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Effects of two extrusion processing conditions on the digestibility of four cereal grains for *Penaeus vannamei*

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Abstract

Four cereal grains (whole wheat, corn flour, rice flour and milo) were examined before and after being subjected to two extrusion processes to determine the effects of extrusion processing on in vivo energy digestibility. Utilizing chromic oxide as an inert marker, apparent digestibility coefficients of the cereal grains were evaluated with 13 g *Penaeus vannamei*. The cereal grains were extruded with a Wenger Extruder (model TX52) under two conditions allowing the production of wet and dry pellets. Test diets for each test ingredient were prepared containing 70% semi-purified reference diet and 30% of the test ingredient. Extrusion processing resulted in increased gelatinization of each of the tested cereal grains with wet extrusion producing the highest values. Processing and/or gelatinization values did not always correspond to increased digestibility of the test ingredients. Highest apparent digestible energy (ADE) values for wheat occurred without extrusion and under dry conditions. Highest ADE values for rice flour occurred without extrusion and under wet extrusion conditions. Dry extrusion of the corn flour and milo resulted in the best energy digestibility coefficients for these grains. However, wet extrusion appeared to significantly reduce the availability of energy from corn flour. Based on these results, extrusion did result in increased ADE values of poorly utilized cereal grains; however, no one extrusion condition was optimal for all cereal grains tested.

Keywords: Carbohydrates; *Penaeus vannamei*; Extrusion processing; Cereal grains; Feeding and nutrition — crustaceans / digestibility

1. Introduction

Extrusion processing is one of the most versatile and energy-efficient processes in food production (Dziezak, 1989). Due to potential improvements in feed quality, increased

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versatility of product lines and cost-effectiveness of the final products, extrusion technology has become accepted in aquatic feed processing. Extrusion cooking is a process which involves the plasticizing and cooking of feed ingredients in the extruder barrel by a combination of pressure, heat and friction (Robinson, 1991). Extrusion processing results in increased water stability and durability of the pellet (Hilton et al., 1981) and generally does not require supplemental binding agents. Although this technology is well accepted and is thought to increase the nutritional value of feeds, there are few data on the effects of processing on the nutritional value of extruded feeds and their individual components.

Cereal grains are an inexpensive binding agent and important source of energy in pelleted feeds. Starch constitutes 70–80% of most cereal grains. Starch digestibility in cereal grains is affected by the plant species, the extent of starch–protein interaction, the physical form of the granule, inhibitors such as tannins, and the type of starch (Rooney and Pflugfelder, 1986). Starch digestion and absorption have been found to be augmented by physical processing and heating of the grain (Gray, 1992). Pre-gelatinization of starch has resulted in increased nutritional value of feedstuffs for fish (Bergot and Breque, 1983; Jeong et al., 1991, 1992; Szlaminska et al., 1991) and *Penaeus vannamei* (Davis and Arnold, 1993).

Carbohydrates appear to be well utilized by shrimp, and feeds containing relatively high levels of carbohydrates are palatable and support good growth (Pascual et al., 1983; Catacutan, 1991; Shiau et al., 1991; Shiau and Peng, 1992). However, digestibility of carbohydrates has been found to be less efficient than protein (Fenucci et al., 1982), and the utilization of carbohydrates by shrimp appears to vary with complexity, processing and source (Chuang, 1991; Davis and Arnold, 1993).

In addition to limited data on energy availability from carbohydrates, the effects of commercial processing have received little attention. With limited information on the digestibility of energy from carbohydrates, the nutritional and economic value of these ingredients is difficult to evaluate properly. Hence, the objective of this research was to determine the apparent digestibility coefficients of pre- and post-extruded cereal grains for *Penaeus vannamei*.

2. Materials and methods

Voluntary consumption of test diets with chromic oxide as an inert marker was utilized to determine apparent digestibility coefficients for pre- and post-extruded cereal grains with *P. vannamei* (13 g mean weight). Each feed ingredient was evaluated utilizing a 30% replacement in the semi-purified reference diet (Table 1). Apparent digestibility coefficients for the reference diet were used to calculate digestion coefficients for the feedstuffs of interest based on the percent substitution of the test ingredient (Wilson and Poe, 1985). Test ingredients were obtained and extruded by Wenger Manufacturing, Inc. Each cereal grain was extruded with a twin-screw Wenger Extruder Model TX52. Extrusion conditions were modified to produce a "wet" or "dry" product (Table 2). Due to differences in grain type, extrusion conditions could not be held constant; however, differences within extrusion types (wet or dry) were minimized. After extrusion the samples were dried and reground. In preparing test diets, ingredients were homogenized in a food mixer (Hobart Corporation, Troy, OH) for 30 min. After mixing, boiling water was blended into the mixture until a

