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Processing Flaxseed for Food and Feed Uses

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Abstract Flaxseed is outstanding for lignans and oil rich in α-linolenic acid which protect against several major illnesses. Better understanding of processing and storage characteristics of flaxseed will increase options for food use. Lignans and oil are found in the hull and embryo, respectively. Comparison of pearling and impact-dehulling processes for separation of lignan and oil-rich fractions showed the impact process was less effective, but easier to scale-up. Screw-pressing embryo reduced oil yield compared to whole seed, but doubled productivity and sharply reduced frictional heating of the oil. Flaxseed hull and embryo, also whole, ground and steamed-ground samples, were stable up to 30 weeks in closed containers at 23°C. Steamed-ground samples in open trays at 40°C deteriorated markedly (peroxide value > 100 by 22 weeks); yet, whole seed remained stable. Incorporation of 18% flaxseed embryo into yellow perch feed increased α-linolenic acid to 13 to14% of muscle and liver lipids, compared to 0.5 to 0.7% in the no-embryo control. Feed conversion ratio, weight gain, and survival were similar. These studies are helping to establish the technological base for processing and utilizing flaxseed and flaxseed fractions to improve human diets.

Keywords: aquaculture, α-linolenic acid, dehulling, flaxseed, oxidative stability

Introduction

Flaxseed (*Linum usitatissimum*) is currently receiving much attention for functional food use, because it is rich in the omega-3 fatty acid, α-linolenic acid, and lignan secoisolariciresinol diglucoside (SDG). Health benefits have been linked to these and other flaxseed components (1-3). A flaxseed consists of two flattened cotyledons or embryo, contained within an outer seed coat or hull that includes the true hull and much of the endosperm (4). The hull represents 40% of the seed weight and is particularly rich in water-soluble mucilage or fiber (5). The SDG content of hull was at least 46 times greater than that of the embryo in an analysis of hand-dissected flaxseed (6).

Due to the adherent endosperm tissue (4), the oil content of flaxseed hull is much higher than those of most oilseeds. Nevertheless, dehulling offers a simple means of obtaining a lignan-rich fraction (hull) separate from the oil-rich fraction (embryo). The separation of hull from embryo and resulting enrichment of SDG and α-linolenic acid will allow those fractions to be used in food products in controlled amounts and in ways that are most compatible with the desired attributes of the food. The use of mechanical methods, as opposed to the use of synthetic or petroleum-derived solvents such as hexane, is compatible with products to be labeled "organic" under the US National Organic Program (7). Recent reports of flaxseed dehulling involved the use of either abrasive or cutting forces to loosen the hull before final separation with an aspirator, sieve, and/or gravity table (8-9). Among the drawbacks of these approaches were low capacity and inability to produce both hull and embryo fractions at good yields.

If demand for flaxseed lignans becomes substantial, it will be necessary to develop suitable markets for the flaxseed embryo. One such use is to press dehulled flaxseed for its edible oil, rather than the whole flaxseed. Scientific studies of the screw-pressing of flaxseed for food use are very limited (10), and pressing of dehulled flaxseed was only recently reported for the first time (11). Studies on the screw-pressing of other oilseeds have shown that press oil yield is affected, in particular, by the seed moisture content (12). As a food oil, flaxseed oil is sensitive to heat, oxygen, and light, and must thus be regarded as a perishable oil. This concern extends to a lesser degree to all edible flaxseed products, however, ground flaxseed appears to be fairly shelf-stable at room temperature; in contrast, the oil is typically stored refrigerated in dark bottles and intended for use within 3 to 6 months. The oil is mainly pressed in small presses operated at low temperatures with little or no seed preparation. Non-ruminant animal feeds represent another potential use of flaxseed embryo. Livestock such as fish and poultry can only handle low levels of whole flaxseed in their diets due to the high fiber content. The embryo is low in fiber, and thus would be an excellent alternative to water-washed flaxseed used to boost omega-3 fatty acids in farm-raised fish (13).

