.13)$$

$$\pi_3 = |P_A{}^q . D_S{}^r . \rho_F{}^s . F_R| \quad (2.14)$$

$$\pi_4 = |P_A{}^q . D_S{}^r . \rho_F{}^s . N_R| \quad (2.15)$$

$$\pi_5 = |P_A{}^q . D_S{}^r . \rho_F{}^s . B_s| \quad (2.16)$$

Where q, r, and s are constants determined using dimensional homogeneity by substituting the values of the dimensions of the variables into equations 2.12 to 2.16. Simplifying the resulting equations, the pi terms are obtained as:

$$\pi_1 = \eta_{PE} \quad (2.17)$$

$$\pi_2 = \frac{F_D \rho_F D_S}{P_A} \quad (2.18)$$

$$\pi_3 = \frac{F_R}{D_S{}^2\sqrt{\rho_F P_A}} \quad (2.19)$$

$$\pi_4 = N_R \quad (2.20)$$

$$\pi_5 = \frac{B_S}{D_S} \quad (2.21)$$

Equations 2.12 through 2.16 were substituted into equation 2.10 to obtain equation 2.22:

$$f_1\left|\eta_{PE} . \frac{F_D \rho_F D_S}{P_A} . \frac{F_R}{D_S{}^2\sqrt{\rho_F P_A}} . N_R . \frac{B_S}{D_S}\right| = 0 \quad (2.22)$$

The rearrangement of equation 2.22 gives equation 2.23:

$$\boldsymbol{\eta_{PE} = \frac{F_D F_R N_R B_S \sqrt{\rho_F}}{|P_A|^{3/2} D_S{}^2}} \quad (2.23)$$

In terms of the driving parameters, the driving force is related to the motor power in the expression:

$$\boldsymbol{F_D = \frac{60P}{\pi DN}} \quad (2.24)$$

Where P is the motor driving power in Watts, N is the driving shaft speed in revolutions per minute, and D is the driving shaft diameter in millimeters.

Equation 2.23 is transformed to equation 2.25.

$$\boldsymbol{\eta_{PE} = \frac{60P . F_R . N_R . B_S . \sqrt{\rho_F}}{\pi DN|P_A|^{3/2} D_S{}^2}} \quad (2.25)$$

Therefore, the pelletization efficiency from initial parameters is computed with either equation 2.23 or 2.25.

Equation 2.23 was tested for dimensional homogeneity:

$$M^0L^0T^0 = \frac{MLT^{-2}.LT^{-1}.M^0L^0T^0.L.(ML^{-3})^{\frac{1}{2}}}{(ML^{-1}T^{-2})^3.L^2} \quad (2.26)$$

Equation 2.26 was found to be dimensionally homogeneous.

Thereafter, a computer-based implementation program was required to eliminate the error-prone and rigorous manual computations (Edeh *et al.*, 2022).

A Matlab program was therefore written for the model using set of design data (F_D = 713.38N, P_A = 1200017.3N/m^2, B_S = 0.00722m, D_S = 0.135m, ρ_F = 720kg/m^3) as provided by Nnadi (2024) at varying feed rate (0–25 mm/s) and number of orifices (0-25) :

```
% Implementation of Efficiency Model
FR=0:0.1:25; FD=713.38; PA=1200017.3; BS=0.00722; NR= 6;
DS=0.135; PF=720;
EFF=(FD.*FR.*NR.*BS.*sqrt(PF))./(PA.^(3/2).*DS^2);
plot(FR,EFF,':.r','linewidth',2)
NR=0:0.1:25; FD=713.38; PA=1200017.3; FR=10; BS=0.00722;
DS=0.135; PF=720;
hold on
EFF1=(FD.*FR.*NR.*BS.*sqrt(PF))./(PA.^(3/2).*DS^2);
plot(NR,EFF1,'-.','linewidth',2)
hold off
grid on
xlabel('Feed Rate [mm/rev]/No.of Orifices')
ylabel('EffPE [%]')
legend('Feed Rate','No. of Orifices')
```

3.0 Results and Discussions

The variables considered in the pelleting efficiency model were the feed rate and the number of orifices as shown in Figure 3.1. This was to determine the point of optimum product delivery of the machine based on a constant driving force of 713.38 N provided by a 3 hp electric motor. It is evident from the plot that pelleting efficiency increases with increase in the feed rate. At feed rate of 10, 15 and 20 mm/rev the efficiencies are 35 %, 55 % and 70% respectively. Moreover, at 10, 15 and 20 number of orifices, the efficiency exhibited a similar trend as the machine performs at efficiencies of 60 %, 80 % and 110 % respectively. The optimum pelleting efficiency was therefore determined by desirability function at target of 1.0 as 86.9 % at optimal settings of feed rate and number of orifices of 20mm/rev and 15 respectively.