Table 1
Composition of reference diet

Ingredient[a]	g/100 g dry weight
Casein	42.0
Gelatin	8.0
Menhaden fish meal[b]	5.0
Wheat starch	27.0
Menhaden fish oil[b]	7.4
Aqualipid 95[c]	1.0
Fish solubles[b]	1.0
Carboxymethyl cellulose	2.0
Vitamin premix[d]	2.0
Stay-C (10.28% active vitamin C)[e]	0.1
AIN76 mineral premix [a]	4.0
Chromic oxide sesqui[f]	0.5

[a]United States Biochemical Corporation, Cleveland, OH, USA. [b]Zapata Haynie Corporation, Hammond, LA, USA. [c]Central Soya, Fort Wayne, IN, USA. [d]Equivalent to Davis et al. (1992). [e]L-Ascorbyl-2-polyphosphate. Hoffman-LaRoache Inc. Nutley, NJ, USA. [f]Fisher Scientific, Pittsburgh, PA, USA.

consistency appropriate for pelleting was reached. Each diet was pelleted utilizing a meat grinder with a 3-mm die and then dried by forced ambient air to a moisture content of 8–10% and stored at $-10°C$.

Shrimp were maintained in a semi-closed recirculating system consisting of 32-culture chambers (105 liters), a rapid-rate sand filter and a biological filter. Salinity, temperature and dissolved oxygen were maintained at (mean ± standard deviation) 30 ± 3.4 ppt, $26.4 \pm 1.0°C$ and 5.8 ± 0.4 mg/l, respectively. Prior to the initiation of the experiments, shrimp were acclimated to the experimental conditions and reference diet. Each of the test diets was fed to 4 replicate tanks of shrimp (10 shrimp per tank) over a 3-day conditioning period followed by a 3-day collection period. Exuviae and feces were removed from the tanks before the shrimp were given an initial feeding. To ensure that previously consumed material (feces and exuviae) was cleared from the digestive system, feces from the first feeding were discarded. Shrimp were allowed to feed for 30–40 min after which feces was collected by siphoning from the tank into a 48-μm sieve, and uneaten feed removed from the tanks. Fecal samples were immediately rinsed with distilled water. Once all the tanks had been siphoned, the feeding process was repeated, allowing at least 5 collections per day. Fecal samples collected from the same tank/treatment were pooled, resulting in 4 samples/treatment water, and then oven-dried (65°C to constant weight) for subsequent analyses.

Chromic oxide was determined by the method of McGinns and Kasting (1964) and gross energy by micro-bomb calorimetry (Parr adiabatic calorimeter, Parr Instrument Co., Moline, IL). Starch gelatinization, also referred to as damaged "starch content", was analyzed by the Wenger Analytical Laboratories (Sabetha, KS) utilizing a modification of Chiang and Johnson (1977) glucoamylase methodology. Results are presented in Table 3.

Data were analyzed using a one-way analysis of variance to determine significant ($P < 0.05$) differences among treatment means. Student-Neumann-Keuls' multiple range test (Steel and Torrie, 1980) was used to evaluate significant differences among treatment

Table 2
Extrusion conditions utilized to produce a wet and dry pellet with a twin-screw extruder (Model TX52, Wenger Manufacturing, Inc.)