Research has been underway at North Dakota State University since 1998 to increase the food and feed uses of flaxseed. Objectives of the research include identification of the optimum methods for mechanical fractionation of

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flaxseed, development of screw-pressing methods for dehulled flaxseed, characterization of the stability of flaxseed fractions, and evaluation of the use of dehulled flaxseed in aquaculture.

Materials and Methods

Materials Flaxseed was of the golden-seeded variety "Omega" produced in North Dakota. Feed ingredients included Special Select Menhaden Meal (Zapata Protein USA, Inc., Hammond, LA,USA), corn starch (Cargill, Cedar Rapids, IA, USA), vitamin premix (Rovimix 2118, Roche, Parsippany, NJ, USA), trout mineral premix (Nelson & Sons, Murray, UT, USA), and Choline Chloride 70 and amino acid blend (Trouw Nutrition, Highland, IL, USA).

Dehulling study Duplicate 10-kg lots of flaxseed were processed on separate days by pearling (abrasive dehulling), sifting, and fractionation (Fig. 1). Product fractions were weighed, recorded, labeled, and stored in plastic bags at 4°C for further analysis. Hull, embryo, and fines fractions were analyzed for moisture and oil contents. A subset of samples was analyzed for SDG content.

The pearling unit consisted of three Strong-Scott barley pearlers aligned vertically on a steel frame; product from the first, uppermost pearler flowed by gravity into the second pearler, and product from the second pearler flowed into the third pearler (6). Each pearler contained a 30-grit stone disk (25.4 mm thick ¥ 165 mm diameter) driven directly at 1,730 rev/min. The curved surface of the disk was surrounded by a 7-mesh screen spaced 10 mm from the disk. The gap between the sides of the disk and the flat, unfinished, sand-cast plate surfaces was 8 mm on each side of the disk. Flaxseed entered the pearling chamber just above the axis of rotation of the disk through an external hopper on the plate opposite the motor. A screw feeder (Model E-2, Zero-Max Company, Minneapolis, MN, USA) was calibrated to deliver flaxseed to the first pearler at either 75 or 150 g/min.

Flaxseed discharged from the third pearler stage dropped into the base of a screw-conveyor that elevated product to a continuous-flow, flat-bed sifter. The sifter (Rotex, Style No. 12, The Orville Simpson Co., Cincinnati, OH, USA) shook the 18-mesh screen (1.0 m long × 0.4 m wide) at 140 cycles/min with a 5-cm amplitude. The coarse product from the sifter was separated into three fractions, hull, embryo, and intact plus cracked seed, using a gravity table with a 12-mesh deck (Forsberg, Model 10-M2, Thief River Falls, MN, USA). The trapezoidal-shaped deck measured 47, 82, and 43 cm at the back base, front base or discharge end, and feed edge (low side), respectively. Deck oscillation was 120 cycles/min with an 11-mm amplitude. The coarse fraction from the sifter was fed to the deck via vibratory feeder at 650 to 700 g/min. Airflow of 0.7 to 2 m/sec, side slope of 2 to 4°, and end slope of 4 to 9° were adjusted by the operator as needed to improve separation. The hull and embryo fractions were collected from the zone of the front base that extended from its left end to a point 8 to 12 cm and 18 and 32 cm from that end, respectively. The fraction between these two zones, a mixture of hull and embryo, was recycled to the feed.

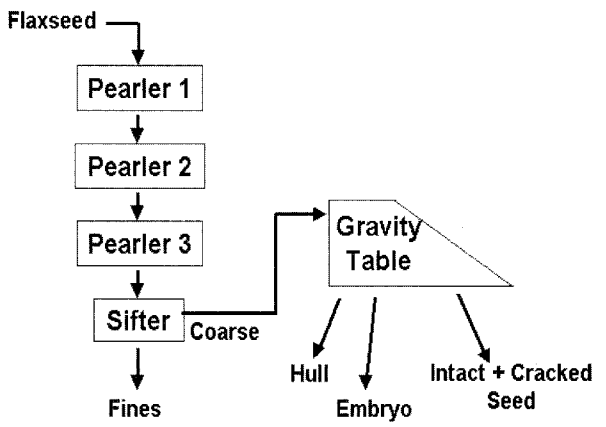

Fig. 1. Three-stage pearler process for abrasive dehulling of flaxseed.

