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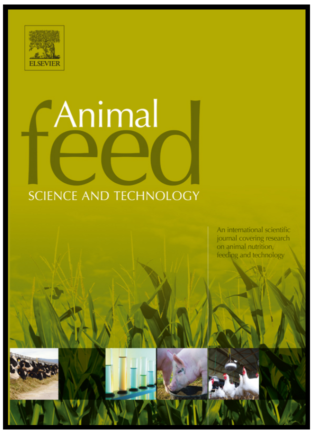

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Effect of Different Extrusion Conditions and Pellet Size on the Physical Properties of Extruded Fish Feeds

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Abstract

This work presents useful information on how different temperature profiles during the extrusion process affect the physical quality properties of the extrudates. In this study, feed mixtures were extruded using a twin-screw extruder; the barrel temperature profile was set at 110^{o}C for cooking extrusion process, and no additional heat for cold process. Four extruded diets were designed: D2LT and D4LT for 2 mm and 4 mm diet produced with cold process, respectively, and D2HT and D4HT for 2 mm and 4 mm diet produced with cooking extrusion. Pellet durability index (PDI), expansion ratio (ER), sinking velocity (SV), water stability (WS) and water absorption index (WAI) were affected with the temperature condition. The pellets produced with cooking extrusion had a higher PDI, SV, WAI and WS compared to cold process (*p* <0.0001). There was no significant difference in terms of ER between the extruded diet processed with different temperature at the same particle size. Reducing particle size from 4 mm to 2 mm significantly affect the PDI, WAI. SV, WAI and WS in cooking extrusion diet. In cold process, the significant differences were found in PDI, ER, and WS, but no significant differences in SV and WAI.

Keywords: Cooking extrusion, Cold process, Physical quality, Size, Extrudates,

1. Introduction

Aquaculture is one of the fastest growing food production sectors in agriculture and plays a significant role in improving national food security, income and nutritional status of people in many regions (Yu et al., 2025; Kannadhason & Muthukumarappan, 2010;). As intensive aquaculture continues to expand, research on diet quality and feeding strategies is being continually refined (Thornburg, 2025; Bu et al., 2024; Hertrampf & Piedad-Pascual, 2012). In the evaluation of diet quality, producers must consider an extensive array of fish with different feeding habits (Hyatt, 1979). Since aquaculture species occupy different strata within the water column, a comprehensive knowledge on physiology and feeding behavior is required to maximize the opportunity for the fish to consume the diets being offered, avoid the loss of nutrients due to disintegration and leaching in the water (Turchini &Hardy, 2024; Parker, 2011) and maximize feed conversion efficiencies (Stark, 2012; Guillaume, 2001). Thus, the feed manufacturing process must accommodate all the specific nutritional requirements to ensure optimal growth performance and health condition of the cultured species.

In commercial aquaculture feed, important physical properties that constitute feed quality include the hardness, water stability, absorption, buoyancy, and resiliency (Cheng et al., 2024; Sørensen, 2012). These properties ensure the feed remains intact during production, transportation, and until it reaches the feeding devices in fish farms (Sørensen et al., 2009). Durability and water stability are affected by various biochemical changes that occur inside the extruder barrel (Sørensen et al., 2009; Thomas et al., 1999), while the floatability of the diet is affected by the expansion achieved during the extrusion process (Adeparusi & Famurewa, 2011). Extrusion processes improve the water stability, durability, hardness and buoyancy control compared to steam pelleted diets (Sørensen et al., 2009), making extrusion the most effective manufacturing technology for compound fish feed (Bowzer et al., 2016; Brown et al., 2015; Hertrampf & Piedad-Pascual, 2012; Khater et al., 2014).

Extrusion processing integrate multiple operations, including simultaneously mixing, cooking, kneading shearing, shaping and forming (Yadaf et al., 2021; Riaz, 2000; Riaz, 2008). According to Pennels et al. (2025) and Guillaume (2001), Extrusion processing uses a barrel housing one or two screws that compress a mixture of raw materials using a combination of pressure and heat along the length of the barrel over a short period. At the end of the barrel, the mixture is shaped by being forced through one or several openings in a die, with the resulting strands cut by a knife. The product is then cooled and dried (Bowzer et al., 2016; Guillaume, 2001). During extrusion, a combination of moisture, pressure and heat can partially denature the protein and gelatinize the starch in raw materials (Friesen et al., 1992; Jeong et al., 1991; Kim et al., 2006). This process significantly affects starch chemistry, feed digestibility, expansion, and water stability of the pellets (Rosentrater et al., 2009).