	Wheat		Corn flour		Rice flour		Milo	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Dry recipe information								
Moisture (%)	12.01	12.01	12.38	12.38	9.68	9.68	11.5	11.5
Feed screw speed (rpm)	21	21	21	21	21	21	21	21
Preconditioning information								
Preconditioning speed (rpm)	161	161	161	162	168	168	165	168
Steam flow to preconditioner (kg/h)	0	1.36	0	0	0	0	0	0
Water flow to preconditioner (kg/h)	6.35	8.98	6.67	11.79	7.98	8.16	6.35	9.53
Preconditioner discharge temperature (°C)	46	61	36	55	35	36	35	35
Moisture entering extruder (%)	22.62	24.62	20	21.64	18.08	17.48	19.85	26.42
Extrusion information								
Extruder shaft speed (rpm)	358	358	358	358	352	341	358	358
Motor load (%)	37	28	40	16	43	25	43	24
Steam flow to extruder (kg/h)	0	0	0	2.72	0	2.72	0	2.72
Water flow to extruder (kg/h)	0	5.9	0	2.72	0	4.99	0	2.72
Control/temperature 2nd head (C)[1]	CW/36	CW/30	CW/30	CW/79	CW/45	CW/64	CW/43	CW/43
Control/temperature 3rd head (C)	CW/34	CW/31	CW/31	CW/69	CW/72	CW/61	CW/33	CW/33
Control/temperature 4th head (C)	CW/40	CW/35	CW/47	CW/71	CW/57	CW/56	CW/49	CW/49
Control/temperature 5th head (C)	S/97	S/78	S/106	S/103	S/98	S/99	S/106	S/104
Control/temperature 6th head (C)	S/118	S/100	S/135	S/121	S/130	S/112	S/143	S/126
Head/pressure (kPa)	6/2758	6/2758	6/1379	6/1379	6/2413.25	6/2758	6/1379	6/1379
Head/pressure (kPa)	5/2068.5	5/2068.5	5/1379	5/1379	5/2068.5	5/2068.5	5/2068.5	5/1379
Knife drive speed (rpm)	389	389	382	454	453	453	453	452
Final product information								
Extruder discharge moisture (%)	19.38	28.63	17.18	32.79	15.09	20.03	17.64	29.56
Extruder discharge rate (kg/h)	84.37	114.31	87.09	108.86	NR	119.75	95.26	NR

[1]CW = cooling water; S = steam; NR = not recorded.

means. All statistical analyses were conducted using the Statistical Analysis System (SAS Institute Inc., 1988).

Table 3
Percent starch gelatinization of the test ingredient[1]

Ingredient	Extrusion condition		
	Pre	Dry	Wet
Wheat	23.0	92.3	97.3
Corn flour	18.6	77.8	85.1
Rice flour	93.2	87.8	94.5
Milo	14.8	84.9	87.8

[1]Data represent analyses conducted by Wenger Manufacturing Inc.

3. Results and discussion

Starch gelatinization of the various grains as affected by extrusion conditions is presented in Table 3. Starch gelatinization can be caused by mechanical, thermal or chemical agents or various combinations of these conditions (Rooney and Pflugfelder, 1986). Because the presence of free water is of critical importance in starch gelatinization, the utilization of two extrusion conditions (wet or dry) would be expected to result in different gelatinization levels in the test ingredients. With the exception of the rice flour, the reported extrusion conditions resulted in increases in the gelatinization of the test ingredients; the highest values were observed for wet-extrusion. Gelatinization values for rice flour, prior to extrusion, indicate this to be a pre-gelatinized product. Gelatinization of the pre-extruded rice flour was confirmed with polarized light microscopy.

Based on visual observations, the test diets produced a quick feeding response and were readily consumed by the shrimp. Apparent dry matter digestibility (ADMD) and apparent digestible energy (ADE) values of 83.1 and 92.2% were observed for the reference diet. These values are in accordance with digestibility coefficients reported for penaeid shrimp (Akiyama et al., 1989; Shiau and Peng, 1992) including work within this laboratory (Davis and Arnold, 1993). Two-way analysis of variance of the ingredient digestibility data indicated significant effects of processing, cereal type and their interaction. Because the primary objective of this study was to identify the effects of processing on each cereal grain, the data were sorted and analyzed by cereal grain (Table 4).

Wheat is the most commonly used carbohydrate and binding source in crustacean diets (Sheen and Chen, 1993) and is considered to be a highly available energy source (Shiau et al. 1991; Sheen and Chen, 1993). Apparent dry matter digestibility and ADE values were highest for wheat samples prior to extrusion and poorest for wet-extruded samples (Table 4). Apparent digestible energy values for pre- and post-extruded wheat samples, determined in the present study, were considerably higher than those previously reported for whole wheat (67.7%) and wheat starch (71.3%) utilizing the same technique and species of shrimp (Davis and Arnold, 1993). It should be noted that in a concurrent study which utilized the same population of shrimp but a separate source of whole wheat, ADE values for the basal diet (91.7%) and the test ingredients (whole wheat, 90.2%) were similar to those observed in the current study.

