

FINAL REPORT

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Project Title: “Purification of pollock oil using short path distillation”

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PROJECT ABSTRACT

The beneficial health effects of a diet rich in long chain polyunsaturated omega-3 fatty acids (LC- ω 3-PUFAs) have been fully described in recent years. Marine oils are an important dietary source of LC- ω 3-PUFAs, being especially rich on two of the most important fatty acids of this class namely, EPA (eicosapentaenoic acid; 20:5 ω 3) and DHA (docosahexaenoic acid; 22:6 ω 3). Due to its nutritional value, there is growing interest in refining fish oil for human consumption. In Alaska there are large quantities of fishery byproducts being used for the production of fishmeal and fish oil. Most fish oil produced in Alaska is crude or unrefined, thus it can only serve as an ingredient for animal feed, unless further processing steps are included to handle fishery byproduct components as raw materials for the production of food. In this case, unrefined human-grade fish oil can be produced and may be further purified to meet specifications. The aim of this research was to investigate the applicability of short-path distillation for the purification of pollock oil produced at sea and pollock liver oil produced under laboratory conditions. Pollock oils were subjected to short-path distillation and a significant decrease in free fatty acids and lipid oxidation products was observed. As a result, purified oils met the quality standard specified for edible fish oils. The main advantages of using this technology, as compared to traditional fish oil purification steps, are that it reduces the use of chemicals during processing and subsequent effluent discharge volumes, and it decreases the number of steps needed to refine fish oils.

INTRODUCTION AND BACKGROUND

The beneficial health effects of a diet rich in long chain polyunsaturated omega-3 fatty acids (LC- ω 3-PUFA's) have been fully described in recent years (Kinsella, 1987; Gurr, 1999; Gunstone, 2003). There has been convincing evidence provided by several independent research groups showing that these fatty acids have a positive effect on preventing the development of cardiovascular diseases (Gurr, 1999; Gunstone, 2003). LC- ω 3-PUFA's provide protection against development of different types of tumors, are claimed to have anti-inflammatory properties, and can play a role in boosting the immune system (Gunstone, 2003). Additionally, LC- ω 3-PUFA's are essential to proper brain and retina development in infants, are used to ameliorate rheumatoid arthritis and related disorders, have been successfully administered to treat symptoms related with a variety of neuropsychiatric disorders such as schizophrenia, depression and maniac-depressive illness. These oils are also precursors to mainly metabolites essential to humans such as hormones and prostaglandins (Gunstone, 2003). Marine oils are an important dietary source of LC- ω 3-PUFA's, being especially rich in two of the most important fatty acids of this class namely, EPA (eicosapentaenoic acid; 20:5 ω 3) and DHA (docosahexaenoic acid; 22:6 ω 3) (Gurr, 1999; Gunstone, 2003). Due to its nutritional value, there is growing interest in refining fish oil for human consumption. Refined human grade fish oil can be consumed in the form of a nutraceutical (fish oil capsules), or it can be added as an ingredient to boost levels of LC- ω 3-PUFA's in various food items such as baked goods, orange juice and yogurt among others (Barrow et al., 2006).

Presently, the aquaculture feeds industry consumes approximately 75% of the current total global fish oil production (Figure 1), up from 15% 12 years ago (Oliveira et al., 2008). It has been estimated that by 2010, increasing aquaculture production will exhaust existing global fish oil supplies and an additional 380,000 T of oil from other sources will be required. Currently, most of the fish oil used in aquaculture feeds is produced from non-food fisheries focused on forage species in Peru and Northern Chile, along the Mexican and Central American Pacific coasts, the US Gulf and Atlantic coasts, Norway, Iceland and other regions. Most of these industrial fisheries are harvested at sustainable levels and increased oil production from these sources is unlikely (Oliveira et al., 2008). Fish oils extracted from Alaskan seafood processing by-products can increase the amount of fish oil in the Americas. Alaskan fish oil production, while difficult to document, is probably between 30,000 and 45,000 T per annum (Oliveira et al., 2008). The volume of oil that could be extracted from Alaska seafood by-products could be upwards of 70,000 T. The value of fish oil will continue to rise and demand for product in future years will increase further; thus, an increase in fish oil production from Alaska fisheries byproducts is likely to increase harvest profits for seafood processors in the State.

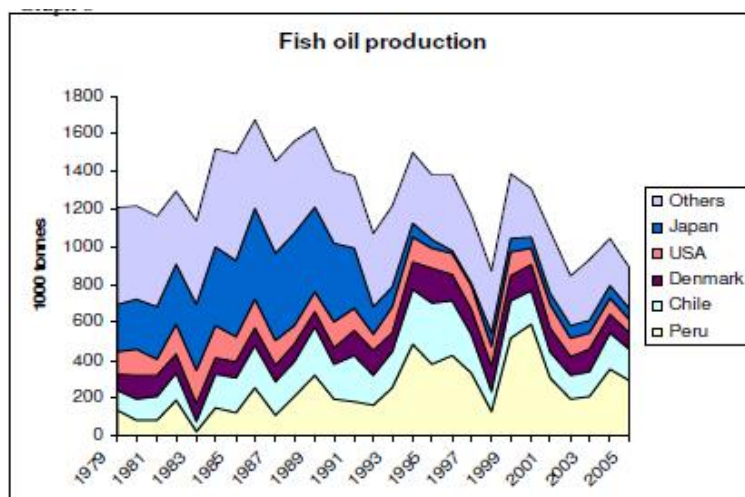


Figure 1. Global fish oil production (FAO, 2007)

In Alaska, large quantities of fishery byproducts are already utilized for the production of fishmeal and fish oil. However, most fish oil produced is crude; only serving as ingredient for animal feed. The demand and value of human-grade fish oils is also on the rise, and Alaska seafood processors may profit from producing food-grade fish oils. This can be achieved by including further processing steps to handle specific fishery byproduct components as raw materials for the production of food-grade fish oil. In this case, unrefined or crude human grade fish oil can be produced and may be further purified to meet specifications. Alaska walleye pollock (*Theragra chalcogramma*), the largest volume fishery in Alaska, is harvested during set seasons that are spread throughout the year. Different from salmon byproducts that are only available during part of the year, the availability of pollock byproducts allows seafood processors in Alaska to offer a constant supply of pollock oil to buyers (Oliveira and Bechtel, 2005). The combination of volume and availability make pollock byproducts appealing raw materials for the production of human grade fish oil.

Among pollock byproducts, livers are of particular interest due to their high content of lipids (Oliveira and Bechtel, 2005). Pollock is similar to cod concerning their ability to store lipid reserves in the liver tissue (Shahidi, 2007). Pollock and Pacific cod (*Gadus macrocephalus*) muscle are lean and may vary from as low as 0.5% to about 1.4% lipids (Oliveira and Bechtel, 2006a), while livers may contain as much as 50% lipids depending on season, sexual maturity and overall health of the animal (Oliveira and Bechtel, 2006b; Bechtel and Oliveira, 2006). During gonad development, sexually mature fish utilize lipids (energy) from their liver for ovary (females) or testes (males) development (Babbitt, 1990). Soon after spawning, pollock will slowly start accumulating lipids in the liver tissue to allow for gonad development during the following spawning season (Babbitt, 1990). Therefore, pollock livers may make up as much as 10% of whole fish weight during the summer, the season in which fish are actively feeding (Babbitt, 1990). During spawning (late winter-early Spring), gonads may make up as much as 19% of whole fish weight (Babbitt, 1990). Kizevetter (1971) recorded a yearly range of 1.6% to 10% of weight ratio of pollock livers to whole fish. It is important to establish the differences in lipid content for pollock livers for the different harvest seasons, and its impact on oil recovery and chemical characteristics of the refined product. Livers can be easily separated from other viscera components during processing of pollock and used for the production of human grade pollock oil (Bechtel and Oliveira, 2006; Oliveira and Bechtel, 2006b).

Traditionally, fish oil purification is composed of four consecutive steps. These are degumming, neutralization, bleaching and deodorization. Degumming aims at the removal of soluble and insoluble impurities such as proteins, phospholipids, waxes and trace metals (Young, 1978). Degumming is accomplished by washing the oil with an aqueous solution of an organic acid such as citric acid under mild heat (Dijkstra and Opastal, 1989). Neutralization is used to remove free fatty acids and this is accomplished by treating the degummed fish oil with caustic soda (aqueous solution) under mild heat (Young, 1978). This step is also called saponification, and produces soap that needs to be washed off with demineralized water. It is noteworthy to mention that the processing waste resulting from degumming and neutralization steps need to be properly handled for discarding according to EPA regulations. Bleaching the neutralized fish oil further purifies it by removing pigments, traces of soap, sulfur- and carbonyl-containing compounds, pigment breakdown products and trace metals (Young, 1978). Bleaching is accomplished by treating the oil with an absorbent such as activated earth (bleaching clay), activated carbon, or chitosan (Sathivel and Prinyawiwatkul, 2004). Deodorization is the final purification step and consists of removing aldehydes and ketones that are responsible for the peculiar fish oil odor, which in most cases is not appealing to consumers. Aldehydes and ketones are formed during lipid oxidation, and this degradation of fatty acids may occur during raw material handling and storage, and/or during the rendering process. The bleached fish oil is subjected to deodorization by distilling off the carbonyl-containing volatiles (Gavin, 1978).

In summary, the general objective of purification is to remove impurities that have negative health effects and detrimental sensorial impact to edible oils such as odor and taste (Bimbo, 1998). Table 1 presents the quality guidelines for crude fish as previously summarized by Bimbo (1998). As pointed out by the author, the quality guidelines for purified fish oils still lack specificity for several of the parameters listed in Table 1 as ‘no standard’ (Bimbo, 1998; Bimbo 2009). Many quality parameters serve as an indication of the abundance of lipid oxidation products. Lipid oxidation products do not only impart unpleasant taste and smell to fish oils but they also exert cytotoxic and genotoxic effects (Halliwell and Chirico, 1993; Esterbauer, 1993). Ingestion of these compounds may cause low density lipoprotein cytotoxicity (Morel et al., 1983), atherogenesis and arteriosclerosis (Kubow, 1993), and liver enlargement indicating nutrition-induced toxicity (Nwanguma et al., 1998). For these reasons, it is critical to monitor the quality and oxidative stability of edible fish oils (Shahidi, 2007).

Table 1. Chemical characteristics of crude and refined fish oil

Quality guidelines	Crude fish oil	Potential problem areas and potential parameter disadvantages	Codex specification (CAC/RS 19-1981 Rev. 1 1989) for refined oils
Moisture and impurities (%)	Usual basis 0.5 up to 1% max	Considered an impurity. High levels of moisture in an oil can lead to deterioration in storage	0.2% 0.1% max**
Free fatty acid (% oleic acid)	1-7% (usually 2-5%)	High FFA values may indicated poor-quality raw material or deterioration during oil storage	0.1% max** 3 (Acid value) which corresponds to approximately 6 % FFA*
Peroxide value (PV)	3-20 meq/ Kg	Primary measure of rancidity (oxidation) in an oil or fat. It measures the abundance of primary products of oxidation	10 meq/ Kg oil max virgin and cold-presses oils; 5 meq/ Kg oil max other oils 5 meq/ Kg nutraceutical grade oil*

			5 meq/ Kg max**
<i>p</i> -Anisidine number (<i>p</i> -AV)	4-20 4-60*	Measures secondary products of oxidation	>20* 10 max**
Thiobarbituric acid value (TBA)	No standard	Measure secondary products of oxidation	No standard
Iodine index	95-200	Iodine index is a measure of the unstauration in oils. This standards depend on fish species with capelin having the lowest value range (95-160) and anchovies the highest (180-200)	No standard
Iron (ppm)	0.5-7	Considered a pro-oxidant in fish oil, normally removed during degumming and refining	1.5 ppm max in refined oils; 5 ppm max in virgin oils; 5 ppm in cold-pressed oils
Copper (ppm)	Less than 0.3	Considered a pro-oxidant in fish oil, normally removed during degumming and refining	0.1 ppm max in refined oils; 0.4 ppm max in virgin oils; 0.4 ppm in cold-pressed oils
Phosphorus (ppm)	5-100	Reflects the abundance of phospholipids in the oil, which can degrade during storage	No standard
Color Gardner	less 14	Dark-colored oils may be crude and contain contaminants normally removed by refining, or the color may indicate overheating during refining	No standard 5**

Source: Bimbo,1998; * Source: Bimbo 2009; ** Source: OmegaPure edible menhaden oil specifications (http://www.omega-pure.com/productinfo_specs.html; last accessed Jan 2010)

Molecular distillation offers advantages for separation, purification and/or concentration of natural products, usually constituted by complex and thermally sensitive molecules such as fat-soluble vitamins and PUFAs, because it minimizes losses caused by thermal degradation (Fregolente et al., 2006; Batistella and Maciel, 1998). In this context, short-path distillation (SPD) provides an alternative to the traditional fish oil purification process by removing unwanted free fatty acids, deodorizing (removes aldehydes and ketones), and removing environmental contaminants under low pressure conditions (<http://www.uic-gmbh.de/index.php?lang=en>; last accessed Jan 2010). One of the main advantages of using this technology, as compared to traditional fish oil purification steps, is that SPD does not require chemical treatments during processing, thus reducing processing effluents and decreasing the number of steps needed to refine fish oils. The schematic sketch of an SPD unit, designed by Pope Scientific Inc., is shown in Figure 2. The sample to be purified by SPD, after being fed into the ‘still’, is subjected to low pressure (high vacuum) and is immediately spread into a very thin film (rotating wiper blades or rollers) while being forced down the evaporator surface. Heated walls (orange) and high vacuum (yellow) drive the more volatile components (distillate) to the closely positioned internal condenser, as the less volatile components (residue) continue down the cylinder. The resulting fractions are separated and exit through individual discharge outlets. Depending on the application, the desired product is either the distillate or the residue fraction. Condensable low MW

compounds are collect in the cold trap upstream of the vacuum system (<http://www.popeinc.com/>).