The present study evaluates the effect of two different barrel temperatures during twin-screw extrusion processing and the effects of two different pellet sizes on the durability index, expansion ratio, sinking velocity, water stability, and water absorption index of the extruded products.

2. Material and Methods

2.1 Feed formulation and preparation

Four diets with similar compositions were manufactured using commercial methods with a twin-screw extruder (DNDL-44, Buhler Inc., Plymouth, MN, USA) by the U.S. Fish and Wildlife Service, Bozeman Fish Technology Center, Bozeman, MT, USA. The ingredients (excluding the Menhaden fish oil, which was applied to the feeds post-extrusion; see below) were mixed in a paddle mixer (Marion Mixers, Inc., Marion, IA, USA) in a 100-kg batch followed by grinding to a particle size of <200 µm using an air-swept pulverizer (Model 18H; Jacobsen, Minneapolis, MN, USA) (**Table 1)**. Two-extrusion processes were evaluated: (1) extrusion- cooking, defined as using temperatures above 110^{o}C to gelatinize the starch and (2) cold process, defined when the starch is not gelatinized, and ingredients are primarily pressed into a form. The cooking-extrusion diets were exposed to an average of 110^{o}C for approximately 14 seconds in five-barrel sections, with the last section maintained at 62^{o}C. Pressure at the die head was approximately 50 bars, and screw speed was maintained at 423 rpm. Portions of the feeds were extruded through a 3 mm die for 4.0 mm pellets (D4HT) and 1.5 mm die for 2 mm pellets (D2HT). The diets were dried in a pulse bed drier (Buhler AG) until moisture readings were below 6%. Pellets were dried at approximately 107°C with an upper limit outflow air temperature of approximately 88°C. The diets were then cooled at ambient air temperatures for final moisture levels of less than 10%. Fish oil was then applied using a Phlauer vacuum infusion coater (A & J Mixing, Ontario, Canada) after the pellets were cooled.

The cold process diet consisted of two distinct sizes of feeds, with all the oil mixed in the mash prior to pelleting, and also manufactured with the Buhler twin-screw extruder. No additional heat was added, and barrel tempering units were set at 15^{o}C, which resulted in an average barrel temperature of 23.2^{o}C mid-way through production. The cold-extruded diet's solids feed rate was half that of the cooking extruded pellets, which resulted in a longer retention time in the barrels (28 seconds), but only 13 bars of pressure at the end plate. The 2mm (D2LT) and 4mm pellets (D4LT) were manufactured with 2- and 4-mm dies, respectively. All finished diets were bagged and stored in a temperature-controlled room until analysis and shipment.

2.2 Proximate and amino acid composition of diets

The protein, moisture, lipid, fiber and ash content were determined using standard methods described by Association of Official Analytical Chemists (AOAC, 1990). The amino acid composition of the diet was quantified by Agricultural Experiment Station Chemical Laboratories, University of Missouri (Columbia, MO, USA) and the mean of each treatment was taken.

2.3 Analysis of physical properties

2.3.1 Pellet durability index (PDI)

Approximately 500 g of each diets were manually sieved (U.S.A. standard testing, ASTM E-11 specification, Daigger, Vernon Hills, IL, USA) to remove initial fines, and then tumbled in a pellet durability tester (Model PDT-110, Seedburo Equipment Company, Chicago, IL, USA) for 10 min. Afterwards, the samples were again sieved, and then weighed on an electronic analytical balance (Mettler Toledo ML6001E precision balances, Switzerland). Pellet durability index was calculated as follow:

$$\text{Pellet Durability Index (\%)} = \frac{Mat}{Mbt} \times 100$$

Where: M_{at} is the mass of pellet after tumbling (g) and M_{bt} is the mass before tumbling (g)

2.3.3 Expansion ratio

Expansion ratio (ER) was determined as the ratio of the extrudate diameter to the diameter of die nozzle (Conway & Anderson, 1973). The diameter of the extrudates for each treatment was measured with a digital caliper (Digimatic Series N0. 293, Mitutoyo Co., Tokyo, Japan)

