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Evaluation of a Counter Current Cooling System of a Fish Feed Extrusion

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Abstract

This study explores the application of a counter-current cooling system to manage the excess heat generated during fish feed extrusion, a process critical for producing high-quality, nutritionally balanced feed. During extrusion, elevated temperatures caused by friction can degrade nutrients, damage product structure, and lead to economic losses. To address this, the research employed a counterflow cooling mechanism designed to enhance thermal regulation and product quality. An optimal experimental design approach was adopted using Response Surface Methodology (RSM) to analyze the influence of three key process variables: screw speed (150, 200, 250, and 300 rpm), die size (4, 6, and 8 mm), and water flow rate (25, 50, 75, and 100 Lmin¹). Response parameters included extrudate temperature, cooling efficiency, and bulk density. The study incorporated replication and error analysis to improve the reliability of optimization results. Maximum extrudate temperature reached 319°C at the highest screw speed, while the optimal conditions were at screw speed of 254.97 rpm, 5 mm die size, and 100 Lmin¹ water flow resulted in effective heat reduction and desirable product characteristics with a desirability score of 0.633. The study also highlights the adaptability of the proposed cooling system for various food matrices, including high-protein and fortified blends. Additionally, it considers scalability, operational cost, and maintenance aspects, suggesting that the system is practical for both small- and large-scale aquafeed production. Overall, the counter-current cooling approach demonstrated a significant improvement in process control, product safety, and energy efficiency, offering a sustainable solution for modern aquafeed manufacturing.
Keywords: extrusion, temperature, counter current, cooling, efficiency.

Introduction

Providing farmed fish with a nutritionally complete and balanced diet is central to maximizing aquaculture productivity. Prepared fish feeds play a critical role, not only due to their nutrient density but also because of their influence on feed conversion efficiency, water quality, and fish health (Mohanty et al., 2019). Among feed production techniques, extrusion has become a preferred method, enabling control over feed texture, floatability, and nutrient availability (Robb et al., 2013; Chaabani et al., 2022). However, suboptimal formulations, inadequate thermal management, and poor process control during extrusion can result in feed with inconsistent sizes, reduced floatability, increased fines and oil leakage, and deteriorated nutritional quality. All of these problems are caused by substandard raw materials, formulations, and process controls. The method or process adopted in making fish feed as an impact on the feed quality and due to the rising demand for fish products, the fish farming business has been growing quickly recently to meet the increasing demands of aquaculture, efficient and effective fish feed extrusion devices have been developed (Phuong and Oanh, 2010).

Extrusion processing was primarily used in the food processing industry in the early stages, since 1950s, America had started to use this technology for feed processing field, especially in the process of pet food and pre-treatment of feed ingredients (Georganas et al., 2022). In the 1980s, it has become the fastest developing technology of feed processing industry in the world, and has started to be applied in each area of feeding industry such as livestock feed and fish feed in form of dry foods (Van Der Poel, et al., 2020). The growth of aquaculture must adhere to the principle of producing green food without pollution in light of the ongoing advancement of technology and the improving living standards of people, which has drawn considerable attention to and extensive research into aqua feed production technology (Asche et al., 2022). This has brought a consensus to the adoption of extrusion process to make fish feed which is the major means to ensure production of high quality and safe aquatic products for human health, which is also a trend for feed industry progress in the future (Georganas et al., 2022).

Fish feed is extruded by heating a blend of ingredients under high pressure, moisture, and temperature using an extruder; the high temperature is produced by friction in the case of dry extrusion or by preconditioning and steam injection in the case of wet extrusion (Oduntan and Bamgboye, 2020). The extrusion can be divided into two types – dry type and wet type extrusion. In dry type extrusion process, it adopts the heat from friction for warming the materials and forcing the materials to pass through a die hole and also get certain pressure simultaneously under action of screw extrusion (Oduntan and Bamgboye, 2020). The materials pressure decreases sharply as the moisture evaporate with water of 15 – 20% while in wet type extrusion process with the principle similar to dry type extrusion but it requires the addition of water and vapour to make moisture up to 20% or more than 30% due to rise in material temperature which is depended on the addition of vapour. Extrusion of fish feed contributes significantly to the aquaculture sector by giving fish a complete diet that is simple to digest with a basic function of killing germ, mycete and fungus in feed ingredients, improve the hygienic quality and provide safe fodder for fish (Hixson, 2014). Due to the mechanical energy and friction produced inside the extruder during the extrusion process, the temperature of the feed mixture rises noticeably (Kantrong et al., 2018; Romano et al., 2018). Extruding fish feed requires blending a variety of raw materials into a homogeneous mixture. The homogeneous mixture is then heated, compressed, and pushed through a die in the extruder.