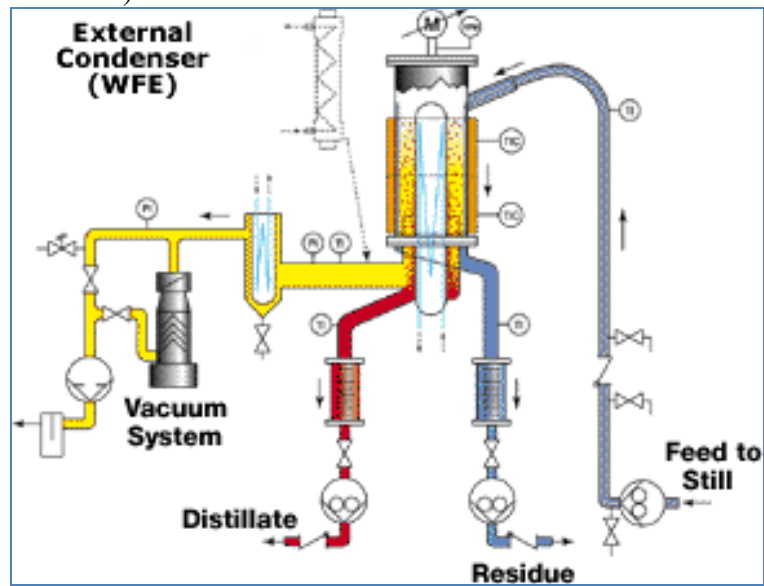


Figure 2. Schematic sketch of an SPD unit (<http://www.popeinc.com/>)

Short-path distillation has a wide range of applications especially suitable for purification, separation, or fractionation of heat sensitive substances or mixtures such as fish oil. A variety of chemicals, pharmaceuticals, intermediate plastic products, cosmetics, mineral oil products and food ingredients and additives can be distilled for purification or enrichment using this technology. In the case of fish oils, SPD can be applied for the production of concentrates, physical refining, and removal of pollutants or undesirable minor components (<http://www.uic-gmbh.de/index.php?lang=en>; last accessed Jan 2010). Omega-3 fatty acids concentrates can be prepared using SPD through fractionation of their ethyl ester counterparts. This technology is especially useful to prepare LC- ω 3-PUFA concentrates because the short chain fatty acid esters C-14 to C-18 can be distilled off easily. The resulting ester mixture is mainly composed of C-20 and C-22 fatty acid esters in which EPA and DHA are predominant. A secondary concentration step may also be added that can result in a fraction containing up to 70% LC- ω 3-PUFA's (Breivik et al., 1997). Physical refining of edible oils is easily accomplished using SPD. This technology enables removal of free fatty acids and volatile compounds that impart off-flavors and off-odors (lipid oxidation products) to fish oils. During SPD-assisted fish oil refining, the most volatile compounds can be removed at temperatures ranging from 80 °C to 160 °C (<http://www.uic-gmbh.de/index.php?lang=en>; last accessed Jan 2010). Operated at higher temperatures (<200 °C) SPD will remove heavier compounds such as environmental contaminants, sterols, and other higher molecular weight compounds. Care must be taken at this stage to preserve nutrients such as fat-soluble vitamins (<http://www.uic-gmbh.de/index.php?lang=en>; last accessed Jan 2010). When compared to steam stripping in a classical column, one important advantage of SPD is the removal of free fatty acids under low operating temperatures. Moreover, SPD reduces the use of chemicals, production of effluents, and it decreases oil loss. The removal of persistent organic pollutants (POPs) such as dioxins and furans may also be of interest, especially for fish oils derived from aquacultured fish species grown in waters surrounding industrialized centers or for oils derived from wild caught fish known to have higher levels of POPs (Breivik, 2007). Overall, SPD brings different options within the refining and processing of edible oils and offers promises for the purification of human grade

fish oil. There is a need to evaluate this process for the production of human grade oils from Alaska byproducts.

PROJECT OBJECTIVES

This research had three main objectives:

1. Determine quality parameters in crude pollock oil produced at sea by catcher processor vessels harvesting pollock in the Bering sea during early Spring months (Mar.; Pollock A season), and early Fall months (Sept.; Pollock B season).
2. Render fish oil from pollock livers from fish harvested in the Bering Sea during early Spring months (Mar.; Pollock A season), and early Fall months (Sept.; Pollock B season) using low temperature processing (50 °C and 60 °C). Determine the quality parameters of crude oils rendered in the laboratory, and compare them with the values established for oils produced at sea.
3. Investigate the applicability of short-path distillation to refine crude pollock oils produced at sea and crude pollock oils rendered under laboratory conditions, and determine the quality parameters of the purified oils.

STUDY/FIELD WORK

This research aimed to add value to the largely under-valued pollock by-products. Development of the SPD technology in this area will also reduce the environmental impact of the process. The PCCRC research priorities (2007) included the following (<http://www.sfos.uaf.edu/pcc/rfp07/index.html>):

“Analyses of the nutritional characteristics of Alaska pollock, and how those characteristics vary by product form and processing strategy.”

Our research proposal fitted well within the above research priorities, and filled a void in this area, as suggested by the list of previously funded recent projects. (<http://www.sfos.uaf.edu/pcc/projects/07/index.html>).

It is important to point out that worldwide demand for human grade fish oil will continue to rise. Presently, little human grade fish oil is produced in Alaska (Bechtel, 2007). It is possible to establish a chain of custody over fishery byproducts during processing. In addition, byproduct components such as fish livers can be segregated during fish processing and handled as raw material for the production of human grade crude fish oil (Bechtel and Oliveira, 2006; Oliveira and Bechtel, 2006b). Establishing the chemical characteristics of crude and refined pollock liver oil, and its variability with season, is of interest to Alaska seafood processors that plan on tapping the growing domestic and international markets for fish oil. Investigating the applicability of a purification method that minimizes processing effluents may help Alaska seafood processors to establish the viability of implementing short-path distillation technology to produce a high quality and high value product produced from pollock byproducts. Results from this project can also be of use in future years for cost analysis of both, crude and purified human grade pollock liver oil production. Moreover, our results will be of value to individuals interested in conducting further experiments to

determine the variables affecting ‘scaling up’ (from laboratory bench to pilot plant trials) production and purification of pollock liver oils. Finally, our findings can be readily applicable for the extraction and purification of fish oil from Pacific cod livers, a valuable byproduct of the second largest fisheries in Alaska.

SAMPLES / METHODS

Sample procurement

In the first week of September Mr. Richard Draves (VP Product Development, American Seafoods Co.) and Dr. Oliveira traveled to Dutch Harbor to organize the collection of samples. The fishmeal and fish oil operations of two American Seafoods catcher processor vessels were visited (*F/T American Triumph* and *F/T Northern Jaeger*) and it was decided that the catcher-processor *F/T American Triumph* could produce a trial run of pollock liver oil during Fall of 2008. American Seafoods Co. (Seattle, WA) kindly donated pollock livers and fish oil samples (Figure 3). Samples were collected from catcher processor vessels (Figure 3) fishing pollock in the Bering Sea during Fall (season B) of 2008 and Spring (season A) of 2009. Table 2 and Table 3 provide the complete inventory of samples received during the course of this study. American Seafoods personnel separated fresh livers from viscera components, immediately after catch, and froze the material in blocks (7.5 Kg) onboard of the *F/T American Triumph* (Figure 3). Liver blocks were shipped from Dutch Harbor directly to Kodiak within 60 days of frozen storage. Fish oils were rendered onboard of catcher processor vessels during A and B seasons as indicated in Table 4. Pollock oils were rendered from a mixture of pollock byproducts with and without addition of antioxidant (250 ppm ascorbyl palmitate) during both fishing seasons. Hake oil (*Merluccius productus*) was rendered from a mixture of hake byproducts during late Fall of 2008. Pollock liver oil with and without antioxidant (250 ppm ascorbyl palmitate) was only produced during Fall 2008. The oils produced at sea were rendered from byproducts by passing fresh raw material through a sequence of three inline horizontal cookers operated at about 85-90 °C. Product cook time was less than 2 min through the series of contherms. The cooked material was then separated into oil, water, and a protein sludge using a three-phase centrifuge operated at ~ 85 °C. Ascorbyl palmitate, a GRAS (Generally Recognized as Safe # 182.3149, US Food and Drug Administration) fat soluble antioxidant with no restrictions for usage level, was mixed to the centrifuged crude commercial pollock oil samples at a ratio of 250 mg/ Kg (Timm-Heinrich et. al., 2007).



Figure 3. (A) Catcher processor vessel *F/T American Triumph* (American Seafoods Co).
(B) North Pacific Ocean Map.

Table 2. Pollock liver samples inventory

Type of material	Sample weight		Vessel identification	Product date (package)
	Lb	Kg		
Pollock livers	299.2	136.0	<i>F/T American Triumph</i>	09/04/2008
Pollock livers	49.4	22.5	<i>F/T Northern Hawk</i>	03/08/2009
Pollock livers	142.3	64.7	<i>F/T American Triumph</i>	03/11/2009
Pacific cod livers	40.0	18.1	<i>F/V Deep Pacific</i>	07/31/2008
Pacific cod livers	40.1	18.2	<i>F/V North Cape</i>	07/25/2008
Pacific cod liver	51.5	23.4	<i>F/T Katie Ann</i>	03/18/2009
Pacific cod liver	53.0	24.1	<i>F/T Katie Ann</i>	03/31/2009

Table 3. Fish oil samples inventory

Type of material	Sample volume		Vessel Identification	Comments	Product date (package)
	Gal	L			
Pollock oil	3	12.5	<i>F/T American Triumph</i>	with Ascorbyl palmitate	10/22/2008
Pollock oil	4	15	<i>F/T American Triumph</i>	without Ascorbyl palmitate	11/10/2008
Pollock oil	4	15	<i>F/T American Triumph</i>	without Ascorbyl palmitate	11/10/2008
Pollock oil	2.5	9.5	<i>F/T Northern Eagle</i>	without Ascorbyl palmitate	11/10/2008
Pollock liver oil	1.6	6	<i>F/T American Triumph</i>	with Ascorbyl palmitate	11/10/2008
Pollock liver oil	2.1	8	<i>F/T American Triumph</i>	without Ascorbyl palmitate	11/10/2008
Pollock liver oil	2.5	10	<i>F/T American Triumph</i>	without Ascorbyl palmitate	11/10/2008
Hake oil	2.4	9	<i>F/T American Triumph</i>	without Ascorbyl palmitate	11/18/2008
Pollock oil	2.7	10	<i>F/T American Triumph</i>	with Ascorbyl palmitate	03/12/2009
Pollock oil	2.7	10	<i>F/T American Triumph</i>	without Ascorbyl palmitate	03/12/2009
Pollock oil	4	9.5	<i>F/T Northern Hawk</i>	with Ascorbyl palmitate	03/08/2009
Pollock oil	4	9.5	<i>F/T Northern Hawk</i>	without Ascorbyl palmitate	03/08/2009

Rendering liver oils

The process steps used to render liver oils in the laboratory is shown in Figure 4. This process followed the process of rendering oil from catfish viscera with modifications (Sathivel et. al., 2003).

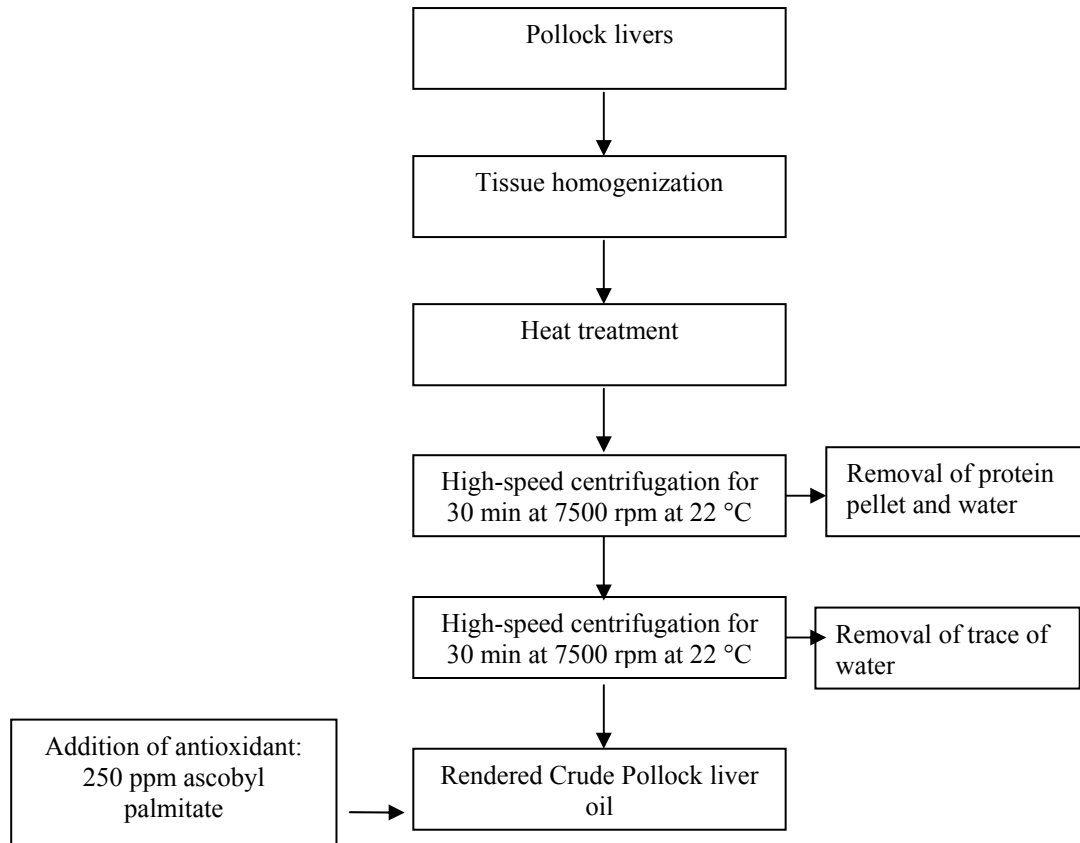


Figure 4. Schematics of the laboratory procedure to render oil from pollock livers

Fall liver oils were rendered as five independent process replicates for each combination of time (30 min; 15 min) and temperature (50 °C; 60 °C). A total of 25 Kg of frozen liver (*F/T American Triumph*) were thawed (about four 7.5 Kg liver blocks), mixed and homogenized to liquid slurry using a commercial blender for 2 minutes at 21,000 rpm. Homogenized livers were stored in 0.5 L glass vials under nitrogen atmosphere and frozen at -35 °C. Storage of homogenates did not exceed 60 days. Liver homogenates (500 g) were heated in a silicon bath to either 50 °C or 60 °C for 30 min or 15 min with constant agitation, as shown in Figure 5. Processing yields for liver oils and liver protein powders were recorded for the five replicates of all four combinations of time (15 min; 30 min) and temperatures (50 °C; 60 °C). Liver protein powders were produced by freeze-drying the liver protein pellet, recovered after first centrifugation. Powders were produced using a Virtis Freezer Dryer (Model35 ES) using a four drying stages program as follows: Stage 1:-20 °C; Stage 2: 0 °C; Stage 3: 10 °C; and stage 4: 25 °C for 1,000 minutes/stage. Protein powders were vacuum packaged and frozen at -80 °C until analysis. Ascorbyl palmitate was added in small increments under continuous stirring to each of the oil samples rendered in the laboratory, while the product was still warm (~50 °C), to a final concentration of 250 ppm (Timm-Heinrich et al., 2007). Oils were stored at -80 °C under nitrogen in glass vials wrapped with aluminum foil. Each rendered fish oil (n=20) and protein powder (n=20) sample from Fall 2008 livers were chemically and physically characterized independently, and results were then average for each group. For

Spring livers, the rendering process was also repeated five times but only carried out at 60 °C for 30 min. Each rendered oil (n=5) and protein powder (n=5) sample from Spring 2009 livers were chemically and physically characterized independently, and results were then average for this group.