The three pearlers were replaced by an impact dehuller in one series of experiments. The impact dehuller consisted of a 12-vane, 50-cm diameter horizontal rotor that propelled flaxseed radially outward from the center, causing the seed to impact against a beveled granite stone. Process variables were seed rate of 500 to 2,000 g/min, tangential rotor speed of 39 to 47 m/sec, and seed moisture content of 4.2 to 6.6%. The combination of 1,000 g/min, 47 m/sec, and 6.6 % appeared to give very satisfactory results, and triplicate 10 kg samples were processed under these conditions for comparison with the pearling method.

Moisture content was determined with an infrared moisture analyzer (Mettler LJ 16 Dryer, Mettler-Toledo, Inc., Hightstown, NJ, USA). Intact seed, hull, and embryo samples were first milled to pass through a 1-mm screen in an ultra-centrifugal mill (model ZM1, Brinkmann Instruments Co., Westbury, NY, USA) before analysis. Duplicate 3 to 4 g samples were heated in a 7.5-cm diameter aluminum dish at 120°C. The instrument was programmed to stop when the rate of weight loss fell to less than 2 mg/30 sec.

For oil content determination, duplicate 2.5 to 3.5 g samples were extracted at 70°C with hexane for 16 hr using a Soxhlet apparatus. The solvent was evaporated gently under vacuum pressure at 40°C using a Brinkmann Model RE 111 Rotavapor equipped with a 461 Buchi water bath (Brinkmann Instruments Company, Westbury, NY, USA), and the residual oil weighed for calculation of oil content.

Screw press study Flaxseed was pressed on demand in a Komet screw press (Model S 87G, IBG Monforts Gmbh & Co., Mönchengladbach, Germany) with a 6-mm inside-diameter choke at 24 rpm screw speed for maximum compression and residence time, respectively (11). Temperatures at the drainage cage and choke were monitored with Type T thermocouples and logged with a CR10X datalogger (Campbell Scientific, Inc., Logan, UT, USA) at 10-sec intervals, and monitored via PC in real time. An electrical resistance-heating ring preheated the press head to 60°C for 30 min before press operation. Samples were introduced into the hopper sequentially in order of decreasing moisture content. Time to achieve steady pressing was about 5 min for the first, and about 1

min for each subsequent sample. Steady pressing was assumed when the change of the oil temperature was less than 1°C for 20 sec. Duplicate oil and meal samples were collected and weighed in direct succession upon achieving steady pressing. Oil was analyzed for sediment content, and meal for oil content.

Two series of experiments are reported here: (a) pressing of whole, intact seed with an R8 shaft having a 16-mm flight-to-flight distance and seed moisture content ranging from 6.1 to 11.6 % (d.b.); and (b) pressing of dehulled seed with an R11 shaft having a 21-mm flight-to-flight distance and seed moisture content ranging from 7.7 to 11.2% (d.b.). To condition seeds to greater moisture content than received, the required distilled water was sprinkled onto and hand-mixed into the flaxseeds. The seeds were held 5 d at 5°C in a closed polyethylene bag. Seed clumps formed by this method were removed by passing through a 9.5-mm sieve. To condition seed to lower moisture content, a 1.5-cm deep bed of seeds was dried at 50°C in a hot air oven to the desired content. To dehull flaxseeds, the seeds (6.8% moisture content) were manually fed into a model VSH-8088 Huller (Codema, Inc., Maple Grove, MN, USA) at 6,500 to 8,500 g/min using a rotor tangential speed of 48 m/sec. The dehulled fraction (embryo) was recovered by sifting/gravity table as described above.