Traditionally, extrusion barrel cooling has relied on ambient air or basic venting mechanisms, which often prove insufficient (Romano et al., 2018). In contrast, counter-current cooling systems offer a more efficient means of heat extraction by allowing a cooling medium (typically water) to flow opposite to the direction of the extrudate, enhancing thermal gradients and maximizing heat transfer efficiency (Singh, 2006; Yacu, 2020). Despite a sound theoretical foundation, existing literature lacks comprehensive details on the physical configuration of such systems such as flow control mechanisms, heat exchanger geometry, or material selection—which are essential for system performance and durability.

Moreover, empirical comparisons between counter-current cooling and other modern cooling methods such as spray cooling or refrigerated die jackets remain scarce. While spray systems offer fast surface cooling, they often require additional post-processing drying steps. Refrigerated die jackets are effective but typically involve higher energy costs and complex maintenance. The operational simplicity, thermal efficiency, and adaptability of counter-current systems make them promising alternatives, particularly for extrusion lines processing heat-sensitive materials.

To support industrial adoption, this study also emphasizes the need for empirical benchmarking: how feed properties such as bulk density, textural integrity, and nutrient retention differ when extrusion is followed by counter-current cooling versus traditional methods are areas to develop. Including such comparisons provides essential performance metrics and decision-making insight for industry stakeholders.

Finally, this study incorporates error analysis and replicated experiments to improve statistical rigor and model accuracy. A schematic of the integrated extrusion-cooling flow system is also presented to guide system replication. The overall objective is to assess the potential of a counter-current cooling system for reducing thermal damage, enhancing product quality, and offering a scalable, low-maintenance solution for aquafeed production.

MATERIALS AND METHODS

Sample preparation

Pineapple pomace was sourced from the National Horticultural Research Institute (NIHORT) in Jericho, Ibadan, Nigeria, and dried according to the method described by Oduntan and Bamgboye (2017) to a moisture content of 10% (wb). The dried pomace was then ground into a fine powder using a disc mill (AS 230, Fexod, Nigeria) fitted with a 0.5 mm screen plate, ensuring particle sizes smaller than the screen size. The powdered pomace, along with other ingredients (Table 1), was incorporated into fish feed through extrusion to a evaluate the efficiency of a counter-current cooling system using a single-screw extruder.

Table 1: Ingredient components in the prepared feed blends

Feed Ingredient	**Mass of ingredients** (g/100g)
Groundnut Cake	22.0
Soya Meal	17.9
Fishmeal (72%)	22.0
Wheat Bran	5.0
Corn Flour	5.0
Cassava Flour	5.0
Pineapple Pomace	20.0
DPC	0.5
Salt	0.5
Lysine	0.1
Methionine	0.1
Vitamin C	0.1
Fish Oil	1.5
Premix	0.5
Total	**100**
Proximate composition (%)	
Moisture Content	9.41
Ash	10.22
Crude Fibre	12.11
Crude Protein	38.02
Ether Extract	10.13

Materials and equipment used for counter current cooling system

The materials for the cooling system were selected based on standard methods, cost, availability, and their resistance to corrosion from the cooling medium (water). They were sourced from a local plumbing store in Apata, Ibadan, Nigeria. The materials included PVC (Polyvinyl Chloride) pipes, a PVC gumball valve, elbow joints, and T-joints. The equipment used consisted of a variable frequency drive (VFD) for adjusting screw speed and torque, a tachometer for real-time speed feedback from the extruder screw, and a flow meter for measuring the fluid flow through the pipe in real-time.