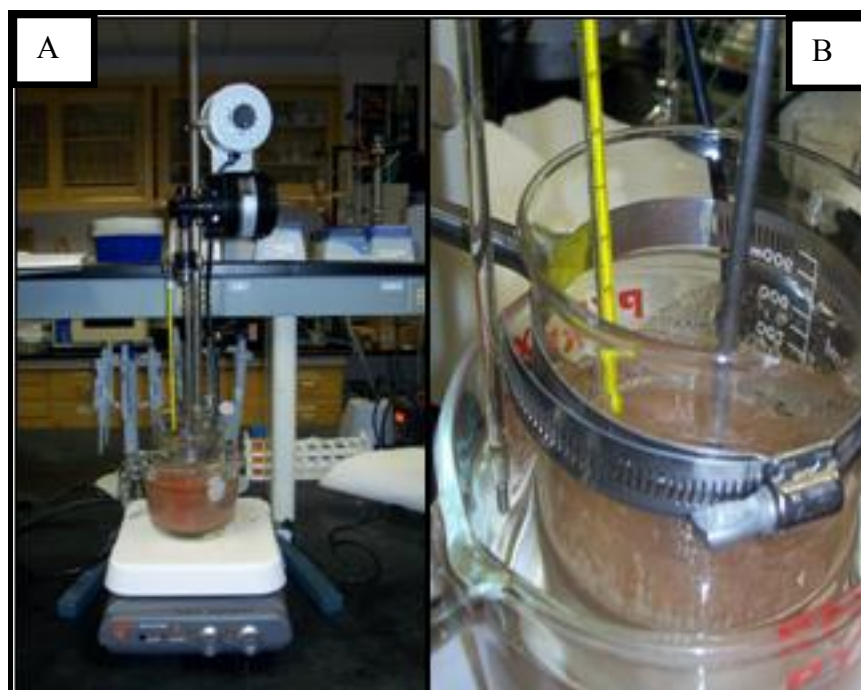


Figure 5. Laboratory apparatus to render oil from pollock liver. (A) Depicts the entire system; (B) Depicts only the sample receptacle, stir bar and thermometers

Purification of fish oil using short-path distillation

The SPD distillation process was conducted using a combination of processing variables in a sequence similar to the ones reported by Breivik et al. (1997), Liang and Hwang (2000), Fregolente et al. (2006), Xu et al. (2002), and Timm-Heinrich et al. (2007) with modifications. Distillation was conducted in a two-step procedure (two passes), commonly used to remove fish oil impurities. Figure 6 depicts the SPD unit and all components of the system. The SPD cold-trap was filled with dry-ice manufactured with a Frigimat dry-ice maker (Bel-Art Scienceware, Lake Charles, CA) connected to a carbon dioxide tank fitted with a dipping tube. A portion of 500 mL of crude fish oil was added to the graduated feed flask (Figure 7A) and the heating tape was set to 60 °C (Figure 7B) to decrease the viscosity of the oil entering the evaporator (Fregolente et al., 2006). The first distillation (first pass) aims at degassing the oil and mainly removes water and highly volatile compounds. Pre-distillation of the oils (first pass) took place with sole aid of the high vacuum pump, thus the diffusion pump was not used during this processing stage. The system parameters were as follows: internal condenser temperature 55 °C; evaporator temperature 150 °C; feeding rate 6-8 mL/ h; roller speed 500 rpm (or 450 rpm); vacuum 0.05-0.06 mbar; high-vacuum pump setting 'on'; diffusion pump settings 'off' and 'closed'. After the degassed oil was collected in the receiving flask, the system was brought back to 1,013 mbar (1 atm) of pressure by turning the high-vacuum pump off and simultaneously opening the upper valve of the feed flask to the nitrogen line. The SPD remained under nitrogen atmosphere while the oil was quickly transferred back to the feed flask (60 °C). The main fish oil distillation (second pass) served to remove most oil impurities from the degassed oil. The second pass was conducted under much lower pressure using both, the high-vacuum pump and the diffusion pumps. The diffusion pump required about 20 min to warm-up; only then the diffusion pump valve could

be set to the 'open' position. The system parameters in the second distillation step were as follows: condenser temperature 55 °C; evaporator temperatures were 190 °C, 200 °C or 210 °C (to test the effect of this variable); evaporator temperature step increase 10 °C/ min; feeding rate 6-8 mL/ h; roller speed 500 rpm or 450 rpm (to test the effect of this variable); vacuum 0.01-0.02 mbar; high-vacuum pump setting 'on'; diffusion pump settings 'on' and 'open'. The refining yields were determined gravimetrically.

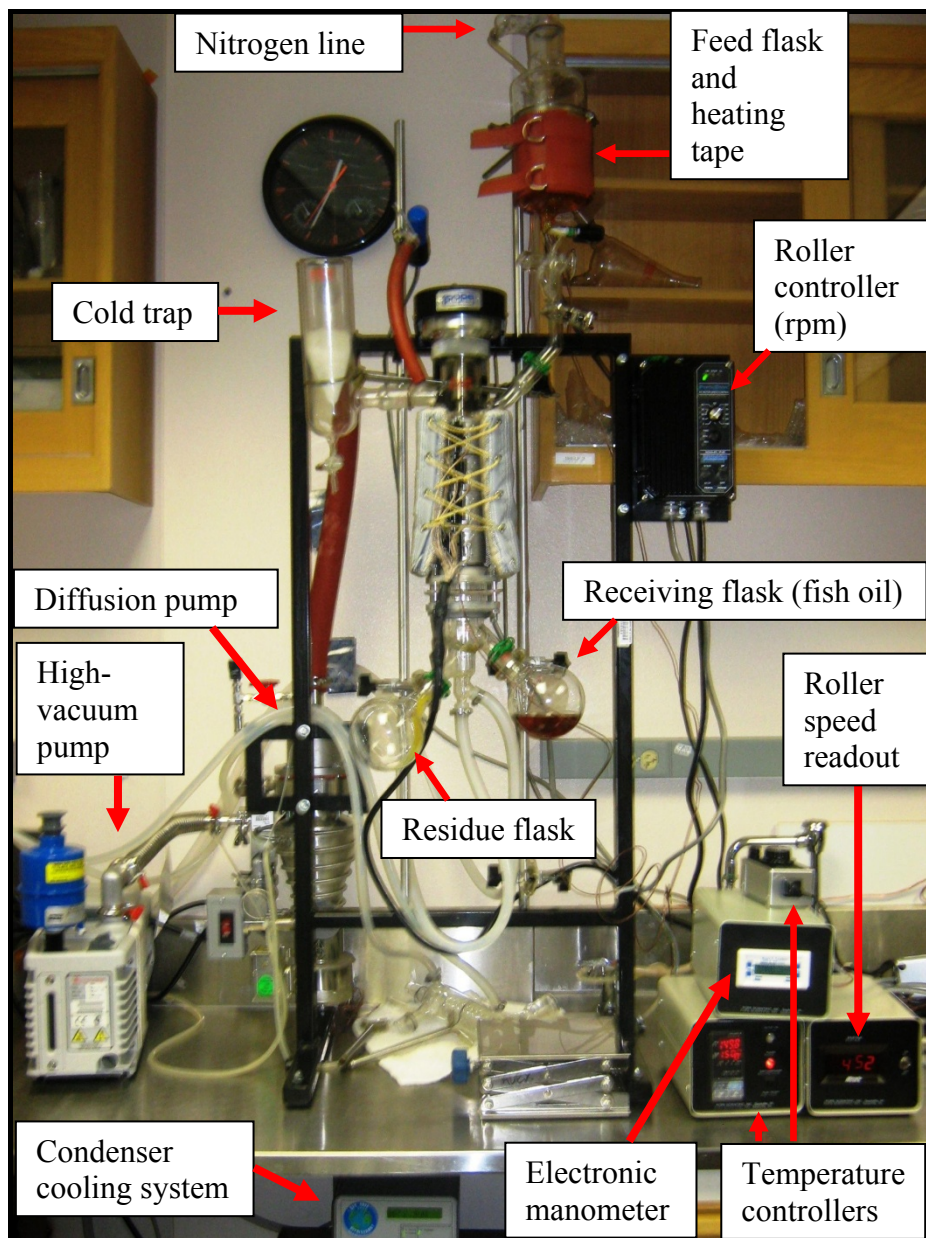


Figure 6. Short-path distillation system

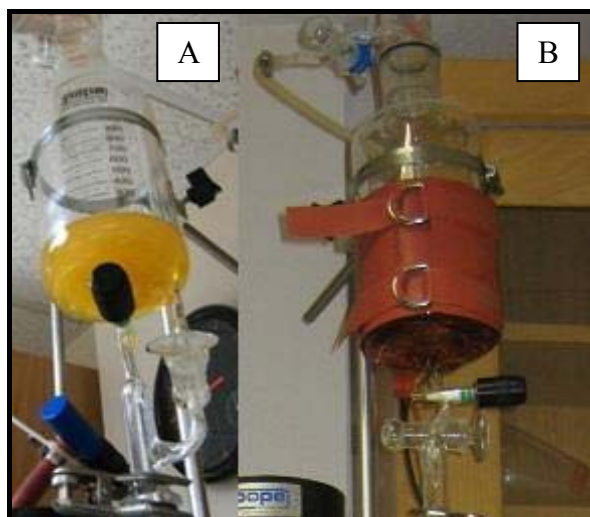


Figure 7. SPD feed flask. (A) Without the heating tape; (B) With heating tape and depicting the nitrogen line connected to the upper fitted joint of the flask

Table 4 shows the experimental design conducted to establish the optimal settings for the SPD unit variables. For trial 1 (Table 4) each combination of system pressure, speed and evaporator temperature was conducted in triplicate using as test sample pollock oil with ascorbyl palmitate (POAP) produced by the *F/T American Triumph* during Fall 08. First, the evaporator temperatures were compared with roller speed set to 500 rpm, which is the upper speed limit of the equipment. Three samples originated from the first pass (evaporator temperature = 150 °C), and nine samples from the second pass (evaporator temperatures 190 °C, 200 °C or 210 °C). Figure 8 depicts the four receiving flask glass joint (commonly referred to as ‘cow’) that allows collection of multiple oil fractions that passed through the evaporator at different temperatures. The evaporator temperature can be programmed to discrete step increases using the evaporator temperature controller (Figure 7). Figure 8 shows POAP fractions purified at 190 °C, 200 °C and 210 °C and the distilled residue (impurities) in the residue receiving flask. Purified POAP fractions were chemically characterized and it was determined that 210 °C was the most adequate evaporator temperature. A second trial (trial 2; Table 4) was conducted in triplicate at reduced roller speed (450 rpm), with evaporator temperatures set for 150 °C during first pass, and 210 °C during the second pass (Table 4).

Table 4. Experimental design to determine SPD parameters

Trial	Distillation steps	Pressure (mbar)	Flow rate (mL/min)	Roller* speed (rpm)	Evaporator temperature (°C)
1	First Pass	0.05-0.06	6.0 – 8.5	500	150
1	Second Pass	0.01	6.0 – 8.5	500	190
1	Second Pass	0.01	6.0 – 8.5	500	200
1	Second Pass	0.01	6.0 – 8.5	500	210
2	First Pass	0.05-0.06	6.0 – 8.5	450	150
2	Second Pass	0.01	6.0 – 8.5	450	210

*Also referred to as ‘wiper-blades’



Figure 8. SPD system. (a) Evaporator showing exposed heating elements and fitted with one receiving flask and one residue flask; (b) Receiving flask glass joint adaptor ('cow') fitted with four receiving flasks

After determining the SPD parameters, the following oils were refined using the conditions described in Table 4 for trial 2: *F/T American Triumph* Fall 08 pollock liver oil with ascorbyl palmitate, *F/T American Triumph* Spring 09 pollock oil with ascorbyl palmitate (SPOAP), *F/T American Triumph* Fall 08 pollock oil with ascorbyl palmitate, and Fall 08 and Spring 09 liver oils rendered in the laboratory at 60 °C for 30 min. For each of these oil samples the refining process was replicated three times using the following SPD processing parameters:

- 1st distillation step (pre-distillation; 1st pass): Internal condenser temperature 55 °C; evaporator temperature 150 °C; feeding rate 6-8 mL/ h; roller speed 450 rpm; vacuum 0.05-0.06 mbar; high-vacuum pump on; diffusion pump off.