Storage stability study Five different flaxseed preparations were used: whole, intact seed; whole, ground seed (Urschel Comitrol, Valparaiso, IN, USA) (9); hull and embryo fractions from the abrasive system described above; and steam-cooked for 10 min at 100°C (12), air-dried, whole, ground seed. Duplicate 45 g portions per storage interval were placed under two storage conditions: (a) sample placed in a plastic zipper bag inside a brown paper bag, secured with a rubber band, and stored at room temperature (22 to 24°C), and (b) sample placed on a 13 ¥ 13 cm plastic tray open to air at 40°C. The latter condition was intended to accelerate oxidation to determine the relative stability of samples. Samples were withdrawn for analysis at 0, 6, 14, 22, and 30 weeks. Oil was obtained by hexane extraction for 2 hr without external heat, desolventized at 35°C, and analyzed for peroxide value by titration. AOCS Method Cd 8b-90 (14) was used within 24 hr. Conjugated dienoic acid content was determined by spectrophotometry as in AOCS Method Ti 1a-64 (14) within 48 hr, free fatty acid content was determined by titration using AOCS Method Ca 5A-40 (14) within 1 week, and moisture content was measured by heating at 130°C for 3 hr as in AOCS Method Af 2-54 (14).

Aquaculture study Three rations were formulated using 0, 9, and 18% dehulled flaxseed, and extruded using a Wenger TX-52 twin-screw extruder with Wengers standard floating-food screw profile. The two die inserts each had six 3-mm openings. Operating conditions, such as feed screw rate, water rates, and temperature set points, were held constant, and product density remained uniform. A fourth ration was a commercial feed (Silver Cup Steelhead Crumble, Nelson & Sons, Murray, UT, USA). The four rations had uniform contents of protein (46%, 9% moisture basis) and lipid (16%), and similar calcium, inorganic phosphorus, lysine, methionine, cysteine, threonine, tryptophan, and choline levels, and caloric content (3,880 kcal/kg).

Yellow perches (*Perca flavescens*) were fed for 6 months in 12 tanks at the Northern Aquaculture Center (Carrington, ND, USA). The tanks corresponded to three replicates each of the four different floating-type rations. Diets were randomly assigned to tanks within replicates. Fish were stocked at 100 fingerlings per 680-L tank. Each tank had an independent filter, and was maintained at 21°C and a photoperiod of 16 hr light:8 hr dark. Water pH, temperature, and un-ionized ammonia levels were checked weekly. Fish were fed to satiation twice daily, and feed weight recorded. Fish weight was recorded monthly. Feed conversion ratio, weight gain, and survival were determined at the completion of the study.

Analysis of fish muscle and liver for linoleic acid, α-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) contents was performed as follows: Samples of muscle and liver tissues from fish harvested at the end of the 6-month period were frozen immediately and shipped to the Bioprocessing Laboratory at NDSU for fatty acid analysis. Oil content was determined by extraction from freeze-dried samples in a Soxhlet apparatus, followed by solvent evaporation under vacuum. An aliquot of the oil was hydrolyzed in NaOH, and the fatty acids were converted into methyl esters and analyzed using a Hewlett-Packard GC (model HP5890, Avondale, PA, USA).

Statistical analysis ANOVA and Duncans Multiple Range Test were performed using the General Linear Model Procedure (SAS System for Windows, release 8.2, SAS Institute, Cary, NC, USA).

Results and Discussion

Dehulling study Pearling 'Dry' seed increased embryo and fines yields relative to pearling 'As Is' seed. Hull yield was not improved by drying. However, a previous investigation showed oil and SDG contents of the fines fraction to be nearly identical to hull particles (6); thus, the sum of fines yield + hull yield in Table 1 better indicates yield of SDG-rich fractions. The decreased moisture content may make the hull more brittle. Intact plus cracked seed (data not shown) accounted for the remainder of the flaxseed. Fraction oil content was not significantly affected by drying ($P \leq 0.05$; Table 1). Based on these oil contents, the SDG contents of embryo and hull fractions were expected to be 2 to 6 and 17 to 18 mg/g, respectively (6).