Corn is an abundant and relatively inexpensive source of energy that is extensively utilized in terrestrial and fish feeds. Although a depression in growth rate has been associated with

Table 4
Gross energy and apparent digestibility coefficients for dry matter (ADMD) and energy (ADE) of the test ingredients

Ingredient		Extrusion condition		
		Pre	Dry	Wet
Wheat	Gross energy[1] (kcal/kg)	4380	4743	4633
	ADMD (%)	82.1^{z}[2]	66.5^{y}	66.7^{y}
	ADE (%)	87.0^{z}	81.3^{yz}	77.1^{y}
	ADE[3] (kcal/kg)	3811^{z}	3857^{z}	3571^{z}
Corn flour	Gross energy (kcal/kg)	4616	4733	4608
	ADMD (%)	70.6^{z}	73.1^{z}	50.7^{y}
	ADE (%)	78.4^{z}	82.8^{z}	65.9^{y}
	ADE (kcal/kg)	3617^{z}	3917^{z}	3037^{y}
Rice flour	Gross energy (kcal/kg)	4419	4174	4221
	ADMD (%)	85.6^{z}	65.4^{y}	83.6^{z}
	ADE (%)	94.4^{z}	74.1^{y}	92.7^{z}
	ADE (kcal/kg)	4173^{z}	3093^{x}	3914^{y}
Milo	Gross energy (kcal/kg)	4246	4538	4423
	ADMD (%)	58.1^{y}	79.4^{z}	64.2^{y}
	ADE (%)	66.4^{x}	83.4^{z}	76.2^{y}
	ADE (kcal/kg)	2821^{x}	3785^{z}	3370^{y}

[1]Based on micro-bomb calorimetry of the test ingredient after processing. [2]Data represent the mean of 4 replicates. Mean values in any row with the same letter are not significantly different from each other. [3]Caloric value of the ingredient adjusted for percent ADE.

the use of corn starch, Shiau et al. (1991) reported no significant difference in apparent digestibility coefficients for protein, dry matter, lipid or carbohydrates in *P. monodon* fed diets containing wheat flour or corn starch. In the present study, pre-extruded wheat had considerably higher ADMD and ADE values than that of pre-extruded corn flour but had similar levels of digestible energy (3811 and 3617 kcal/kg, respectively). Wet extrusion processing resulted in a significant decrease in ADMD and ADE values as compared to dry extrusion and pre-extruded corn starch. These results would indicate that dry extrusion conditions resulted in a higher energy availability for corn flour.

Rice is another excellent energy source with a low but fairly good quality protein (Sheen and Chen, 1993) and is a major agricultural product of many of the shrimp-producing countries. The utilization of rice products, particularly those of low commercial value, in shrimp feeds may facilitate a reduction in ingredient costs. In the present study, ADMD and ADE values for pre-extruded and wet-extruded rice flour were significantly higher than those for dry-extruded rice flour. Dry extrusion of rice flour lowered the starch gelatinization values for this ingredient and may have resulted in the reduced digestibility values. These results would indicate that pre-extruded rice flour and wet extrusion resulted in the highest energy availability for this ingredient.

Milo or grain sorghum is drought-tolerant and adapts to tropical growing conditions (Rooney and Serna-Saldivar, 1991). Sorghum has proximate composition, amino acid content and nutritional value similar to corn. However, sorghum is generally considered to have 95% of the nutritional value of corn for most terrestrial livestock species and requires more thorough processing to achieve optimal nutritional value (Rooney and Serna-Saldivar, 1991). In the present study, the extrusion of sorghum resulted in significant increases in ADMD and ADE values, with dry extrusion producing the most digestible product. Similar increases of digestibility were reported by Davis and Arnold (1993) when comparing grain sorghum to Nutribinder® (gelatinized, partially pre-digested grain product, primarily sorghum), thus confirming that processing of this cereal type significantly improves the digestibility of nutrients.

The digestibility of starch is affected by the composition and physical form of the starch, protein–starch interactions, the cellular integrity of the starch-containing units, antinutritional factors and the physical form of the feed or food material (Rooney and Pflugfelder, 1986). Extrusion processing has been demonstrated to increase the digestibility of some cereal grains for fish (Wilson and Poe, 1985; Jeong et al., 1991) presumably through increased gelatinization of the starch (Bergot and Brenque, 1983; Jeong et al., 1991). The results of the present study indicate that extrusion processing increases the gelatinization of each of the tested cereal grains with wet extrusion producing the highest values. Processing and/or gelatinization values did not always correspond to increased digestibility of the test ingredients. Optimal results for wheat and rice flour occurred without extrusion and/or under dry and wet extrusion conditions, respectively. Dry extrusion of the corn flour and sorghum resulted in the best digestibility coefficients for these grains. However, wet extrusion appeared to significantly reduce the availability of energy from corn flour. Extrusion did result in increased ADE values of poorly utilized cereal sources; however, no one extrusion condition was optimal for all cereal grains tested. Based on the results of the current study and previously reported results with other species, further investigation into the effects of processing, source and level of inclusion on digestible energy values is warranted.

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