2.3.4 Sinking velocity

Sinking velocity (SV) was measured using the method developed by Das et al. (1993) and was determined by monitoring the time taken for an extrudate to reach the bottom of a 1000 mL measuring cylinder filled with distilled water. Distance travelled for the time taken gave the sinking velocity (ms^{-1})

2.3.5 *Water absorption index (WAI)*

Approximately, 2 g of extrudates for each diet was placed in 20 mL of distilled water and stirred with a magnetic stirrer (Southeast Science, Model H4000-HS, Korea) at low speed, which simulates the movement of water of pond, until the extrudates broke or disintegrated over a period of 30 min, and then centrifuged at 3000 x g for 10 min. The mass of remaining gel was weighed, and WAI was calculated as the ratio of gel mass (*Wg)* to the sample mass (*Wds*) (Jones et al., 2000).

Water absorption index (unitless) = $\frac{Wg}{Wds}$

2.3.6 *Water stability*

Water stability (WS) was measured as the ratio of pellet retained on a wire screen after immersion of 3 – 5 g of each replicate diet in 100 mL water for 20 min and oven drying at 105^0 C for 24 h to the initial pellets (Lim & Cuzon, 1994).

2.4 Statistical analysis

Mean results per physical properties were expressed as a mean ± standard deviation (SD) and subjected to two-way analysis of variance (ANOVA) with interaction using diet size and extrusion temperature condition as the independent variables. Prior to analysis, Cramer-von Mises test and Anderson-Darling test were performed to analyze the normal distribution of the physical parameters. Student's *t* test was applied to assess any difference in PDI, expansion ratio, sinking velocity, WAI and water stability were compared between two different diet sizes subjected to the same treatment. Statistical significance was defined at $p<0.05$ and analysed using the General Linear Model procedure in the SAS system (V9.4, SAS Institute, Cary, NC, USA).

3. Results

3.1 *Nutrient composition of experimental diets*

The proximate composition of crude protein, moisture, crude fat, crude fiber and ash are presented in **Table 2.** The level of crude fat was higher in D4LT compared to D2LT. However, crude protein, moisture and ash content showed comparable levels among the treatments. In addition, no differences were observed on the amino acid profile of the diet produced by using two different extrusion processes, cooking-extrusion and cold process.

3.2 Physical properties of diets

Two-way ANOVA showed that the expansion ratio, sinking velocity (SV), water absorption index (WAI) and water stability (WS) were significantly influenced by temperature conditions during the extrusion process and the size of the diet ($p<0.0001$). However, for the Pellet Durability Index (PDI, %)., barrel temperatures during twin-screw extrusion processing had a more significant effect ($p<0.0001$, by two-way ANOVA) compared to the size of the diet ($p = 0.1663$).

Based on student *t* test results to determine the differences between two different sizes of diet subjected to the same treatment, bigger size (4 mm) significantly increased the expansion ratio, SV and WS compared to lower size (2 mm) of diet either produced by using cooking-extrusion condition or cold process. In addition, smaller size of diet produced by using cooking-extrusion process had higher water absorption index and no significant differences in diet extruded by using cold process. Finally, 2 mm diet extruded in cold process had the higher PDI (%) compared to 4 mm.

Discussion

The choice of feed production methods for the aquaculture industry largely depends on species characteristics, production cost, and their impact on the culture environment (Bektursunova et al., 2023; Ebbing et al., 2022; Espinoza-Ortega et al., 2024; Guillaume, 2001; Wang et al., 2021). In a study with rainbow trout (*Salmo gairdneri* R.), extruded diets had better physical properties than steam pellets and resulted in prolonged gastric emptying and higher feed efficiency compared to the group of fish reared on steam pellets (Hilton et al., 1981). In addition, a study performed by Misra et al. (2002) showed that the extruded pellets induced better feed conversion ratio (FCR) and protein utilization of post-larvae of *Macrobrachium rosenbergii* in comparison to those maintained with steam pellets. While steam pelleting can sometimes replace the function of extruded diet for aquaculture purposes, extrusion remains the preferred method (Guillaume, 2001; Riaz, 2023; Xing et al., 2024).