Doubling the pearler feed rate relative to the baseline feed rate of 75 g/min reduced the embryo, fines, and hull yields by half (Table 1). Consequently, the productivity (yield × feed rate) of each fraction remained almost constant; the increased feed rate merely served to dilute the product with intact seed. This feed rate comparison demonstrated the limited capacity of this pearler system. Subsequently, an impact dehuller was developed, modeled after commercial-scale impact dehullers for sunflowers and other crops. The impact dehuller achieved lower hull yield and embryo purity relative to the pearled 'As Is' trial, but similar embryo yield and hull purity (Table 1). The much

Table 1. Yield and oil content of flaxseed produced by either a pearler or an impact dehuller.

	Yield (g/kg seed)			Oil Content (%)		
	Embryo	Hull	Fines	Embryo	Hull	Fines
As Is	218[b]	179[c]	64[f]	52.4[a]	27.4[d,e]	29.6[c,d]
Dry	393[a]	171[c]	114[d,e]	50.4[a]	28.0[c,d,e]	30.1[c]
High	123[d]	87[e]	32[g]	n.d.	n.d.	n.d.
Impact	230[b]	115[e,f]	116[d,e]	47.0[b]	26.9[c]	n.d.

'As Is' denotes seed dehulled with moisture as received (9%) and a baseline feed rate of 75 g/min; 'Dry' seed was dried to 5% before dehulling at the baseline rate; 'High' seed was fed as received at twice the baseline rate (150 g/min); and 'Impact' denotes the use of an impact dehuller with seed at 6.6% moisture at 1,000 g/min.
Yields and contents having the same letter to the right of the mean value are not significantly different (P≤0.05).
n.d. = not determined

higher capacity of the impact dehuller necessitated its use in the subsequent studies involving dehulled flaxseed.

Screw press study Dehulled flaxseed could not be pressed under the conditions used to press whole seed, but instead formed a stationary plug within the screw press barrel. Dehulled flaxseed has a much higher oil content and much lower fiber content than whole seed, and thus is a substantially softer material. However, the dehulled seed was successfully pressed by use of a screw having a greater flight-to-flight distance.

Screw press performance differed in striking ways between dehulled and whole seeds. Oil yield steadily increased with decreased moisture content in the case of whole seed, down to the minimum moisture content (6.1%) at which whole seed could be pressed. However, in the case of dehulled seed, the maximum oil yield was achieved at 9.9% moisture content, and then decreased with further decrease in moisture content (Fig. 2A). Oil yield from whole seed was generally superior, although the advantage was only slight (77% versus 73%) at the optimal moisture content for dehulled seed. On the other hand, the initial oil content of dehulled seed was much higher than that of whole seed (49% versus 42%, dry basis), and use of a screw with greater flight-to-flight distance resulted in a higher press rate, given the same shaft speed. Consequently, maximum oil productivity in kg oil/hr from dehulled seed was twice that from whole seed (Fig. 2B).

Another difference between pressing of dehulled versus whole flaxseed was that the oil temperature was much lower in the case of dehulled flaxseed. The temperature of oil from whole seed increased from 50 to 65°C as moisture content decreased from 6.1 to 11.6%, reflecting the high fiber content of the seed and the increased frictional effects associated with a higher oil yield. In contrast, temperature of oil removed from dehulled seed was only 35°C and independent of moisture content. Press temperature is a concern with flaxseed oil, because a high temperature may accelerate oxidation of α-linolenic acid. Consequently, edible flaxseed oil is typically pressed in small screw presses to minimize thermal stress. Processors typically market this product as "cold-pressed oil". There is no universally accepted definition for the term "cold-pressed", although 50°C is the upper limit allowed in some countries.