Description of the extruder

The experimental evaluation of the counter-current cooling system was conducted using an existing single-screw extruder (SE 2014; UI, Ibadan, Nigeria), located at the University of Ibadan, Nigeria, as developed by Oduntan and Bamgboye (2015). The extruder is a motorized, feed-grade processing device specifically designed for producing floating fish feed. It features a single-threaded screw, encased in a double-jacketed barrel constructed from stainless steel. The barrel has a diameter of 48 mm, and the system is powered by a 3.0kW electric motor, ensuring sufficient torque and mechanical energy to drive high-moisture feed blends.

The extruder barrel includes a dual water-jacket cooling mechanism, with cylindrical jackets installed over approximately two-thirds of the barrel's length, positioned toward the die end. The jackets are outfitted with inlet and outlet pipes positioned at 90° angles, facilitating counter-current flow; where cooling water enters from the outlet side and flows in the opposite direction to the feed mash. This layout, detailed in the schematic diagram (Figure 1), ensures a steeper thermal gradient and enhanced heat extraction. To validate the thermal gradient, water temperature was measured at both inlet and outlet points using digital thermocouples (±0.5°C accuracy). Flow rate was controlled via an adjustable gate valve, and monitored to ensure stable pressure. The specific heat (Cp) of water was assumed to be 4.18kJ/kg·K, based on standard thermophysical property tables (ASHRAE, 2022), while extrudate Cp was not measured directly but referenced from Hixson (2014).

Each feed mash formulation used in the trials was prepared to a uniform moisture content of 45% (wet basis) and a standardized initial feed temperature of 25±1°C to minimize variation. The final extruded feed was analyzed to verify if its crude protein content met aquafeed standards (32–35%), using AOAC-approved proximate analysis protocols. During operation, die size was varied (4, 6, and 8 mm), and its influence on backpressure, torque, and feed expansion was qualitatively assessed. Increased die diameter was found to reduce backpressure and extrusion torque, while promoting greater feed expansion. Although no torque meter was installed, observations were supported by extrusion flow rates and physical expansion of the extrudates. The system's open-circuit cooling setup involved a non-recirculating water supply from an overhead tank, eliminating the need for a secondary heat exchanger. However, water use efficiency and thermal losses were tracked throughout the runs.

Experimental setup

To evaluate the performance of the counter-current flow system, the cooling system was redesigned. PVC pipes were reconfigured to reverse the water flow from concurrent to counter-current by introducing water at 26°C through the outlet pipe (2), with the original inlet (1) now functioning as the outlet (Figure 1). A flow meter and ball valve were installed to regulate and measure the water flow rate. The ball valve was placed at the reservoir tank outlet, with the flow meter positioned immediately afterward, enabling precise water flow control. The screw speed, adjustable from 0 to 300 rpm, was managed via a Variable Frequency Drive (VFD) and monitored by a tachometer. The VFD, connected to the power supply control box

and wired to the electric motor, allowed for fine-tuning of speed through its control interface. The tachometer, mounted on the screw shaft, provided real-time speed measurements in revolutions per minute (RPM). The feed mash was introduced into the extruder at a rate of 1.6 kg/min.
For die diameter adjustments, various sizes (4, 6, and 8 mm) were available. To use a specific die size, the desired die was left open, while the others were sealed off using screws of corresponding sizes. This setup ensured that only the selected die size was operational, allowing for precise fish feed production with the required diameter

Experimental design

The experimental design for the counter-current cooling system in fish feed extrusion was conducted using Response Surface Methodology. This approach was employed to evaluate the relationship between the response variables and independent variables, aiming to optimize the conditions for the best response values. The operating parameters and their respective ranges are listed in Table 2. The independent variables investigated included screw speed (150, 200, 250, and 300 rpm), die diameter (4, 6, and 8 mm), and water flow rate (25, 50, 75, and 100 L/min). The experiment was designed to include 7 lack of fit points, 3 replicate points and 25 run. These variables were analyzed to assess their impact on the cooling system's performance in the extruder.