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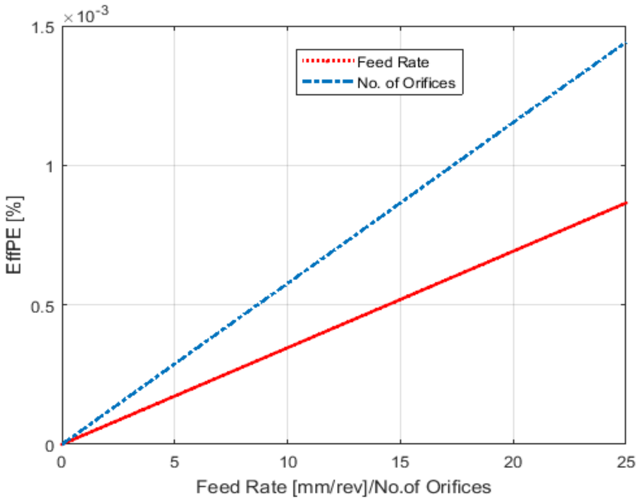

Figure 3.1 Pelleting Efficiency Plot

3.1 Model Validation

Experimental validation of the model result was conducted on the developed machine (at Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria; 5.4836° N, 7.5483° E) using the recommended optimum feed formulations by Nnadi (2024). The formular, Table 2, is for the three growth stages of fish (fingerlings, juvenile and adult). Three replicates were conducted each for a formulation and applying the parameter settings at feed rate of 20 mm/rev, 15 and 20 orifices dies. It was observed that the 20 orifices die yielded greater volume of products per minute, higher efficiency of 97 % but with the less ability of pellet to float (which was determined as the time taken for the pellet to remain on the surface of water before absorbing water and sink). This was attributed to less pelleting pressure. However, the 15 orifices die yielded less volume of products per minute, less pelleting efficiency of 86.21% but produced pellets with more abilities to float. It was also observed that there was no significant difference in the efficiency across the growth stage formulations indicating that pelleting efficiency is independent of particle size. Based on these experimental results the model prediction error of 0.69 % was observed which is within the ± 5% confidence interval, thus, the prediction accuracy over 95 %. The pelletizing efficiency model prediction also compared well with the findings of Kadurumba & Igbo (2020) of 85.7 %. maximum pelleting efficiency. In addition, introduction of a mixture of cassava starch was found to support floatability, which by visual inspection gave a smoother surface finish of the products.

Table 2 Size and Percentage distribution of ingredients

Feeds	**Macro-nutrient**				**Micro-Nutrient**		
	Feed size (mm)	Carbohydrate (%)	Fat (%)	Fish meal (%)	Sugar Molasses (%)	DCP/NaCl (%)	Additives (%)
Fingerlings	1.5	32	6.5	52	1	0.8	0.1
Juveniles	3	38	5.3	48	1	0.8	0.1
Adults	5	42	6	40	1	0.8	0.1

Source: Nnadi (2024)

4.0 Conclusions

The development of a fundamental model for predicting pelleting efficiency at variable feed rates and number of orifices has successfully provided insights into optimizing pelleting conditions. The model demonstrated that pelleting efficiency increases with both feed rate and the number of orifices, with the optimum pelleting efficiency of 86.9% achieved at a feed rate of 20 mm/rev and 15 orifices. Experimental validation confirmed the model's accuracy, yielding a low prediction error of 0.69%, which falls within the ± 5% confidence interval, indicating a high prediction accuracy of 95%. The results also highlighted the trade-offs between pelleting efficiency and pellet characteristics, such as the ability to float. Specifically, a die with 20 orifices provided higher efficiency (97%) but resulted in pellets with lower floatability due to reduced pelleting pressure. In contrast, the die with 15 orifices yielded lower efficiency (86.21%) but produced pellets with enhanced floatability, underscoring the need for balanced optimization depending on specific product requirements. Furthermore, the incorporation of cassava starch improved the floatability and surface finish of the pellets. This research not only reinforces the validity of the developed model but also provides a comprehensive approach to optimizing pelleting processes for fish feed production, with potential applications in both commercial and small-scale operations.

Acknowledgements

The authors appreciate and acknowledge the assistance and supports provided by the staff and members of Mechanical Engineering Workshop, Agric and Bioresources Engineering Laboratory of Michael Okpara University of Agriculture, Umudike during the experimental validation.

Declaration of conflict of interest

The authors have collectively contributed to the conceptualization, model development, and validation of this research. They have worked on drafting and critically revising the article to include significant intellectual content. This manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors do not have any affiliation with any organization that has a direct or indirect financial stake in the subject matter discussed in this manuscript.

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