- 2nd distillation step (2nd pass): Internal condenser temperature 55 °C; evaporator temperature 210 °C; feeding rate 6-8 mL/ h; roller speed 450 rpm; vacuum 0.01-0.02 mbar; high-vacuum pump on; diffusion pump on.

The internal condenser temperature was controlled by standard laboratory water recirculation system with cooling and heating capacity, set to 55 °C. The refining yields were determined gravimetrically, after samples were cooled to room temperature under nitrogen atmosphere wrapped in aluminum foil. Purified oils were transferred to storage glass flasks wrapped in aluminum foil, and stored under nitrogen atmosphere at -80 °C until analysis.

Chemical and physical analyses

Table 5 shows detailed information about the fish oil samples investigated and the type of analyses conducted.

Table 5. Sample identities, codes and types of analysis conducted

Sample code	Sample identity	Chemical analyses	Physical analysis
Pollock livers	Fall 08 and Spring 09 pollock livers (<i>F/T American Triumph</i>)	Proximate composition, fatty acids	
Hake	Late Fall 08 hake oil (<i>F/T American Triumph</i>)	Fatty acids, minerals, vitamins and environmental contaminants (POP)	
FPO	Fall 08 pollock oil without AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, minerals, vitamins and environmental contaminants (POP)	Color and water activity

FPOAP	Fall 08 pollock oil with AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, minerals, vitamins and environmental contaminants (POP)	Color and water activity
FLO	Fall 08 liver oil without AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, minerals, vitamins and environmental contaminants (POP)	Color and water activity
FLOAP	Fall 08 liver oil with AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, minerals, vitamins and environmental contaminants (POP)	Color and water activity
SPO	Spring 09 pollock oil without AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids and minerals	Color and water activity
SPOAP	Spring 09 pollock oil with AP (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids and mineral analysis	Color and water activity
50 FLOAP 30'	Liver oil rendered at 50 °C for 30 min from Fall 08 pollock livers (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, vitamins and minerals	Color and water activity
60F LOAP 15'	Liver oil rendered at 60 °C for 15 min from Fall 08 pollock livers (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, vitamins and minerals	Color and water activity
60 FLOAP 30'	Liver oil rendered at 60 °C for 30 min from Fall 08 pollock livers (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids, vitamins and minerals	Color and water activity
60 SLOAP 30'	Liver oil rendered at 60 °C for 30 min from Spring 09 pollock livers (<i>F/T American Triumph</i>)	FFA, PV, AV, TBA, phosphorus content, lipids classes, fatty acids and mineral analysis	Color and water activity
FPOAP 190°C	Fall 08 pollock oil with AP (<i>F/T American Triumph</i>) after purification at 190°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
FPOAP 200°C	Fall 08 pollock oil with AP(<i>F/T American Triumph</i>) after purification at 200°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
FPOAP 210°C	Fall 08 pollock oil with AP (<i>F/T American Triumph</i>) after purification at 210°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
FLOAP 210°C	Fall 08 pollock liver oil with AP (<i>F/T American Triumph</i>) after purification at 210°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
SPOAP 210°C	Spring 09 pollock oil with AP (<i>F/T American Triumph</i>) after purification at 210°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
F60LOAP30` 210°C	Liver oil rendered at 60 °C for 30 min from Fall 08 pollock livers (<i>F/T American Triumph</i>) after purification at 210°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity
S60LOAP30` 210°C	Liver oil rendered at 60 °C for 30 min from Spring 09 pollock livers (<i>F/T American Triumph</i>) after purification at 210°C	FFA, PV, AV, TBA, phosphorus content, lipids classes and fatty acids	Color and water activity

F5015`	Liver protein power from Fall 08 pollock livers (<i>F/T American Triumph</i>) obtained at 50 °C for 15 min	Proximate composition, FFA, PV, AV, TBA, and amino acid analysis	
F5030`	Liver protein power from Fall 08 pollock livers (<i>F/T American Triumph</i>) obtained at 50 °C for 30 min	Proximate composition, FFA, PV, AV, TBA, and amino acid analysis	
F6015`	Liver protein power from Fall 08 pollock livers (<i>F/T American Triumph</i>) obtained at 60 °C for 15 min	Proximate composition, FFA, PV, AV, TBA, and amino acid analysis	
F6030`	Liver protein power from Fall 08 pollock livers (<i>F/T American Triumph</i>) obtained at 60 °C for 30 min	Proximate composition, FFA, PV, AV, TBA, and amino acid analysis	
S6030`	Liver protein powder from Spring 09 pollock livers (<i>F/T American Triumph</i>) obtained at 60 °C for 30 min	Proximate composition, FFA, PV, AV, TBA, phosphorus content and amino acid analysis	

AP ascorbyl palmitate; F Fall; S Spring; PO Pollock oil; LO liver oil

Proximate analysis

Proximate composition was conducted as an average of three determinations for each replicate sample of fish oil and fish protein powder. Moisture and ash content were determined using AOAC (2005) methods #952.08 and #938.08, respectively. Nitrogen content was determined by pyrolysis with a LECO FP-2000 nitrogen analyzer (Leco Co., St. Joseph, MO). Protein content was calculated as 6.25 times %N. Total lipid content was determined gravimetrically by the method of Folch et al. (1957). After lipid extraction, solvent was removed at 49 °C on a rotary evaporator (Büchi Rotavapor R-205, Westbury, NY) and lipids were transferred into a pre-weighed 10 mL amber screw top vial. The remaining solvent was removed under a N₂ gas stream until constant weight and percent lipids were determined gravimetrically. Oils were stored in hexane containing 0.01% BHT at -80 °C until analysis.

Rancidity and oxidative stability analyses

Rancidity and oxidative stability analysis was determined as an average of two determinations for each replicate sample of fish oil or fish protein powder. The percent free fatty acids (%FFA as oleic acid), the peroxide values (PV), the *p*-anisidine values (*p*-AV), and the 2-thiobarbituric acid values (TBA) were determined using AOCS official methods # Ca 5a-40, Cd 8b-90, Cd 18-90 and Cd 19-90, respectively.

Phosphorus content

The phosphorus content was determined as an average of two determinations for each replicate sample of fish oil using AOCS Ca12-55. The value was expressed in % ppm

Water activity

The water activity was determined as an average of two determinations for each replicate sample, and it was conducted at room temperature using a water activity meter (AquaLab, model Series 3TE, Decagon Devices, Inc., Washington, DC)

Color

Color was determined only in fish oil samples using a Gardner Delta Color Meter (BYK-Gardner, Columbia, MD). This instrument provides Gardner Delta Color Values (GDCV), which were determined as an average of two independent readings for each replicate fish oil sample. This instrument was specifically designed for the determination of oil color, thus it is widely used in the fish oil industry worldwide. The GDCV is based on the standard color scale for oils provided with the instrument.

Lipids classes

An Iatroscan™ TLC/FID Analyzer model MK-6s (Iatron Laboratories Inc., Tokyo, Japan) was used to determine percent area for triacylglycerols (TAG), 1,2-diacylglycerols (1,2-DAG), monoacylglycerols (MAG), free fatty acids (FFA), 1,3-diacylglycerols (1,3-DAG) and sterols (ST), and phospholipids (PL) in the lipid samples. Materials and methods used for lipid class analysis were adapted from Whitsett et al. (1986), Parrish (1987) and Ackman et al. (1990) as previously described (Oliveira and Bechtel, 2006b). Lipid classes were reported as percent TAG, 1,2-DAG, MAG, FFA, PL and the combined percentages of ST and 1,3-DAG. Results were reported as an average of two analyses for each replicate fish oil sample.

Preparation of fatty acids methyl esters and gas chromatography analysis

Fatty acid methyl esters (FAME) were prepared using KOH and methanol as described by Maxwell and Marmer (1983). FAMEs were transferred into 1.5 mL snap-cap amber GC vials (Agilent Technologies, Wilmington, DE) and immediately analyzed. Fatty acid profiles were determined with a GC model 6850 (Agilent Technologies, Wilmington, DE) fitted with a DB-23 (60 m x 0.25 mm id., 0.25 µm film) capillary column (Agilent Technologies, Wilmington, DE). An autosampler performed the GC injections and injection volume was 1 µL. The chromatographic conditions were as previously described by Bechtel and Oliveira (2006). Fatty acids analysis results were reported as an average of two analyses for each sample investigated.

Mineral analysis

Oils and protein fractions were analyzed for mineral content as single observations for sample replicate. Samples for mineral analysis were sent to the School of Natural Resources and Agricultural Sciences Palmer Research Center (Palmer, AK) for analysis. Samples were placed in a furnace operated at 550 °C for 12 h. Ash residues were digested overnight in an aqueous solution containing 10% (v/v) hydrochloric acid and 10% (v/v) nitric acid. Digested solutions were diluted as needed and analyzed for P, K, Ca, Mg, S, Na, Cu, Fe, B, Co, Mo, Mn, and Zn by inductively coupled plasma optical emission spectroscopy on a Perkin Elmer Optima 3000 Radial ICP-OES (Perkin Elmer, Waltham, MA).

Amino acids analysis

Amino acid profiles were determined by the AAA Service Laboratory Inc. (Boring, OR) as single observations for each sample replicate. Samples were hydrolyzed with 6N HCl and 2% phenol at 110 °C for 22 h. Amino acids were quantified using the Beckman 6300 analyzer with post column ninhydrin derivatization. Tryptophan and cysteine content were not determined.

Fat-soluble vitamins

Quantification of the fat soluble vitamins A, D, E and K was carried out to Warren Analytical Laboratories, Inc. (Greeley, CO), and results are reported as single observations. The methods used for vitamins A, D, and E were NOVIT 3.1 (KraftUSA Analytical Test

procedure), AOAC Official Method #995.05 (AOAC, 2005) and method described by Kayden (1983), respectively.

Environmental contaminants

Quantification of 39 environmental contaminants carried out by Minnesota Valley Testing Laboratories, Inc. (MVTL, New Ulm, MN) as single observations for each sample. The official method EPA 8082/3545 was used for the analysis.

Statistical analysis

Statistical analysis was conducted using Statistica 9.0 (Statsoft, Tulsa, AZ, OK). Analysis of variance was performed independently for the datasets resulting from the different experiments conducted, as follows:

- One-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between Fall and Spring pollock livers using season as variable;
- Two-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between liver protein powders using temperature (50 °C; 60 °C) and time (15 min; 30 min) as variables;
- Two-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between pollock liver oils using temperature (50 °C; 60 °C) and time (15 min; 30 min) as variables;
- One-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between Fall and Spring pollock liver oils rendered in the laboratory for 30 min at 60°C using season as variable;
- One-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between crude and purified pollock oils with AP produced at sea (*F/T American Triumph*) during Fall 2008 using evaporator temperature (150 °C; 190 °C; 200 °C; 210 °C) as variable;
- One-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between purified (evaporator T= 210°C) pollock oils with AP produced at sea (*F/T American Triumph*) during Fall 2008 using evaporator speed (450 rpm; 500 rpm) as variable;
- One-way ANOVA followed by Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between purified (evaporator T= 210°C; speed 450 rpm) pollock oils with AP produced at sea (*F/T American Triumph*) during Fall 2008 and Spring 2009, and pollock liver oils with AP produced at sea (*F/T American Triumph*) during Fall 2008 using type of oil as variable.
- One-way ANOVA followed by unequal Tukey HSD test ($P < 0.05$) was used to determine significant differences in composition between crude and purified (evaporator T= 210 °C; speed 450 rpm) Fall and Spring liver oils rendered in the laboratory.

RESULTS AND DISCUSSION

Chemical characterization of pollock livers

Table 6 shows the proximate composition of pollock livers harvested during A and B season. Lipid content from Fall pollock livers was significantly higher than Spring livers. Conversely, moisture and protein contents were significantly higher in Spring livers. The ash contents of Fall and Spring livers were similar. These results are in close agreement with previous findings (Babbitt, 1990; Bechtel and Oliveira 2006; Oliveira and Bechtel, 2006b).

Table 6. Proximate composition of pollock liver (% wt./ wt.)

Sample	Season	Protein	Lipid	Ash	Moisture
Pollock liver (n=3)	Fall	9.4±0.7 ^b	50.0±1.1 ^b	0.7±0.1 ^a	39.9±0.5 ^a
Pollock liver (n=3)	Spring	10.0±0.2 ^a	40.9±0.5 ^a	0.9±0.07 ^a	48.2±0.7 ^b

Different superscript letters within a column indicate statistical differences at P<0.05

Table 7 shows the FA profiles, reported in mg/ g of oil and in %wt./ wt. of the lipid fractions of Spring and Fall pollock livers obtained from chemical extraction of liver lipids (Folch et al., 1957). Data, reported in mg/ g of oil, showed that Fall livers had an average of 35 mg/ g oil of DHA and 71 mg/ g oil of EPA, while Spring livers had 30 mg/ g oil of DHA and 59 mg/ g oil of EPA. Other abundant FA shown in Table 7 are 16:0 (palmitic acid), 16:1 ω 7 (palmitoleic acid), 18:1 ω 9 (*cis*-oleic acid), 20:1 ω 11 (gadoleic acid), and 22:1 ω 11 (cetoleic acid). Only subtle differences in the fatty acid profiles were observed between Fall and Spring livers, despite the large difference in lipid content (~ 10%) reported in Table 6. This is in line with previous observations regarding differences in the fatty acids profiles between male and female pollock livers harvested in the Gulf of Alaska in waters surrounding Kodiak Island (Oliveira and Bechtel, 2006b). The large abundance of C-20 and C-22 monounsaturated ω 11 fatty acids in fish species of northern latitudes have been previously observed (Ackman, 1989a). The origin of these fatty acids in coldwater fish species have been attributed to type of feed, and copepods such as krill have been pointed out as rich sources for these fatty acids (Ackman 1989b; Ackman et. al., 1980). Spring livers had about 105 mg/ g oil and 89 mg/ g oil of 20:1 ω 11 (gadoleic acid), and 22:1 ω 11 (cetoleic acid), while Fall livers has significantly higher quantities of 20:1 ω 11 (gadoleic acid), and 22:1 ω 11 (cetoleic acid) at about 129 mg/ g oil and 105 mg/ g oil, respectively. During summer and early Fall months, Bering Sea pollock feeds heavily on krill and (personal communication with American Seafoods Co. VP Product Development Richard Draves) this explains the differences observed in abundance of these fatty acids in the liver oils extracted using a chemical method under laboratory conditions. Many of the fatty acids that show significantly different abundances between Fall and Spring livers reported in mg/ g oil, are not significantly different when values are reported in %wt./ wt. This is due to the fact that in Spring livers, the fraction of saponifiable matter in the extracted lipids is lower, but when values are converted to percent of total fatty acids, the saponifiable matter (mg/ g oil) is not taken into account.