Measurement of extrusion conditions

The counter-current cooling system was evaluated based on extrusion conditions, including extrudate temperature, cooling efficiency, and extrudate density.

Extrudate temperature

Extrudate temperature is a critical factor in feed extrusion, influencing both the quality and nutritional value of the feed. To measure this temperature, a contact thermocouple was inserted into the extruded feed, and a digital thermometer was used for accurate readings. The Adiabatic Temperature Rise (ATR) formula was employed to calculate the extrudate temperature (Liu et al., 2007). The ATR formula is given by:

$$Q = \ldots 1 \tag{1}$$

where:
Q – specific mechanical energy input ($J \cdot kg^{-1}$);
W – feed flow rate ($kg \cdot hr^{-1}$);
C_p – specific heat of the material ($J \cdot (kgK)^{-1}$);
R – gas constant (8.314 $J \cdot (molK)^{-1}$).

Using the ATR formula, the extrudates temperature can be calculated as:

$$E_t = \ldots 2 \tag{2}$$

where:
E_t – extrudates temperature (°C);
F_t – feed mash temperature (°C).

Cooling efficiency

Cooling efficiency is influenced by various factors, including the type and quantity of coolant, heat transfer rate, cooling system capacity, and extrusion parameters. To assess cooling efficiency, the temperature of the cooling water at both the inlet and outlet of the water jacket cooling system was measured using a handheld glass mercury thermometer. The flow rate of the cooling water through the system was measured with a flow meter. The temperature difference between the inlet and outlet water temperatures was calculated using the equation provided by Richard et al. (2008). Cooling efficiency Cooling efficiency is influenced by various factors, including the type and quantity of coolant, heat transfer rate, cooling system capacity, and extrusion parameters. To assess cooling efficiency, the temperature of the cooling water at both the inlet and outlet of the water jacket cooling system was measured using a handheld glass mercury thermometer. The flow rate of the cooling water through the system was measured with a flow meter. The temperature difference between the inlet and outlet water temperatures was calculated using the equation provided by Richard et al. (2008).

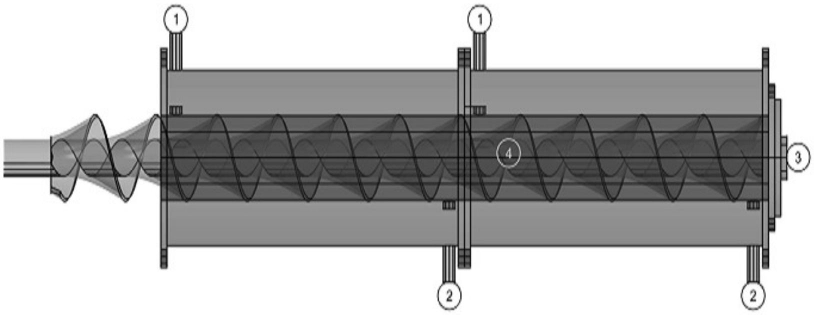

Figure 1: Single screw extruder with a water-cooling jacket. 1.- water Inlet, 2.- water outlet, 3.- die plate, 4.- screw barrel.

Table 2: The design experiments

Run	Screw speed (rpm)	Die diameter (mm)	Water flow rate (L/min)
1	250	8	50
2	200	6	25
3	300	6	75
4	200	8	75
5	200	6	75
6	250	6	50
7	250	4	100
8	250	4	50
9	300	8	25
10	200	4	75
11	150	4	50
12	200	6	25
13	300	4	100
14	200	6	75
15	150	6	100
16	150	8	50
17	250	4	50
18	300	8	100
19	250	8	100
20	150	8	50
21	300	4	25
22	200	6	25
23	150	4	100
24	300	6	75
25	150	4	25

$$\Delta T = T_{out} - T_{in} \quad (3)$$

where:
ΔT – temperature difference (°C);
T_{out} – outlet temperature (°C);
T_{in} – inlet temperature (°C).