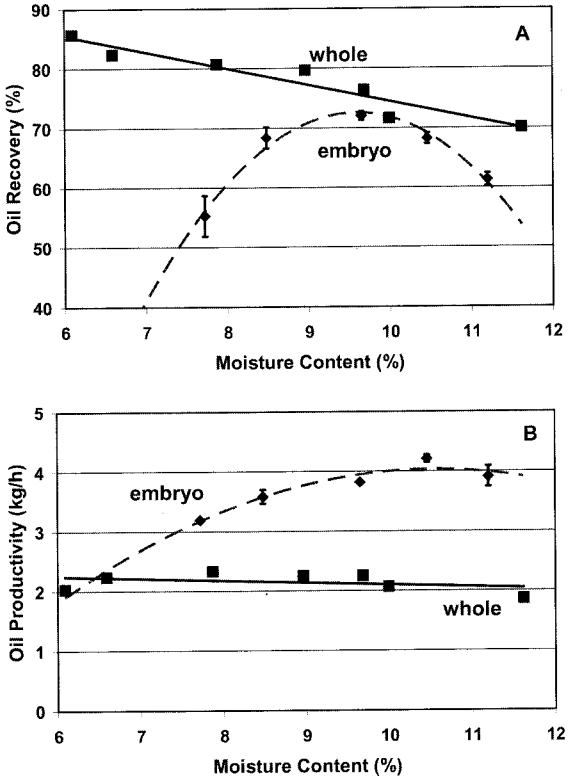

Fig. 2. Oil recovery (A) and oil productivity (B) from whole flaxseed (diamond) and dehulled flaxseed or 'embryo' (square) conditioned to different moisture contents before screw pressing. Error bars denote standard deviation of duplicates.

Storage stability study All samples stored at room temperature in closed packages showed very good lipid stability throughout the full 30 weeks of storage. For example, the peroxide value remained below 1 for all samples and storage times. The one exception was steam-ground seed, which reached a peroxide value of 3 at 30 weeks. The conjugated diene and free fatty acid contents also remained very low and showed little or no change from the initial sample. These results were similar to other reports on stability of ground flaxseed (15) and flaxseed pasta (16). Moisture content ranged from 5 to 8% upon entering storage, and gradually decreased to 4 to 6% after 30 weeks storage.

Moderate to severe lipid oxidation was detected in samples stored under the elevated-temperature/open-air conditions that were expected to stress the lipid (Fig. 3). The relative stability of samples was as follows: whole seed > hull, embryo > whole-ground > steamed-ground. Lipid in whole seed showed no significant deterioration, which was expected due to the protective seed coat. Moderate levels of degradation were observed in lipid from stored hull and embryo fractions. It was thought *a priori* that the high lignan content of the hull might make that lipid more stable than embryo lipid, because lignan is known to have antioxidant properties; however, values of PV, CD, and FFA were similar between these two fractions. Whole, ground seed was much less stable than hull and embryo fractions, probably because of the higher

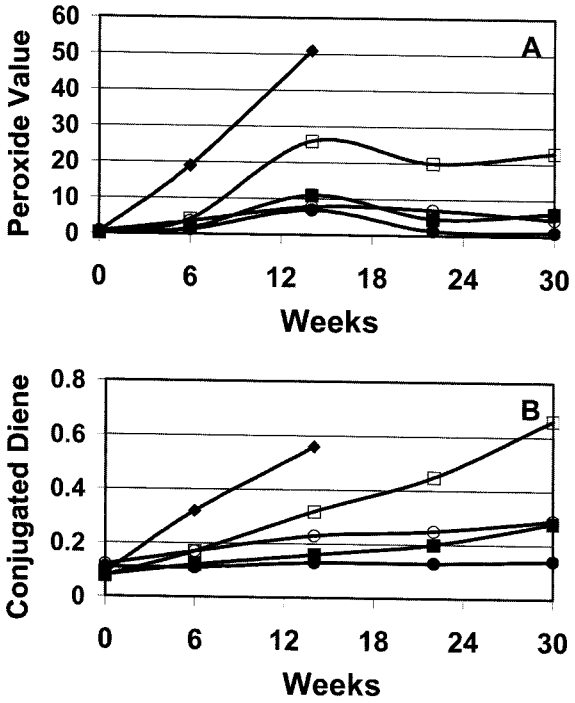

Fig. 3. Peroxide value (A) and conjugated dienoic acid content (B) for oil from flaxseed stored at 40°C in open trays. Treatments were whole, intact flaxseed (filled circle); whole, ground flaxseed (open square); flaxseed hull (open circle); flaxseed embryo (filled square); and steamed, ground flaxseed (filled diamond).

surface-to-volume ratio in ground seed. Steamed-ground seed showed the poorest stability, with a peroxide values in excess of 10 and 100 after storage for 6 and 22 weeks, respectively. The yield of lipid from the steamed product decreased with storage time, indicating the need for a more polar solvent. It was thought *a priori* that steaming would have a protective effect. The conditions used should have inactivated any lipase or lipoxygenase that could potentially degrade lipid; however, steaming also likely disrupts protective cell membranes, directly stresses the lipid, and may reduce antioxidant tocopherol levels. Moisture contents were 5 to 8% at the outset of storage, but decreased to 2 to 4% after 6 weeks storage, and remained within this range thereafter.