Table 7. Fatty acids profiles of lipid fractions of pollock livers

Fatty acid	Fall pollock liver	Spring pollock liver	Fall pollock liver	Spring pollock liver
	(n=3) mg/ g of oil	(n=3) mg/ g of oil	(n=3) % wt./ wt.	(n=3) %wt./ wt.
14:0	41.58 ±0.4 ^a	33.32 ±0.7 ^b	5.66 ±0.0 ^a	5.31 ±0.1 ^b
14:1 ω 7	0.73 ±0.0 ^a	0.57 ±0.0 ^b	0.10 ±0.0 ^a	0.09 ±0.0 ^a
14:1 ω 5	1.02 ±0.0 ^a	0.82 ±0.0 ^b	0.14 ±0.0 ^a	0.13 ±0.0 ^a
Iso or Ante-iso 15:0	0.51 ±0.0 ^a	0.44 ±0.0 ^a	0.07 ±0.0 ^a	0.07 ±0.0 ^a
15:0	1.16 ±0.0 ^a	0.95 ±0.0 ^b	0.16 ±0.0 ^a	0.15 ±0.0 ^a
Iso or Ante-iso 16:0	1.48 ±0.0 ^a	1.28 ±0.0 ^b	0.20 ±0.0 ^a	0.20 ±0.0 ^a
16:0	63.12 ±0.5 ^a	53.14 ±1.1 ^b	8.59 ±0.0 ^a	8.48 ±0.1 ^b
16:1 ω 11	0.50 ±0.0 ^a	0.38 ±0.0 ^b	0.07 ±0.0 ^a	0.06 ±0.0 ^a
16:1 ω 9	1.14 ±0.0 ^a	0.92 ±0.0 ^b	0.16 ±0.0 ^a	0.15 ±0.0 ^a
Unknown 1	0.53 ±0.0 ^a	0.46 ±0.0 ^b	0.07 ±0.0 ^a	0.07 ±0.0 ^a
16:1 ω 7	75.27 ±0.6 ^a	66.43 ±1.4 ^b	10.65 ±0.0 ^a	10.60 ±0.2 ^b

16:1 ω 5	2.18 \pm 0.0 ^a	1.76 \pm 0.0 ^b	0.30 \pm 0.0 ^a	0.28 \pm 0.0 ^b
Unknown 2	0.82 \pm 0.0 ^a	0.62 \pm 0.0 ^b	0.11 \pm 0.0 ^a	0.10 \pm 0.0 ^a
Iso 17:0	0.43 \pm 0.0 ^a	0.36 \pm 0.0 ^a	0.06 \pm 0.0 ^a	0.06 \pm 0.0 ^a
Ante-iso 17:0	6.37 \pm 0.1 ^a	5.20 \pm 0.1 ^b	0.87 \pm 0.0 ^a	0.83 \pm 0.0 ^a
C17:0	4.94 \pm 0.1 ^a	3.82 \pm 0.1 ^b	0.67 \pm 0.0 ^a	0.59 \pm 0.0 ^b
17:1 ω 11	4.33 \pm 0.2 ^a	4.32 \pm 0.3 ^a	0.65 \pm 0.0 ^a	0.65 \pm 0.0 ^a
17:1 ω 9	0.67 \pm 0.0 ^b	0.59 \pm 0.1 ^a	0.09 \pm 0.0 ^a	0.09 \pm 0.0 ^a
Iso or Ante-iso 18:0	8.85 \pm 0.1 ^a	6.69 \pm 0.1 ^b	1.20 \pm 0.0 ^a	1.07 \pm 0.0 ^b
18:0	8.72 \pm 0.1 ^a	7.57 \pm 0.1 ^b	1.29 \pm 0.0 ^a	1.21 \pm 0.0 ^b
18:1 ω 11	1.07 \pm 0.0 ^a	0.81 \pm 0.1 ^b	0.15 \pm 0.0 ^a	0.13 \pm 0.0 ^b
18:1 ω 9 <i>trans</i>	16.64 \pm 0.1 ^a	13.26 \pm 0.2 ^b	2.27 \pm 0.0 ^a	2.11 \pm 0.0 ^b
18:1 ω 9 <i>cis</i>	43.00 \pm 0.3 ^a	39.94 \pm 0.8 ^b	6.37 \pm 0.1 ^a	5.85 \pm 0.0 ^b
18:1 ω 7	25.32 \pm 0.2 ^a	23.62 \pm 0.5 ^b	3.77 \pm 0.0 ^a	3.75 \pm 0.1 ^a
18:2 ω 6 <i>trans</i>	3.94 \pm 0.0 ^a	2.99 \pm 0.1 ^b	0.54 \pm 0.0 ^a	0.48 \pm 0.0 ^b
18:2 ω 6 <i>cis</i>	3.02 \pm 0.0 ^a	2.64 \pm 0.0 ^a	0.42 \pm 0.0 ^a	0.42 \pm 0.0 ^a
18:3 ω 6	2.50 \pm 0.0 ^a	2.05 \pm 0.1 ^b	0.64 \pm 0.0 ^a	0.33 \pm 0.0 ^b
18:3 ω 3	1.42 \pm 0.0 ^a	1.23 \pm 0.0 ^b	0.22 \pm 0.0 ^a	0.20 \pm 0.0 ^a
18:3 ω 4	7.82 \pm 0.1 ^a	6.48 \pm 0.1 ^b	1.06 \pm 0.0 ^a	1.03 \pm 0.0 ^a
18:4 ω 3	2.39 \pm 0.0 ^a	1.72 \pm 0.0 ^b	0.33 \pm 0.0 ^a	0.27 \pm 0.0 ^a
Iso or Ante-iso 20:0	0.00 \pm 0.0 ^b	0.17 \pm 0.0 ^a	0.00 \pm 0.0 ^a	0.03 \pm 0.0 ^a
20:0	0.46 \pm 0.0 ^a	0.31 \pm 0.4 ^a	0.06 \pm 0.0 ^a	0.05 \pm 0.0 ^a
Unknown 3	0.39 \pm 0.6 ^a	0.00 \pm 0.0 ^b	0.05 \pm 0.0 ^a	0.00 \pm 0.0 ^b
20:1 ω 11	128.57 \pm 0.9 ^a	105.42 \pm 1.9 ^b	17.50 \pm 0.0 ^a	16.81 \pm 0.2 ^b
20:1 ω 9	31.70 \pm 0.3 ^a	26.18 \pm 0.5 ^b	4.32 \pm 0.0 ^a	4.18 \pm 0.1 ^b
20:1 ω 7	1.94 \pm 0.0 ^a	1.78 \pm 0.1 ^b	0.26 \pm 0.0 ^a	0.28 \pm 0.0 ^a
20:1 ω 5	0.87 \pm 0.0 ^a	0.34 \pm 0.5 ^b	0.12 \pm 0.0 ^a	0.05 \pm 0.0 ^b
20:2 ω 6	0.78 \pm 0.0 ^a	0.72 \pm 0.0 ^a	0.11 \pm 0.0 ^a	0.11 \pm 0.0 ^a
20:3 ω 6	0.91 \pm 0.0 ^a	0.84 \pm 0.0 ^b	0.13 \pm 0.0 ^a	0.13 \pm 0.0 ^a
20:4 ω 3	1.98 \pm 0.0 ^a	1.64 \pm 0.0 ^b	0.27 \pm 0.0 ^a	0.26 \pm 0.0 ^a
20:5 ω 3 (EPA)	71.29 \pm 1.2 ^a	59.41 \pm 1.2 ^b	9.70 \pm 0.1 ^a	9.47 \pm 0.2 ^b
22:1 ω 11	104.89 \pm 1.2 ^a	88.94 \pm 0.7 ^b	14.28 \pm 0.0 ^a	14.19 \pm 0.2 ^a
22:1 ω 9	6.84 \pm 0.1 ^a	5.68 \pm 0.1 ^b	0.93 \pm 0.0 ^a	0.91 \pm 0.0 ^a
22:1 ω 7	1.94 \pm 0.0 ^a	1.68 \pm 0.0 ^b	0.29 \pm 0.0 ^a	0.27 \pm 0.0 ^a
22:2 ω 6	3.80 \pm 0.0 ^a	3.13 \pm 0.01 ^b	0.52 \pm 0.0 ^a	0.50 \pm 0.0 ^a
22:5 ω 3	5.50 \pm 0.1 ^a	4.52 \pm 0.1 ^b	0.75 \pm 0.0 ^a	0.72 \pm 0.0 ^a
22:6 ω 3 (DHA)	35.23 \pm 0.7 ^a	30.63 \pm 0.6 ^b	4.89 \pm 0.1 ^a	4.80 \pm 0.1 ^b
Unknown 4	1.76 \pm 0.0 ^a	1.49 \pm 0.0 ^b	0.25 \pm 0.0 ^a	0.24 \pm 0.0 ^a
24:1 ω 9	2.54 \pm 0.0 ^a	2.07 \pm 0.0 ^b	0.35 \pm 0.0 ^a	0.33 \pm 0.0 ^b
Saponifiables (mg/ g oil)	734.57 \pm 6.5 ^a	620.21 \pm 10.9 ^b	100.00 \pm 0.0 ^a	100.0 \pm 0.0 ^a
Total fatty acids (% wt./ wt.)				
Σ SAT	138.00 \pm 1.7 ^a	113.24 \pm 1.5 ^b	18.79 \pm 0.1 ^a	18.06 \pm 0.2 ^b
Σ MUFA	451.15 \pm 4.0 ^a	383.73 \pm 6.9 ^b	61.42 \pm 0.1 ^a	61.20 \pm 0.9 ^a
Σ PUFA	140.58 \pm 2.3 ^a	117.99 \pm 2.2 ^b	19.14 \pm 0.1 ^a	18.82 \pm 0.3 ^a
Σ ω -3	117.81 \pm 2.0 ^a	99.14 \pm 1.9 ^b	16.04 \pm 0.1 ^a	15.81 \pm 0.2 ^a
Σ ω -6	14.95 \pm 0.1 ^a	10.31 \pm 0.2 ^b	2.04 \pm 0.0 ^a	1.65 \pm 0.0 ^b
P/S	1.02 \pm 0.0 ^a	1.04 \pm 0.0 ^a	1.02 \pm 0.0 ^a	1.04 \pm 0.0 ^a
ω -3/ ω 6	7.88 \pm 0.1 ^b	9.61 \pm 0.0 ^a	7.88 \pm 0.1 ^a	9.61 \pm 0.0 ^a

Different superscript letters within a row indicate statistical differences at P<0.05

Processing yields of low temperature rendering of liver oils

Table 8 shows the laboratory processing yields resulting from rendering pollock liver oils at different temperatures (50 °C and 60 °C) and times (15 and 30 min). Oil recovery was similar for livers rendered at 50 °C and 60 °C for 30 min (~52%); however, yields were significantly higher when rendering was carried out for 30 min instead of 15 min (~44- 46%). Livers from

pollock harvested in Spring (S60LO30') had lower oil recoveries than oils produced from livers from pollock harvested in Fall (F60LO30'). This result was expected because the lipid content was significantly higher in Fall pollock livers than in Spring livers (Table 6). Protein recovery (protein pellet) determined for samples processed at 50°C for 15 min was significantly higher than all other combinations of processing time and temperature.

Table 8. Processing yields of Fall and Spring pollock liver oils rendered in the laboratory

Sample code	F50LO15'	F50LO30'	F60LO15'	F60LO30'	S60LO30'
Number of process replicates	(n=5)	(n=5)	(n=5)	(n=5)	(n=5)
Sample weight (g)	503.5 ± 1.3	504.5 ± 5.4	502.0 ± 2.1	502.9 ± 1.8	506.1 ± 3.1
Weight of oil after 1st centrifugation (g)	256.0 ± 2.3	293.4 ± 10.2	259.7 ± 2.1	289.1 ± 2.4	250.4 ± 1.09
Weight of oil after 2nd centrifugation (g)	225.2 ± 0.9	257.8 ± 6.0	230.8 ± 0.6	263.1 ± 4.1	213.0 ± 3.3
Weight of protein pellet after 1st centrifugation (g)	106.7 ± 3.1	82.63 ± 1.3	79.5 ± 2.1	82.0 ± 0.8	121.7 ± 2.0
Protein recovery (%)	21.1 ± 0.6 ^a	16.5 ± 0.3 ^b	15.8 ± 0.45 ^b	16.3 ± 0.2 ^{b_y}	23.3 ± 0.4 _x
Oil recovery (%)	44.7 ± 0.3 ^d	51.1 ± 0.9 ^b	46.0 ± 0.2 ^c	52.3 ± 0.8 ^{a_x}	41.3 ± 0.9 _y

F50LO15' Fall liver oil rendered at 50 °C for 15 min; F50LO30' Fall liver oil rendered at 50 °C for 30 min; F60LO15' Fall liver oil rendered at 60 °C for 15 min; F60LO30' Fall liver oil rendered at 60 °C for 30 min; S60LO30' Spring liver oil rendered at 60 °C for 30 min. Different superscript letters within a row indicate statistical differences due to rendering time and temperature for Fall samples (P<0.05). Different subscript letters within a row indicate statistical differences due to season for oils extracted at 60°C for 30 min (P<0.05)

Characterization of commercial oils and oils rendered in the laboratory

Lipid classes

Table 9 shows the results of lipid class analysis of crude fish oils. Statistical analysis was only conducted for lipid class results of oils rendered in the laboratory. All pollock oils were comprised mostly of triacylglycerols. Oils rendered in the laboratory had higher phospholipids, free fatty acids, and diacylglycerols/sterols as compared to the oils produced by catcher-processor vessel *F/V American Triumph*. Oils rendered at higher temperature (60 °C) for longer time (30 min) had significantly higher triacylglycerols and significantly lower phospholipids. These results indicate that rendering liver oils at 60 °C for 30 min results in oils with lipid classes profiles that seem more suitable for SPD distillation because under very low pressures PL can form a gel in the evaporator unit of the SPD disrupting the purification process (Xu et. al., 2002). It is important to point out that impurities in the oils will inflate estimates for the PL peak in the iatrosan chromatogram because the PL peak remains at the origin of the rod, where sample is placed for solvent elution. Therefore, it is likely that PL values shown in Table 9 are higher than the abundance of this lipid class. For this reason, an independent analysis that precisely quantifies phosphorus content (ppm) in the oils was carried out.