The heat absorbed by the cooling water is calculated using the specific heat capacity of water:

$$H_r = m \cdot C \cdot \Delta T \quad (4)$$

where:
H_r – heat absorbed (J);
m – mass flow rate of the cooling water (kg);
C – specific heat capacity of water (J·(kg°C^{-1}));
ΔT – change in temperature (°C).

The cooling efficiency of the system is calculated by dividing the heat absorbed by the cooling water by the total heat generated by the extruder:

$$CE = \frac{H_r}{H_p} \times 100 \quad (5)$$

where:
CE – cooling efficiency (%);
H_r – heat absorbed from the system (J);
H_p – heat generated by the system (J).

Extrudate density

Extrudate density measures the mass of pellets per unit volume. For each run, a sufficiently large representative sample was collected and weighed using an electronic balance (Electronic K-Scale, SF-400, Hangzhou, Zhejiang, China). The volume of the sample was measured using a graduated cylinder, and the measurements were recorded. Pellet density was calculated by dividing the mass by the volume, and the result was expressed in mass per unit volume (kgm-^{3}).

$$p = \frac{m}{v} \quad (6)$$

where:
p – pellet density (kg·m^{-3});
m – mass of the pellet (kg);
v – volume of the pellet (m^3).

Statistical Analysis of Factor

The statistical analysis of the collected data was performed with I-Optimal design using Design Expert 13 software. Analysis of variance (ANOVA) was applied to statistically evaluate the data, assess differences, and determine the significance of the experimental model. 3D model graphs were also utilized to analyze the interaction between the independent variables and their effects on the dependent variables. The experimental responses were related to the coded variables (xi, i = 1 and 2) using a quadratic polynomial, as shown in Equation 7 below.

Y = $b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 - b_{11}x_1^2 + b_{22}x_2^2$

where:
x_1, x_2, x_3, x_4 – the coded values of screw speed (rpm), screw torque (Nm), die diameter (mm), and water flow rate (L/min), respectively;
b_0 – constant;
b_1, b_2, b_3, b_4 – linear effects;
b_{12} – interaction effect;
b_{11}, b_{22} – quadratic effects.

RESULTS AND DISCUSSION

Experimental result The experimental results evaluating the performance of the counter-current cooling system are presented in Table 2, which highlights the effects of processing variables on extrudate temperature, cooling efficiency, and extrudate density. Statistical analysis indicates that the model demonstrated moderate adequacy, with a non-significant lack of fit and satisfactory R^2 values for all responses.

Interaction effect of process factors on the extrudate temperature
The results, fitted into a second-order polynomial model, are presented in Table 3 for the analysis of extrudate temperature using coded factors. The model showed a significant linear impact on extrudate temperature, with a high F-value of 42.45 and a low probability value (Prob. $> F < 0.0001$). According to Korbahti and Tanyolac (2010), P-values below 0.0500 indicate significant

Table 3: Experimental result showing extrudates temperature, cooling efficiency and extrudates density

Run	Extrudates Temperature (°C)	Cooling Efficiency (%)	Extrudates Density (kg·m^{-3})
1	169.91	55.00	0.11
2	106.18	29.82	0.05
3	167.55	65.88	0.11
4	88.61	58.06	0.13
5	96.55	50.89	0.04
6	184.01	59.00	0.13
7	167.92	70.00	0.05
8	141.13	51.62	0.10
9	159.27	43.69	0.11
10	105.22	31.70	0.07
11	92.75	65.00	0.35
12	125.61	28.75	0.05
13	169.29	76.19	0.18
14	98.82	53.19	0.18
15	62.74	50.00	0.03
16	82.66	34.37	0.04
17	139.43	49.22	0.35
18	145.49	78.33	0.07
19	122.45	65.25	0.20
20	80.94	19.35	0.05
21	195.50	32.91	0.05
22	108.61	30.56	0.09
23	71.68	48.75	0.18
24	169.43	66.59	0.07
25	104.64	7.38	0.21

model terms, while values above 0.1000 suggest insignificance. For extrudate temperature, the analysis revealed that screw speed and water flow rate were significant factors, whereas the linear term of die diameter did not significantly affect the response. The coefficient of determination (R^2 = 85.85%) for extrudate temperature was higher than the adjusted R^2, indicating strong agreement between the calculated and observed results within the experimental range. The predicted R^2 (81.12%) was reasonably close to the adjusted R^2 (83.82%), further supporting the model's adequacy. In this case, the variables x1 (screw speed) and x3 (water flow rate) were significant model terms. Based on the data, the response surface model developed for predicting extrudate temperature was considered reliable.