Aquaculture study Yellow perch raised on diets containing 0, 9, and 18% dehulled flaxseed contained progressively more α-linolenic acid (ALA) and less linoleic acid in muscle tissue (fillets) with increased flaxseed addition (Table 2). The content of ALA in liver-tissue lipid showed virtually the same increase, rising from 0.5 to 13.7% with the same increased flaxseed addition (data not shown). The dehulled flaxseed and vegetable oil used in the rations were high in ALA and linoleic acid, respectively; thus, the relative amounts of these two fatty acids in the perch reflected the relative amounts of flaxseed oil and vegetable oil in the rations.

The maximum, net increase in contents of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) with flaxseed addition was 0 to 1% in muscle and 2 to 3% in liver lipids. DHA and EPA may be created *in vivo* from

Table 2. Content of major polyunsaturated fatty acids in lipids from yellow perch muscle raised on rations containing 0 to 18% dehulled flaxseed and a commercial feed (n=3).

Ration	Fatty Acid (mean ± sd as % of total)			
	Linoleic	ALA	EPA	DHA
0% flaxseed	26 ± 3	0.68 ± 0.04	4.0 ± 0.4	9.2 ± 0.3
9% flaxseed	18 ± 1	7.3 ± 0.4	4.1 ± 0.4	9 ± 1
18% flaxseed	9.0 ± 0.5	13 ± 4	4.8 ± 0.0	9.7 ± 0.2
Commercial feed	6.2 ± 0.1	1.10 ± 0.03	8.2 ± 0.7	11 ± 1

Table 3. Yellow perch performance on rations containing dehulled flaxseed

Ration	Feed conversion ratio	Weight gain (%)	Survival (%)
0% flaxseed	3.9[a]	170[a]	81[a]
9% flaxseed	6.2[a]	130[a]	63[a,b]
18% flaxseed	3.6[a]	150[a]	83[a]
Commercial feed	4.1[a]	190[a]	52[b]

Means (n=3) followed by the same letter in a column were not significantly different (P≤0.05).

ALA; however, the DHA and EPA in this case were mainly derived from fish oil, which contributed 45% of the lipid in the rations.

The purpose of dehulling flaxseed before incorporation into feed was to maintain a low fiber content in the feed; fish do not thrive on a high-fiber diet (13). The performance of the yellow perch on the flaxseed rations was comparable to that on two controls (0% flaxseed and commercial feed; Table 3). The best (lowest) feed conversion ratio was achieved with the highest flaxseed diet, and the best (highest) percentage weight gain by the commercial feed control. However, neither result was statistically different from the others (P≤0.05) because of variability within replicates. Survival for all rations was lower than expected, and may reflect lack of hardiness in the fingerlings or environmental stress. Feed conversion ratio is the weight of feed consumed per weight of fish produced. Feed conversion ratios in this study were low relative to typical industry conversions (1 to 1.5), again reflecting lack of hardiness or stress. Even though the feeds used in this study were meant to float, a high proportion of the pellets processed by us immediately sank, thus it was difficult to judge the amount of feed required to feed to satiation. This contributed to the high feed conversion ratios and probably increased fouling of the water, but the poor floating characteristic would not be difficult to overcome.

These results point the way towards flaxseed diets as a low-cost alternative for boosting the content of omega-3 fatty acids in farm-raised fish. This may be an increasingly attractive alternative as the supply of marine fish oil tightens and the public recognizes the importance of dietary omega-3 fats. The removal of the flaxseed hull is a low-cost method for obtaining an acceptable low-fiber ration.

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