Table 9. Lipid classes analysis of pollock oils produced at sea (*F/T American Triumph*) and of pollock liver oils rendered in the laboratory (% wt./ wt.)

Oil sample codes	N	TAG	FFA	DAG/ST	MAG	PL
FPO	2	98.0	1.2	0.6	0	0.2
FPOAP	2	99.2	0	0.6	0	0.2
FLO	2	99.3	0.2	0.3	0	0.1
FLOAP	2	100	0	0	0	0
SPO	2	100	0	0	0	0
SPOAP	2	100	0	0	0	0

50 FLOAP 15'	5	86.9 ^c	5.4 ^a	4.8 ^a	0.5 ^a	2.4 ^a
50 FLOAP 30'	5	89.3 ^b	5.0 ^a	3.7 ^b	0.3 ^a	1.7 ^a
60F LOAP 15'	5	88.7 ^b	5.6 ^a	3.5 ^b	0.4 ^a	1.7 ^a
60 FLOAP 30'	5	91.5 ^{a_y}	3.5 ^{b_x}	3.4 ^{b_y}	0.6 ^{a_x}	1.0 ^{b_x}
60 SLOAP 30'	5	93.0 _x	4.3 _x	1.6 _x	0.0 _x	1.1 _x

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate; F50LO15' Fall liver oil rendered at 50 °C for 15 min; F50LO30' Fall liver oil rendered at 50 °C for 30 min; F60LO15' Fall liver oil rendered at 60 °C for 15 min; F60LO30' Fall liver oil rendered at 60 °C for 30 min; S60LO30' Spring liver oil rendered at 60 °C for 30 min; TAG triacylglycerols; FFA free fatty acids; DAG/ST diacylglycerols/sterols (co-eluting classes); MAG monoacylglycerols; PL phospholipids. Different superscript letters within a column indicate statistical differences due to rendering time and temperature P<0.05; Different subscript letters within a column indicate statistical differences due to season for oils extracted at 60 °C for 30 min (P<0.05).

Color

Color analysis results (GDC values) of fish oils are shown in Table 10. Commercial Spring pollock oils (A season) with and without additive were yellow (Figure 9) while commercial Fall pollock oils (B season) with and without additive were reddish orange (Figure 9). Bering Sea pollock feeds heavily on krill during summer and Fall and diet is the main cause of the orange/reddish color recorded for pollock oils produced from a mixture of pollock byproducts (FPO; FPOAP). Liver oils produced by the *F/T American Triumph* during Fall was light yellow; thus, indicating that the orange color of Fall pollock oil does not come from pollock liver tissue but from other pollock byproducts such as heads, frames and viscera components. Interestingly, the GDC value of liver oils rendered in the laboratory were lower for oils extracted at 60 °C, but as depicted in Figure 10 most oils were light yellow with the exception of oils rendered at 50 °C for 15 min, which were slightly darker.

Table 10. Color of pollock oils produced at sea (*F/T American Triumph*) and of pollock liver oils rendered in the laboratory

Oil sample codes	N	GDC value
FPO	2	11
FPOAP	2	12
FLO	2	4
FLOAP	2	4
SPO	2	6
SPOAP	2	7
50 FLO 15'	5	9
50 FLO 30'	5	5
60 FLO 15'	5	7
60 FLO 30'	5	4
60 SLO 30'	5	4

GDC Gardner Delta Color Meter; FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate; F50LO15' Fall liver oil rendered at 50 °C for 15 min; F50LO30' Fall liver oil rendered at 50 °C for 30 min; F60LO15' Fall liver oil rendered at 60 °C for 15 min; F60LO30' Fall liver oil rendered at 60 °C for 30 min; S60LO30' Spring liver oil rendered at 60 °C for 30 min

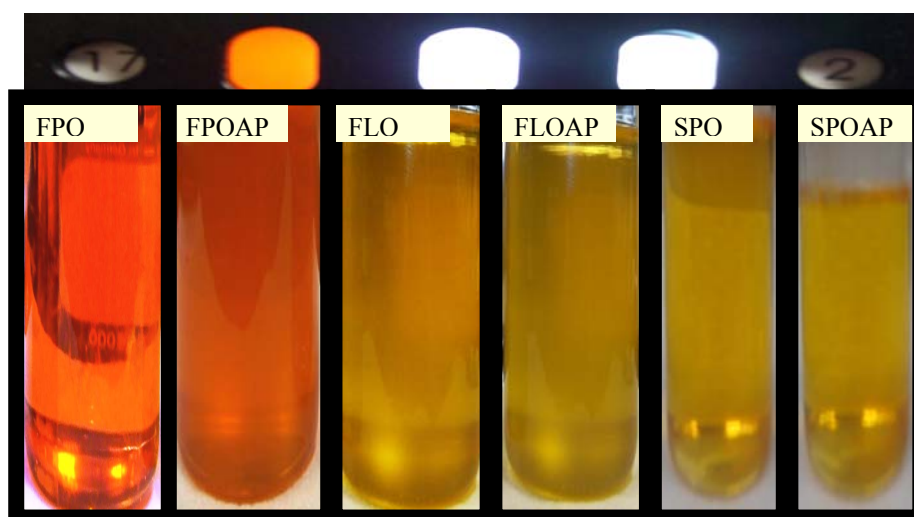


Figure 9. Picture of pollock oils produced by the *F/T American Triumph*

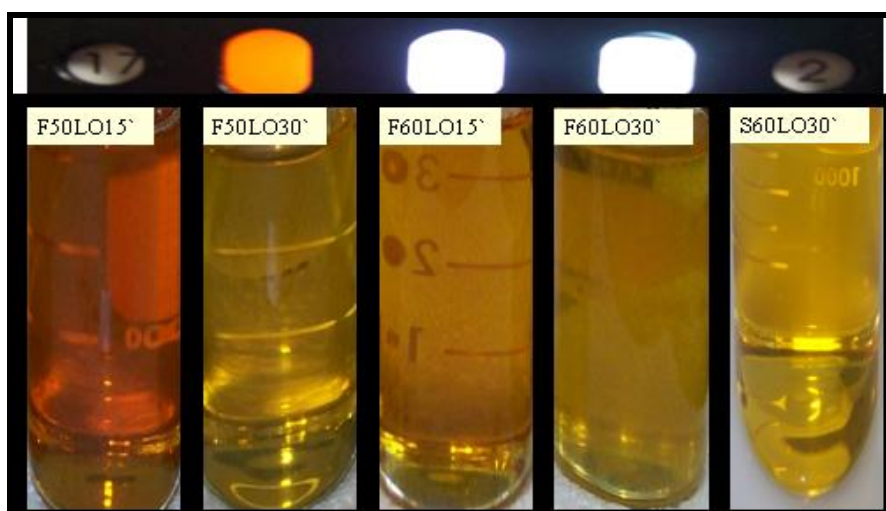


Figure 10. Picture of pollock liver oils rendered in the laboratory

Fatty acid profiles

Fatty acid profiles of hake oil are presented in Table 11. The fatty acid profile of hake was typical for cold-water fish species. Note that about 25% of the oil is comprised of omega-3 FA with DHA and EPA making up approximately 9% and 13% of the oil. Data in mg/ g of oil showed an average of 74 mg/ g oil of DHA and about 104 mg/ g oil of EPA. Other abundant FA were 16:0 (palmitic acid), 16:1 ω 7 (palmitoleic acid), and 18:1 ω 9 (*cis*-oleic acid). Hake oil has higher levels of ω -3 FA than pollock, especially due to the higher content of DHA. Conversely, the MUFAs in hake oil tend to be lower, with fewer quantities of ω -11 FAs than the ones found in pollock livers (Table 7).

Table 11. Fatty acids profile of hake oils produced at sea (*F/T American Triumph*)

Fatty acid	Hake oil (n=2) mg/ g of oil	Hake oil (n=2) % wt./ wt.
14:0	11.58 ± 0.0	1.44 ± 0.0
15:0	1.59 ± 0.0	0.20 ± 0.0
16:0	168.47 ± 0.1	20.88 ± 0.0
16:1 ω 11	1.71 ± 0.0	0.21 ± 0.0
16:1 ω 9	1.51 ± 0.0	0.19 ± 0.0

16:1 ω 7	48.31± 0.0	5.99± 0.0
16:1 ω 5	1.76 ± 0.1	0.22 ± 0.0
Iso 17:0	0.94 ± 0.0	0.12 ± 0.0
Ante iso 17:0	4.24 ± 0.0	0.53± 0.0
17:0	2.56 ± 0.0	0.32 ± 0.0
Unknown 1	10.13 ± 0.0	1.25 ± 0.0
17:1 ω 9	3.6 ± 0.0	0.45 ± 0.0
Iso or Anteiso 18:0	2.9 ± 0.0	0.36 ± 0.0
18:0	25.06 ± 0.1	3.11 ± 0.0
18:1 ω 9 <i>cis</i>	218.24 ± 0.0	27.04 ± 0.0
18:1 ω 7	48.34 ± 0.0	5.99 ± 0.0
18:1 ω 5	1.63 ± 0.0	0.2 ± 0.0
18:2 ω 6 <i>cis</i>	7.92 ± 0.0	0.98 ± 0.0
18:3 ω 6	2.23 ± 0.0	0.28 ± 0.0
18:3 ω 3	4.86 ± 0.0	0.60 ± 0.0
18:4 ω 3	10.27± 0.1	1.27 ± 0.0
Iso or Ante iso 20:0	1.3 ± 0.0	0.16 ± 0.0
20:1 ω 11	5.65 ± 0.0	0.70 ± 0.0
20:1 ω 9	10.92 ± 0.0	1.35 ± 0.0
20:1 ω 7	2.09 ± 0.0	0.26 ± 0.0
20:2 ω 6	1.54 ± 0.0	0.19 ± 0.0
20:4 ω 6	5.89 ± 0.1	0.73 ± 0.0
20:4 ω 3	3.56 ± 0.0	0.44 ± 0.0
20:5 ω 3 (EPA)	104.28± 0.4	12.92 ± 0.0
22:1 ω 11	5.94 ± 0.0	0.74 ± 0.0
22:1 ω 9	2.24 ± 0.0	0.28 ± 0.0
22:2 ω 6	4.59± 0.0	0.57± 0.0
22:5 ω 3	7.24 ± 0.0	0.9 ± 0.0
22:6 ω 3 (DHA)	73.94 ± 0.3	9.16 ± 0.0
<hr/>		
Saponifiables (mg/ g oil); Total fatty acids (% wt./ wt.)	807.03 ± 0.9	100 ± 0.0
Σ SAT	224.3 ± 0.2	27.79± 0.0
Σ MUFA	348.33 ± 0.0	43.16 ± 0.0
Σ PUFA	226.31± 0.7	28.04 ± 0.1
Σ ω-3	204.14 ± 0.8	25.3 ± 0.1
Σ ω-6	22.17 ± 0.1	2.75 ± 0.0
P/S	1.0 ± 0.0	1.0 ± 0.0
ω-3 / ω-6	9.2 ± 0.1	9.2 ± 0.1

SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids

Table 12 and Table 13 present the fatty acid profiles of *F/T American Triumph* crude fish oils in %wt./ wt. and in mg/ g oil, respectively. The profiles of the commercial oils were fairly similar with about 45 mg/ g oil of DHA (~5%) and 90 mg/ g oil of EPA (~10%). Other abundant FA were 16:0 (palmitic acid), 16:1ω7 (palmitoleic acid), 18:1ω9 (*cis*-oleic acid), 20:1ω11 (gadoleic acid), and 22:1ω11 (cetoleic acid). Monounsaturated ω-11 FAs with 20 and 22 carbons appear to be slightly higher in Fall oils than in Spring oils. The origin of these FAs have been attributed by Ackman et al. (1980) to type of feed, with copepods being a significant source of these FA (Ackman, 1989b).

Table 12. Fatty acid profiles of pollock oils produced at sea (*F/T American Triumph*) in % wt./ wt.