From Table 4, variations in the linear terms of screw speed (x_1) and water flow rate (x_3) have a significant impact on extrudate temperature ($p \leq 0.05$). However, changes in the linear term of die diameter (x_2) do not significantly affect the extrudate temperature ($p \geq 0.05$).

The 3D response surface graph is illustrated in Figure 2. Figure 2a shows a contour plot highlighting the effects of screw speed and water flow rate on extrudate temperature, while Figure 2b depicts the interaction between these factors on extrudate temperature through a response surface plot.

The contour plot indicates that increasing screw speed benefits the extrusion process,

Table 4: Regression coefficients of second order polynomials

Coefficient	Extrudates Temperature (°C)	Cooling Efficiency (%)	Extrudates Density (kg·m^{-3})
b_0	+126.16*	+18.46	+0.1169*
Linear			
b_1	+47.48*	-5.87*	-0.0419*
b_2	-7.35	-16.65*	+0.0647*
b_3	-10.54*	+3.93	-0.0417*
R^2	0.8585	0.8966	0.9840
Adjusted R^2	0.8112	0.8621	0.9787
Adequate Precision	19.85	16.95	43.44
Lack of Fit		0.1755	

* Significant at $p \leq 0.05$

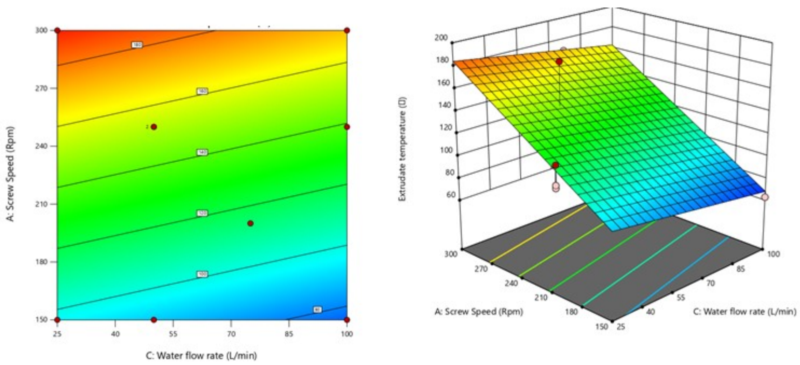

Figure 2: Contour plot (a) and 3D response surface plot for extrudate temperature (b)

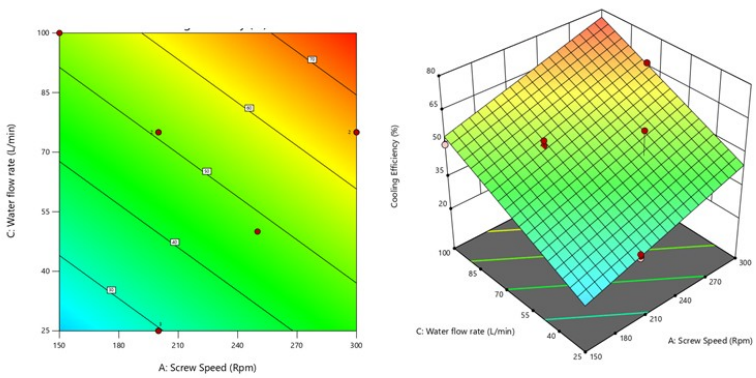

Figure 3: Contour plot (a) and (b) 3D response surface plot for the cooling efficiency