In the present study, changing the conditioning temperature in the barrel section of double-screw extrusion process and pellet size significantly affected the physical properties of the diets. Results shown in Table 3 indicated that the PDI of the extrudates processed with cooking-extrusion were higher than those produced with the cold process. Increasing pellet size from 2 to 4 mm resulted in an increase in durability of extrudate produced by using cooking-extrusion process. However, at the cold-process, smaller size yielded significantly higher PDI compared to bigger sizes. The effects of barrel and die temperature of pellet mill have been reviewed (Tumuluru et al., 2010), highlighting the ability of the densified biomass to remain intact during the handling process as die temperature increased. Moreover, the presence of non-starch polysaccharides (NSP) in the diet might also contribute to the pellets not being crushed during the handling process (Kraugerud et al., 2011). The effect of changing size on resulting extruded strength was observed by others with different ingredients. For example, Khater et al. (2014) reported that the mean durability was increased as the pellet size decreased from 3.0 to 1.0 mm at two different protein ratios. Likewise, the PDI of extruded catfish feed formulated by using 47.3% of soybean meal as the protein source was increased when the particle size reduces from 1.2 mm to 0.7 mm (Rolfe et al., 2001). However, considering the interaction effect on this study, changes in durability are more attributed to changes in temperature rather than changes in size.

In aquaculture, manufacturing low-polluting diets and avoiding the risk of leaching nutrients caused by disintegration of pellets has received much attention with significant quality innovations (Guillaume, 2001). In the present study, changes in temperature, die pressure, and screw speed during cooking extrusion produced more stable feed compared to the cold process. In agreement with current results, better WAI was also observed in pellets produced with cooking extrusion with chamber temperature condition raised up to 90% compared to steam pelleting (Larrea et al., 2005). According to Misra et al. (2002) The superior water stability of the extruded diet might be attributed to starch gelatinization under high temperature, combined with high pressure and shear during the manufacturing process. Additionally , the density and moisture content of extruded diet might play a role in determining the absorption index (Misra et al., 2002; Singh & Muthukumarappan, 2016) and can have significant implications in the storage stability of pellets (Chevanan et al., 2007).

Although no clear trend was observed, this study indicated that when the pellet size of cooking extrusion pellet increased from 2 mm to 4 mm, the mean WAI was decreased from 3.60 to 2.52. On the other hand, no significant difference was observed between 2 mm and 4 mm pellet produced with cold process. Since WAI values could vary depending on the diet composition and processing (Thomas et al., 1999), changes in this study were mostly influenced by the temperature.

In this study, an increase in SV (cm s^{-1}) was observed in diets produced by the cooking extrusion process compared to those produced by the cold process. Within the same treatment, bigger size also caused significant increase in SV. Since SV was associated with air entrapped in particles to reduce the specific gravity and capability of diet to absorb the water (Chevanan et al., 2010; Hilton et al., 1981), higher numerical value gives the impression that cooking-extrusion produces a more dense and compact diet compared to cold-process. Indeed, the heavier density of 4 mm diet compared to 2 mm will cause a significant increase in SV for extruded diet either produced with cooking-extrusion or cold process.

The highest water stability was obtained in cooking-extrusion process and bigger size of diet subjected to different extrusion process. The poorer stability found in cold process of 2 mm diet might be related to the compacted conditions and density of the diet (Rout & Bandyopadhyay, 1999). Meanwhile, extrusion process and size of the diet also had a significant interaction to the expansion ratio. Several studies have indicated that the expansion ratio of the extrudates depends on extrusion condition (Chevanan et al., 2007; Miller, 1985; Moore et al., 1990), residence time (Fan et al., 1994; Mitchell et al., 1994) and the die design (Bouzaza et al., 1996). Among the variables, barrel temperature plays a critical role in controlling the expansion properties by lowering the melt viscosity and increasing the longitudinal expansion (Chinnaswamy, 1993; Singh et al., 2014).

4. Conclusion

In present study, changes in extrusion conditions, specifically the barrel temperature, significantly affected the physical properties of extruded diets, including the durability index, expansion ratio, sinking velocity, water absorption index and water stability. A significant interaction was also found between the extrusion conditions and size of the extruded diet on these physical properties when all ingredients exposed to an average of 110°C for approximately 14 seconds in five-barrel sections.

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Table 1. Composition (g 100 g^{-1} *as is*) of diet manufactured using two-extrusion process.