Fatty acid	FPO (n=2)	FLO (n=2)	FPOAP (n=2)	FLOAP (n=2)	SPO (n=2)	SPOAP (n=2)
14:0	5.31 ± 0.0	5.4 ± 0.0	5.41 ± 0.0	5.41 ± 0.0	4.54± 0.1	4.45 ± 0.0

14:1 ω 5	0.12 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.13 ± 0.0	0.112 ± 0.0	0.12 ± 0.0
Iso or Ante iso 15:0	0.10 ± 0.0	0.10 ± 0.0	0.10 ± 0.0	0.10 ± 0.0	0.14 ± 0.0	0.14 ± 0.0
15:0	0.19 ± 0.0	0.19 ± 0.0	0.19 ± 0.0	0.19 ± 0.0	0.24 ± 0.0	0.24 ± 0.0
Iso or Ante-iso 16:0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.18 ± 0.0	0.19 ± 0.0
16:0	8.85 ± 0.0	9.79 ± 0.0	8.84 ± 0.0	10.03 ± 0.1	10.98 ± 0.4	10.6 ± 0.1
16:1 ω 11	0.2 ± 0.0	0.17 ± 0.0	0.2 ± 0.0	0.17 ± 0.0	0.14 ± 0.0	0.15 ± 0.0
16:1 ω 7	10.46 ± 0.0	11.86 ± 0.0	10.42 ± 0.0	11.83 ± 0.1	9.36 ± 0.01	9.05 ± 0.0
16:1 ω 5	0.31 ± 0.0	0.29 ± 0.0	0.31 ± 0.0	0.29 ± 0.0	0.31 ± 0.0	0.31 ± 0.0
Unknown 2	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.11 ± 0.0	0.11 ± 0.0
Ante-iso 17:0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.88 ± 0.0	0.89 ± 0.0
17:0	0.6 ± 0.00	0.64 ± 0.0	0.61 ± 0.0	0.63 ± 0.0	0.45 ± 0.0	0.45 ± 0.0
17:1 ω 11	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.96 ± 0.0	1.01 ± 0.1
17:1 ω 9	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.15 ± 0.0	0.15 ± 0.0
Iso or Ante-iso 18:0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.62 ± 0.0	0.65 ± 0.0
18:0	1.34 ± 0.0	1.5 ± 0.0	1.27 ± 0.0	1.48 ± 0.0	1.58 ± 0.1	1.43 ± 0.0
18:1 ω 9 <i>trans</i>	2.2 ± 0.1	2.00 ± 0.0	2.05 ± 0.0	1.98 ± 0.0	1.95 ± 0.0	1.93 ± 0.0
18:1 ω 9 <i>cis</i>	6.00 ± 0.0	7.48 ± 0.0	5.435 ± 0.0	7.47 ± 0.0	11.28 ± 0.1	11.50 ± 0.0
18:1 ω 7	3.52 ± 0.0	4.44 ± 0.0	3.28 ± 0.0	4.45 ± 0.0	4.72 ± 0.0	4.65 ± 0.0
18:2 ω 6 <i>trans</i>	0.54 ± 0.0	0.48 ± 0.0	0.55 ± 0.0	0.48 ± 0.0	0.35 ± 0.0	0.32 ± 0.0
18:2 ω 6 <i>cis</i>	0.58 ± 0.0	0.53 ± 0.0	0.57 ± 0.0	0.51 ± 0.0	0.64 ± 0.0	0.65 ± 0.0
18:3 ω 6	0.35 ± 0.0	0.38 ± 0.0	0.36 ± 0.0	0.36 ± 0.0	0.29 ± 0.0	0.28 ± 0.0
18:3 ω 3	0.32 ± 0.0	0.26 ± 0.0	0.32 ± 0.0	0.24 ± 0.0	0.42 ± 0.0	0.44 ± 0.0
18:4 ω 3	1.63 ± 0.0	1.26 ± 0.0	1.62 ± 0.0	1.24 ± 0.0	1.44 ± 0.0	1.52 ± 0.0
20:1 ω 11	15.42 ± 0.0	14.39 ± 0.1	15.56 ± 0.0	14.34 ± 0.0	10.49 ± 0.1	10.63 ± 0.0
20:1 ω 9	4.47 ± 0.0	3.96 ± 0.0	4.47 ± 0.0	3.94 ± 0.0	5.35 ± 0.0	5.36 ± 0.0
20:1 ω 7	0.30 ± 0.0	0.31 ± 0.0	0.30 ± 0.00	0.31 ± 0.0	0.29 ± 0.0	0.25 ± 0.0
20:1 ω 5	0.06 ± 0.0	0.00 ± 0.0	0.13 ± 0.0	0.00 ± 0.0	0.0 ± 0.0	0.10 ± 0.0
20:2 ω 6	0.14 ± 0.0	0.07 ± 0.1	0.14 ± 0.00	0.07 ± 0.9	0.17 ± 0.0	0.16 ± 0.0
20:3 ω 6	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.19 ± 0.0	0.18 ± 0.0
20:4 ω 3	0.39 ± 0.0	0.33 ± 0.0	0.38 ± 0.00	0.33 ± 0.0	0.45 ± 0.0	0.48 ± 0.0
20:5 ω 3 (EPA)	10.18 ± 0.0	10.90 ± 0.1	10.26 ± 0.0	10.83 ± 0.0	9.77 ± 0.1	10.0 ± 0.0
22:1 ω 11	14.67 ± 0.1	12.67 ± 0.1	15.23 ± 0.0	12.65 ± 0.0	11.72 ± 0.1	12.2 ± 0.1
22:1 ω 9	1.04 ± 0.0	0.93 ± 0.0	1.08 ± 0.0	0.92 ± 0.0	1.35 ± 0.0	1.4 ± 0.01
22:1 ω 7	0.3 ± 0.0	0.275 ± 0.0	0.33 ± 0.0	0.27 ± 0.0	0.25 ± 0.0	0.24 ± 0.0
22:2 ω 6	0.5 ± 0.0	0.54 ± 0.0	0.52 ± 0.0	0.53 ± 0.0	0.50 ± 0.0	0.51 ± 0.0
22:5 ω 3	0.81 ± 0.0	0.72 ± 0.0	0.81 ± 0.0	0.73 ± 0.0	0.90 ± 0.0	0.93 ± 0.0
22:6 ω 3 (DHA)	5.25 ± 0.0	4.93 ± 0.0	5.16 ± 0.0	4.84 ± 0.0	5.15 ± 0.6	5.15 ± 0.0
Unknown 3	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.21 ± 0.0	0.20 ± 0.0
C24:1 ω 9	0.44 ± 0.0	0.35 ± 0.0	0.46 ± 0.0	0.35 ± 0.0	0.58 ± 0.0	0.58 ± 0.0
Total fatty acids	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0
Σ SAT	16.29 ± 0.1	17.54 ± 0.1	16.31 ± 0.1	17.74 ± 0.1	18.63 ± 0.6	17.16 ± 0.1
Σ MUFA	60.12 ± 0.1	59.58 ± 0.2	59.97 ± 0.0	59.56 ± 0.1	58.02 ± 0.2	57.92 ± 0.2
Σ PUFA	20.27 ± 0.1	19.97 ± 0.1	20.26 ± 0.1	19.74 ± 0.3	20.10 ± 0.2	20.93 ± 0.1
Σ ω-3	18.54 ± 0.1	18.39 ± 0.1	18.53 ± 0.1	18.21 ± 0.1	18.14 ± 0.2	17.29 ± 0.0
Σ ω-6	1.73 ± 0.0	1.59 ± 0.2	1.73 ± 0.0	1.53 ± 0.2	2.13 ± 0.0	2.11 ± 0.0
P/S	1.24 ± 0.0	1.14 ± 0.0	1.24 ± 0.0	1.11 ± 0.0	1.08 ± 0.0	1.22 ± 0.5
ω-3 / ω-6	10.71 ± 0.1	11.73 ± 1.86	10.71 ± 0.02	11.99 ± 1.40	9.23 ± 0.1	9.44 ± 0.15

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate; SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids

Table 13. Fatty acids profiles of of pollock oils produced at sea in mg/ g oil

Fatty acid	FPO (n=2)	FLO (n=2)	FPOAP (n=2)	FLOAP (n=2)	SPO (n=2)	SPOAP (n=2)
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14:0	47.21 ± 0.74	44.80 ± 1.6	46.82 ± 0.5	45.98 ± 0.2	40.56 ± 0.9	40.15 ± 0.2
14:1 ω 5	1.08 ± 0.0	0.90 ± 0.0	1.03 ± 0.0	1.13 ± 0.0	1.10 ± 0.0	1.06 ± 0.0
Iso or ante sio 15:0	1.00 ± 0.0	1.00 ± 0.0	1.00 ± 0.0	1.00 ± 0.0	1.20 ± 0.0	1.24 ± 0.0
15:0	1.65 ± 0.0	1.62 ± 0.1	1.63 ± 0.0	1.59 ± 0.0	2.18 ± 0.1	2.12 ± 0.0
Iso or Ante-iso 16:0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	1.59 ± 0.2	1.72 ± 0.2
16:0	78.66 ± 0.9	81.14 ± 2.6	76.44 ± 1.2	85.29 ± 0.4	97.99 ± 3.4	95.42 ± 0.6
16:1 ω 11	1.74 ± 0.0	1.37 ± 0.1	1.72 ± 0.0	1.45 ± 0.0	1.26 ± 0.1	1.32 ± 0.0
16:1 ω 7	92.97 ± 1.1	98.18 ± 2.8	90.13 ± 1.3	100.57 ± 0.1	83.60 ± 0.3	81.50 ± 0.2
16:1 ω 5	2.78 ± 0.0	2.43 ± 0.1	2.68 ± 0.4	2.48 ± 0.0	2.74 ± 0.0	2.75 ± 0.0
Unknown 1	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	1.00 ± 0.0	0.95 ± 0.0
Ante-iso 17:0	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	7.83 ± 0.1	8.03 ± 0.1
17:0	5.30 ± 0.1	5.3 ± 0.2	5.29 ± 0.1	5.35 ± 0.0	4.03 ± 0.0	4.03 ± 0.0
17:1 ω 11	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	8.58 ± 0.2	9.11 ± 0.4
17:1 ω 9	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	1.32 ± 0.0	1.33 ± 0.0
Iso or Ante-iso 18:0	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	5.55 ± 0.0	5.80 ± 0.0
18:0	11.93 ± 0.1	12.43 ± 0.8	10.98 ± 0.2	12.57 ± 0.2	14.11 ± 0.5	12.85 ± 0.1
18:1 ω 9 <i>trans</i>	19.75 ± 1.1	16.56 ± 0.6	17.75 ± 0.6	16.80 ± 0.0	17.38 ± 0.1	17.37 ± 0.0
18:1 ω 9 <i>cis</i>	53.31 ± 0.5	61.97 ± 1.9	47.03 ± 0.9	63.47 ± 0.9	100.72 ± 1.0	103.62 ± 0.5
18:1 ω 7	31.22 ± 0.3	36.79 ± 0.9	28.42 ± 0.4	37.79 ± 0.9	42.15 ± 0.4	41.88 ± 0.2
18:2 ω 6 <i>trans</i>	4.78 ± 0.6	3.925 ± 0.0	4.72 ± 0.1	4.04 ± 0.0	3.10 ± 0.0	2.91 ± 0.0
18:2 ω 6 <i>cis</i>	5.18 ± 0.0	4.325 ± 0.2	4.96 ± 0.1	4.33 ± 0.0	5.74 ± 0.1	5.86 ± 0.0
18:3 ω 6	3.08 ± 0.0	3.1 ± 0.2	3.08 ± 0.1	3.08 ± 0.0	2.61 ± 0.0	2.54 ± 0.0
18:3 ω 3	2.83 ± 0.0	2.11 ± 0.2	2.71 ± 0.0	2.07 ± 0.0	3.72 ± 0.0	3.93 ± 0.0
18:4 ω 3	14.28 ± 0.1	10.40 ± 0.2	14.01 ± 0.2	10.54 ± 0.9	12.85 ± 0.1	13.73 ± 0.0
20:1 ω 11	136.98 ± 1.3	119.21 ± 2.9	134.64 ± 2.3	121.91 ± 0.5	93.67 ± 1.2	95.72 ± 0.4
20:1 ω 9	39.71 ± 0.4	32.75 ± 0.9	38.66 ± 0.6	33.47 ± 0.1	47.80 ± 0.6	48.30 ± 0.2
20:1 ω 7	2.67 ± 0.0	2.50 ± 0.0	2.6 ± 0.1	2.59 ± 0.0	2.60 ± 0.0	2.28 ± 0.0
20:1 ω 5	0.54 ± 0.7	1.11 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.93 ± 0.0	0.90 ± 0.0
20:2 ω 6	1.28 ± 0.0	0.63 ± 0.7	1.22 ± 0.0	0.56 ± 0.8	1.51 ± 0.0	1.49 ± 0.0
20:3 ω 6	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	1.67 ± 0.0	1.65 ± 0.0
20:4 ω 3	3.42 ± 0.08	2.72 ± 0.1	3.3 ± 0.08	2.78 ± 0.0	4.03 ± 0.1	4.31 ± 0.0
20:5 ω 3 (EPA)	90.43 ± 0.9	90.26 ± 2.2	88.73 ± 1.3	92.03 ± 0.6	87.25 ± 1.0	90.37 ± 0.3
22:1 ω 11	130.37 ± 1.6	104.98 ± 2.8	131.745 ± 2.1	107.52 ± 0.3	104.57 ± 1.4	110.04 ± 0.7
22:1 ω 9	9.20 ± 0.1	7.7 ± 0.3	9.29 ± 0.1	7.835 ± 0.0	12.01 ± 0.1	12.56 ± 0.1
22:1 ω 7	2.66 ± 0.0	2.27 ± 0.0	2.88 ± 0.0	2.32 ± 0.0	2.26 ± 0.0	2.16 ± 0.0
22:2 ω 6	4.47 ± 0.0	4.47 ± 0.2	4.49 ± 0.1	4.49 ± 0.0	4.39 ± 0.1	4.60 ± 0.0
22:5 ω 3	7.16 ± 0.0	5.94 ± 0.1	6.96 ± 0.2	6.20 ± 0.0	8.08 ± 0.1	7.19 ± 0.1
22:6 ω 3(DHA)	46.64 ± 0.6	40.85 ± 1.0	44.65 ± 0.5	41.16 ± 0.5	45.97 ± 0.5	46.41 ± 0.1
Unknown 2	0 ± 0.0	0 ± 0.00	0 ± 0.0	0 ± 0.0	1.86 ± 0.0	1.77 ± 0.1
C24:1 ω 9	3.87 ± 0.1	2.915 ± 0.2	3.98 ± 0.0	2.99 ± 0.1	5.20 ± 0.1	5.18 ± 0.0
Saponifiables	888.67 ± 6.6	828.56 ± 25.8	864.98 ± 6.8	850.26 ± 2.6	848.96 ± 12.9	902.0 ± 5.1
Σ SAT	144.76 ± 1.8	145.3 ± 5.3	141.17 ± 2.0	150.78 ± 0.7	158.88 ± 4.8	154.57 ± 1.0
Σ MUFA	534.29 ± 4.9	493.6 ± 13.6	519.02 ± 9.5	506.38 ± 0.9	514.03 ± 5.3	522.76 ± 2.4
Σ PUFA	180.14 ± 1.8	165.46 ± 6.1	175.35 ± 2.5	167.80 ± 2.9	181.64 ± 2.1	187.01 ± 0.7
Σ ω-3	164.75 ± 1.8	152.29 ± 3.7	160.37 ± 2.3	154.8 ± 1.0	151.30 ± 1.8	155.72 ± 0.6
Σ ω-6	15.38 ± 0.1	13.17 ± 2.4	14.98 ± 0.2	13.01 ± 1.6	16.39 ± 0.2	16.50 ± 0.1
P/S	1.24 ± 0.0	1.14 ± 0.0	1.24 ± 0.0	1.11 ± 0.0	1.14 ± 0.4	1.21 ± 0.7
ω-3 / ω-6	10.71 ± 0.1	11.73 ± 1.9	10.71 ± 0.0	11.99 ± 1.4	9.23 ± 0.1	9.44 ± 0.2

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate; SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids

Table 14 and Table 15 present the fatty acid profiles of liver oils rendered in the laboratory at different processing temperatures (50 °C and 60 °C) and times (15 and 30 min) in % wt./ wt.

and in mg/ g oil, respectively. The omega-3 FA content is higher in liver oils rendered at high temperature (60 °C) and for longer time (30 min). Moreover, liver oils rendered from Spring 09 livers had significantly higher omega 3 FA than liver oil rendered from Fall livers under identical processing conditions. On the whole, the differences in EPA and DHA content were irrelevant, despite being statistically significant. Worthy of attention is the lower overall content of MUFA is liver oils from Spring livers, reflecting lower content of ω-11 FA containing 20 and 22 carbons and this observation is in line with the values for these fatty acids in Fall and Spring pollock oils rendered onboard of the *F/T American Triumph*. Overall, the fatty acids profiles of pollock oils are in close agreement with previous findings (Bechtel and Oliveira, 2006; Oliveira and Bechtel 2006b).