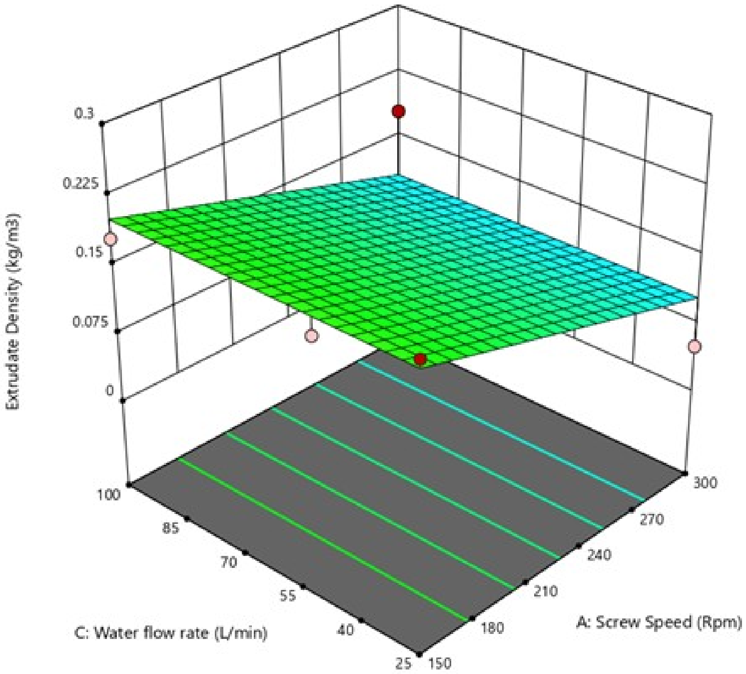

Figure 4: 3D surface plot for extrudate density

as higher speeds lead to increased extrudate formation and elevated temperature, thereby promoting faster drying after the extrudates exit the die. This observation aligns with Censi et al. (2021), who reported that the extrusion process, influenced by different screw designs, alters the physicochemical properties of extrudates, such as thermal and mechanical characteristics, affecting their stability. The continuous rise in screw speed contributed to a corresponding increase in extrudate temperature. Figure 3b further illustrates the linear relationship between screw speed and water flow rate in relation to extrudate temperature. As screw speed increases, extrudate temperature rises from 64°C to 163°C across the range of applied speeds. Conversely, an increase in water flow rate into the cooling chamber decreases the extrudate temperature. High extrudate temperatures were observed at lower water flow rates, while lower extrudate temperatures were achieved at higher flow rates. Optimal extrudate temperature was found within the screw speed range of 277-300 rpm and a water flow rate between 25-55 L/min. These results are consistent with findings by Sandrin et al. (2018), who explored the effects of extrusion temperature and screw speed on oat and rice flour extrudates, and Langauer et al. (2015), who studied the influence of pellet shape on single-screw extrusion. The data suggest that small changes in response values can be achieved with minimal adjustments to the independent variables, as the screw speed values align closely with the water flow rate axis, as seen in Figure 3b.

Interaction effect of process factors on cooling efficiency

The interaction effects of each factor on cooling efficiency are presented in Table 3, where cooling efficiency ranged from 7.38% to 78.33%. Analysis of variance revealed that cooling efficiency was significantly influenced by the linear factors of extruder screw speed and water flow rate. The coefficient of determination (R^2) for cooling efficiency was 0.7161, indicating that 71.61% of the total variability in cooling efficiency was explained by the variation in the independent variables. The adjusted R^2 was 0.6754, and the adequate precision value, which measures the signal-to-noise ratio, was 13.55 well above the desirable threshold of 4 indicating a strong signal and that the model is significant and reliable for navigating the design space.

According to Table 4, cooling efficiency increases with higher water flow rate (x_3) and decreases with lower screw speed (x_1) and die diameter (x_2). The contour plot suggests that increasing both screw speed and water flow rate improves the machine's cooling efficiency. This is due to the increased water flow rate, which leads to the formation of more durable extrudates, enhancing their handling during transfer to the dryer. This aligns with the findings of Li et al. (2020), who reported that discharge capacity and shaft power increase with water flow rate, and an optimal flow rate is necessary to achieve maximum isentropic efficiency. As shown in the 3D response surface graphs in Figure 3b, water flow rate and screw speed had the greatest effect on cooling efficiency. High efficiency values were observed when water flow rate ranged between 60 and 100 Lmin-1, and screw speed was between 150 and 180 rpm. As screw speed decreased while water flow rate increased, cooling efficiency peaked. The optimal cooling efficiency was found to be between 60% and 70%. These results are similar to those reported by Abeykoon et al. (2021) on energy efficiency in extrusion-related polymer processing.