Ingredient	Inclusion rate (% as-is)
Menhaden fishmeal, Special Select®	12
Corn protein concentrate, Empyreal® 75	10
Soybean meal 48% CP	10
Chicken 42 – ADF	10
Wheat gluten meal	4

Blood meal, spray dried	2.5
Wheat flour, durum	30.03
Menhaden fish oil[a]	10.01
Lecithin (Yelkinol AC dry)	1
Vitamin C (Rovimax® Stay-C® 35)	0.15
Vitamin premix, ARS 702	1
Trace mineral premix, ARS 1440	0.1
Sodium chloride	0.28
Magnesium oxide	0.06
Potassium chloride	0.56
Monocalcium phosphate	2.28
Choline Chloride 50%	1
DL-Methionine	0.56
Lysine HCl	2.66
Threonine	0.63
Taurine	1
Yttrium oxide	0.1
Carophyll® Pink, 10% astaxanthin,	0.08

[a] incorporated via post extrusion top-coating

Table 2. Proximate and Amino acid (AA) composition (g kg^{-1}, dry matter) of experimental diets. D2LT: 2-mm pellets processed with low temperature (cold process); D2HT: 2-mm pellets processed with high temperature (cooking-extrusion); D4LT: 4-mm pellets processed with low temperature; D4HT: 4-mm pellets processed high temperature.

AA (g kg^{-1}, dry matter)	**D2LT**	**D2HT**	**D4LT**	**D4HT**
Taurine	1.11	1.12	1.24	1.23
Hydroxyproline	0.26	0.24	0.24	0.23
Aspartic Acid	3.08	3.10	3.02	3.07
Threonine	2.03	2.05	1.96	1.97
Serine	1.46	1.52	1.47	1.45
Glutamic Acid	7.75	7.84	7.86	7.94
Proline	3.00	2.99	3.00	3.01
Lanthionine	0.00	0.00	0.00	0.00
Glycine	1.99	1.97	1.91	1.87
Alanine	2.42	2.43	2.37	2.39
Cysteine	0.53	0.54	0.52	0.53
Valine	2.13	2.15	2.11	2.14
Methionine	1.29	1.29	1.26	1.28
Isoleucine	1.66	1.68	1.66	1.69

Leucine	3.94	3.97	3.93	3.99
Tyrosine	1.52	1.51	1.51	1.53
Phenylalanine	2.18	2.19	2.16	2.20
Hydroxylysine	0.10	0.10	0.09	0.10
Ornithine	0.01	0.01	0.01	0.01
Lysine	4.14	4.19	4.09	4.16
Histidine	1.00	1.01	0.99	1.00
Arginine	2.08	2.10	2.07	2.11
Tryptophan	0.44	0.45	0.38	0.35
Crude Protein	45.11	45.82	44.73	45.64
Moisture	3.37	2.42	3.71	3.56
Crude Fat	14.84	14.31	17.02	12.70
Crude Fiber	0.92	0.93	0.97	1.39
Ash	7.42	7.59	7.38	7.51

Table 3. Physical properties of extruded diets produced by using two different extrusion processes

Extrusion	Diet Size	Pellet Durability Index (%)	Expansion ratio	Sinking velocity (cm s^{-1})	Water absorption index	Water stability (%)
Cooked (D2HT)	2 mm	99.41±0.19	1.01±0.02	12.92±9.46	3.60±0.06*	86.20±0.15
Cooked (D4HT)	4 mm	99.87±0.09*	1.13±0.04*	64.35±4.49*	2.52±0.07	88.18±0.08*
Cold (D2LT)	2 mm	97.53±0.11*	1.06±0.02	0.40±0.09	2.23±0.15	82.60±0.54
Cold (D4LT)	4 mm	97.34±0.07	1.11±0.02*	0.55±0.16	2.28±0.23	87.72±0.18*
Goodness-of-Fit for Normal distribution						
Cramer-von Mises		p >0.250	p >0.250	p =0.034	p >0.250	p >0.250

Anderson-Darling	$p > 0.250$	$p > 0.250$	$p = 0.033$	$p > 0.250$	$p > 0.250$
Two-way ANOVA (Type I SS)					
Extrusion Process	$p < 0.0001$	$p = 0.0181$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Diet Size	$p = 0.1663$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Interaction	$p = 0.0058$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$

* = Significant differences (*t* test, $p < 0.05$) between two different size produce within the same treatment

Different superscript letters denote significant differences among the treatments

Author's Statement

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Conflicts of Interest

All authors state no conflict of interest