Interaction effect of process factors on extrudate density

The minimum extrudate density was observed at a screw speed of 150 rpm, screw torque of 210 Nm, die diameter of 6 mm, and water flow rate of 62.5 $\mathrm{L\,min^{-1}}$. Extrudate density gradually decreased with increasing die diameter. The maximum density (0.35 $\mathrm{kg\,m^{-3}}$) was recorded at a 4 mm die diameter, while the minimum value (0.03 $\mathrm{kg\,m^{-3}}$) occurred at 6 mm. Similar findings were reported by Ribeiro (2021), who optimized pellet density and durability using response surface methodology in ultrasonic vibration-assisted pelleting of corn stover. As screw speed increased, extrudate density also rose, enhancing cooking and starch gelatinization (Su *et al.*, 2009). This results in improved physical properties, such as increased extrudate density and hardness.

As shown in Table 4, the *p*-value of less than 0.05 indicates that the model terms are significant, with die diameter being a key factor. The coefficient of determination (R^2) for extrudate density was 0.9840, meaning that 98.40% of the total variability can be used to predict the response. The adjusted R^2 was 0.9787, and the adequate precision was 43.444, which is well above the desirable threshold of 4, indicating a strong signal. This model is reliable and can be used to navigate the design space.

From Table 4, extrudate temperature increased by varying the linear term (x_2) and the interaction terms (x_1x_3), while it decreased with reductions in the linear terms (x_1 and x_3) and the interaction terms (x_1x_2 and x_2x_3).

Optimization of the extrusion processing conditions

Optimal response variables were achieved by adjusting the independent variables to their optimal values. This investigation employed numerical analysis, setting specific targets for each response. Through this approach, the independent variables were optimized: the die size was minimized, while screw speed and water flow rate were maximized. The extrudate temperature was minimized, and both cooling density and efficiency were maximized. The results indicated that the optimal processing conditions for improved response values were a screw speed of 254.97 rpm, a die size of 5 mm, and a water flow rate of 100 $\mathrm{L\,min^{-1}}$, yielding a desirability score of 0.633.

Conclusions

Extrusion is a widely used process for producing innovative food and feed products that are otherwise difficult to manufacture using conventional methods. However, precise control of processing temperature is essential to avoid nutrient degradation, textural defects, or scorching of the final products. While several cooling techniques have been explored, this study introduces a novel application of a counter-current cooling system, engineered specifically to address excess heat generated through friction in single-screw extrusion. This approach directly addresses a longstanding challenge in maintaining the physical and nutritional integrity of extruded feeds. Using a structured experimental design and Response Surface Methodology (RSM), this study evaluated the influence of four controlled variables—screw speed (150 to 300 rpm), die diameter (4 to 8 mm), and water flow rate (25 to 100 L·min^{1})—on extrudate temperature, bulk density, and cooling efficiency. The maximum extrudate temperature reached was 319°C at 300 rpm, while the optimal process settings were identified as 254.97 rpm screw speed, 5 mm die diameter, and 100 L·min^{1} water flow, achieving a composite desirability index of 0.633. The system consistently reduced thermal stress, leading to more uniform and stable product outputs. Beyond immediate heat regulation, this study underscores the broader utility of counter-current cooling in aquafeed production. The approach holds significant promise for industrial scale-up, offering enhanced energy efficiency, reduced mechanical stress on equipment, and improved feed quality retention, especially in high-protein and thermally sensitive formulations. Moreover, the system can contribute to lower operational costs, improved nutrient conservation, and sustainability in large-scale aquafeed manufacturing. These findings position counter-current cooling as a strategic innovation with long-term benefits for precision thermal control in the feed processing industry.

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