Table 14. Fatty acid profiles of pollock liver oils rendered in the laboratory (% wt./ wt.)

Fatty acid	F50LO15` n=5	F50LO30` n=5	F60LO15` N=5	F60LO30` n=5	S60LO30` n=5
14:0	5.44 ± 0.1 ^a	5.46 ± 0.1 ^a	5.50 ± 0.1 ^{ab}	4.40 ± 2.4 ^b _x	4.05 ± 0.2 _y
Unknown 1	0.09 ± 0.0 ^a	0.02 ± 0.0 ^b	0.09 ± 0.0 ^a	0.04 ± 0.1 ^a _x	0.08 ± 0.0 _y
14:1 ω 5	0.14 ± 0.1 ^a	0.06 ± 0.1 ^a	0.14 ± 0.0 ^a	0.10 ± 0.0 ^a	0.11 ± 0.0
Iso or anteiso 15:0	0.09 ± 0.0 ^b	0.10 ± 0.0 ^b	0.12 ± 0.0 ^b	0.15 ± 0.0 ^a _y	0.19 ± 0.0 _{8x}
15:0	0.17 ± 0.0 ^a	0.15 ± 0.0 ^a	0.16 ± 0.0 ^a	0.13 ± 0.0 ^a _y	0.24 ± 0.0 ^x
15:1	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.0 ± 0.0 ^a	0.04 ± 0.0 ^b _x	0.00 ± 0.0 _y
Iso or Ante iso16:0	0.21 ± 0.0 ^a	0.20 ± 0.0 ^a	0.22 ± 0.0 ^a	0.22 ± 0.0 ^a _y	1.85 ± 0.0 _x
16:0	8.84 ± 0.1 ^{ab}	9.17 ± 0.2 ^a	8.67 ± 0.0 ^b	7.05 ± 3.9 ^c _y	8.8 ± 0.0 _x
16:1 ω 11	0.06 ± 0.0 ^a	0.01 ± 0.0 ^b	0.06 ± 0.0 ^a	0.0 ± 0.0 ^c _y	0.15 ± 0.0 _x
16:1 ω 9	0.15 ± 0.0 ^b	0.16 ± 0.0 ^b	0.15 ± 0.0 ^b	0.25 ± 0.0 ^a _x	0.15 ± 0.0 _y
16:1 ω 7	10.67 ± 0.2 ^a	10.78 ± 0.2 ^a	10.34 ± 0.0 ^a	8.56 ± 0.63 ^b	8.54 ± 0.2
16:1 ω 5	0.29 ± 0.0 ^b	0.29 ± 0.0 ^b	0.29 ± 0.0 ^b	0.41 ± 0.3 ^a _x	0.27 ± 0.0 _y
Iso 17:0	0.10 ± 0.0 ^a	0.00 ± 0.0 ^b	0.11 ± 0.0 ^a	0.02 ± 0.0 ^b _y	0.10 ± 0.0 _x
Ante iso17:0	0.61 ± 0.0 ^b	0.64 ± 0.0 ^b	0.85 ± 0.0 ^a	0.68 ± 0.0 ^b _x	0.36 ± 0.0 _y
17:0	0.69 ± 0.0 ^a	0.70 ± 0.1 ^a	0.64 ± 0.0 ^a	0.52 ± 0.3 ^b _y	1.41 ± 0.1 _x
17:1 ω 9	0.0 ± 0.0 ^b	0.01 ± 0.0 ^b	0.00 ± 0.0 ^b	0.21 ± 0.0 ^a _x	0.14 ± 0.0 _y
Iso or Ante iso18:0	1.03 ± 0.0 ^b	1.12 ± 0.0 ^a	1.13 ± 0.0 ^a	1.18 ± 0.0 ^{ay}	0.50 ± 0.0 _x
18:0	1.32 ± 0.0 ^b	1.31 ± 0.0 ^b	1.21 ± 0.0 ^b	1.46 ± 0.42 ^a _x	0.0 ± 0.0 _y
18:1 ω 9 <i>trans</i>	2.19 ± 0.1 ^b	2.15 ± 0.1 ^b	2.20 ± 0.0 ^b	2.58 ± 0.9 ^a _x	1.44 ± 0.1 _y
18:1 ω 9 <i>cis</i>	6.52 ± 0.3 ^a	6.79 ± 0.4 ^a	6.27 ± 0.2 ^{ab}	5.13 ± 2.6 ^b _y	15.08 ± 0.1 _x
18:1 ω 7	3.87 ± 0.13 ^a	3.95 ± 0.2 ^a	3.64 ± 0.1 ^a	3.09 ± 0.48 ^b _y	5.90 ± 0.3 _x
18:2 ω 6 <i>trans</i>	0.50 ± 0.0 ^a	0.51 ± 0.0 ^a	0.52 ± 0.0 ^a	0.42 ± 0.2 ^b _y	0.27 ± 0.0 _x
18:2 ω 6 <i>cis</i>	0.44 ± 0.0 ^b	0.44 ± 0.0 ^b	0.42 ± 0.0 ^b	0.41 ± 0.0 ^a _y	0.64 ± 0.0 _x
18:3 ω 6	0.29 ± 0.0 ^b	0.33 ± 0.0 ^b	0.33 ± 0.0 ^b	0.29 ± 0.0 ^a _x	0.26 ± 0.0 _y
Unknown 2	0.12 ± 0.1 ^a	0.00 ± 0.0 ^b	0.01 ± 0.0 ^a	0.00 ± 0.00 ^b _x	0.00 ± 0.00 _x
18:3 ω 3	0.20 ± 0.0 ^b	0.18 ± 0.6 ^b	0.19 ± 0.0 ^b	0.26 ± 0.0 ^a _y	0.34 ± 0.0 _x
18:3 ω 4	0.99 ± 0.0 ^b	1.11 ± 0.0 ^b	1.03 ± 0.0 ^b	1.44 ± 0.3 ^a _x	1.45 ± 0.0 _x
18:4 ω 3	0.28 ± 0.0 ^b	0.31 ± 0.0 ^b	0.31 ± 0.0 ^b	0.25 ± 0.1 ^a _x	0.25 ± 0.0 _y
Unknown 3	0.03 ± 0.0 ^a	0.01 ± 0.0 ^a	0.06 ± 0.0 ^b	0.0 ± 0.0 ^a _x	0.0 ± 0.0 _x
20:0	0.13 ± 0.0 ^a	0.00 ± 0.0 ^b	0.10 ± 0.0 ^a	0.0 ± 0.0 ^b _x	0.0 ± 0.0 _x
20:1 ω 11	17.05 ± 0.6 ^a	16.81 ± 0.6 ^a	17.65 ± 0.1 ^a	14.83 ± 0.8 ^b _y	7.51 ± 0.6 _x
20:1 ω 9	4.35 ± 0.1 ^a	4.25 ± 0.1 ^a	4.30 ± 0.0 ^a	3.57 ± 1.8 ^b _y	4.49 ± 0.3 _x
20:1 ω 7	0.28 ± 0.0 ^a	0.29 ± 0.0 ^a	0.27 ± 0.0 ^a	0.23 ± 0.1 ^b _x	0.24 ± 0.0 _x
20:1 ω 5	0.12 ± 0.0 ^a	0.01 ± 0.0 ^b	0.12 ± 0.0 ^a	0.01 ± 0.0 ^b _x	0.05 ± 0.0 _x
20:2 ω 6	0.12 ± 0.0 ^a	0.01 ± 0.0 ^b	0.11 ± 0.0 ^a	0.00 ± 0.0 ^b _y	0.17 ± 0.0 _x
Unknown 4	0.13 ± 0.0 ^a	0.03 ± 0.0 ^b	0.12 ± 0.0 ^a	0.04 ± 0.0 ^b _y	0.19 ± 0.0 _x
20:3 ω 3	0.00 ± 0.0 ^b	0.22 ± 0.0 ^a	0.00 ± 0.0 ^b	0.00 ± 0.00 ^b _x	0.00 ± 0.0 _x
20:4 ω 3	0.27 ± 0.0 ^b	0.29 ± 0.0 ^b	0.27 ± 0.0 ^b	0.37 ± 0.0b ^a _y	0.44 ± 0.0 _x
20:5 ω 3 (EPA)	8.92 ± 0.5 ^b	9.86 ± 0.1 ^a	9.35 ± 0.2 ^a	9.68 ± 0.1 ^a _y	11.38 ± 0.4 _x

22:1 ω 11	14.46 ± 0.6 ^a	13.98 ± 0.3 ^a	14.51 ± 0.1 ^a	14.49 ± 0.5 ^a _x	9.30 ± 0.9 _y
22:1 ω 9	0.96 ± 0.0 ^a	0.91 ± 0.0 ^a	0.92 ± 0.0 ^a	0.94 ± 0.0 ^a _y	1.27 ± 0.1 _x
22:1 ω 7	0.28 ± 0.0 ^a	0.27 ± 0.0 ^a	0.26 ± 0.0 ^a	0.29 ± 0.0 ^a _x	0.22 ± 0.0 _y
22:2 ω 6	0.48 ± 0.0 ^a	0.51 ± 0.0 ^a	0.49 ± 0.0 ^a	0.51 ± 0.0 ^a _y	0.58 ± 0.0 _y
22:5 ω 3	0.68 ± 0.0 ^a	0.72 ± 0.0 ^a	0.71 ± 0.0 ^a	0.73 ± 0.0 ^a _y	0.81 ± 0.0 _x
22:6 ω 3 (DHA)	4.42 ± 0.34 ^b	4.79 ± 0.0 ^a	4.55 ± 0.1 ^b	4.87 ± 0.14 ^a _y	5.15 ± 0.17 _x
Unknown 6	0.24 ± 0.0 ^a	0.03 ± 0.0 ^b	0.24 ± 0.0 ^a	0.00 ± 0.0 ^c _y	0.09 ± 0.0 [*] _x
24:1 ω 9	0.36 ± 0.0 ^a	0.33 ± 0.0 ^a	0.34 ± 0.0 ^a	0.35 ± 0.0 ^a _y	0.51 ± 0.0 _x
Total fatty acids	100.0 ± 0.0	100.0 ± 0.0	100.00 ± 0.0	100.00 ± 0.0	100.0 ± 0.0
Σ SAT	18.78 ± 0.2 ^b	18.93 ± 0.1 ^{ab}	18.58 ± 0.1 ^b	19.33 ± 0.3 ^a _y	21.04 ± 0.52 _x
Σ MUFA	60.92 ± 0.4 ^b	61.10 ± 0.4 ^{ab}	61.50 ± 0.4 ^a	61.48 ± 0.6 ^a _x	54.95 ± 0.8 _y
Σ PUFA	18.69 ± 0.5 ^c	19.16 ± 0.2 ^b	18.43 ± 0.4 ^c	19.30 ± 0.2 ^a _y	22.02 ± 0.4 _x
Σ ω-3	13.55 ± 0.1 ^c	13.55 ^a ± 0.2 ^c	15.92 ± 0.1 ^b	16.69 ± 0.8 ^a _y	18.49 ± 0.3 _x
Σ ω-6	1.35 ± 0.1 ^b	1.12 ± 0.3 ^c	1.52 ± 0.0 ^a	1.36 ± 0.1 ^b _y	2.12 ± 0.0 _x
P/S	1.10 ± 0.0 ^a	1.10 ± 0.3 ^a	1.10 ± 0.43 ^a	1.10 ± 0.0 ^a _x	0.98 ± 0.1 _x
ω-3 / ω-6	10.0 ± 0.2 ^b	12.10 ± 0.1 ^a	10.50 ± 0.3 ^b	12.30 ± 0.1 ^a _x	8.72 ± 0.1 _y

F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min; SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids. Different superscript letters within a row indicate statistical differences due to rendering time and temperature P<0.05. Different subscript letters within a row indicate statistical differences due to season for oils extracted at 60 °C for 30 min (P<0.05).

Table 15. Fatty acid profiles of pollock liver oils rendered in the laboratory (mg/ g oil)

Fatty acids	50FLO15` N=5	50FLO30` n=5	60FLO15` n=5	60FLO30` N=5	60SLO30` n=5
14:0	38.42 ± 1.2 ^b	41.76 ± 1.3 ^{ab}	41.44 ± 0.5 ^{ab}	45.45 ± 2.2 ^a _x	25.68 ± 0.8 _y
Unknown 1	0.66 ± 0.0 ^b	0.86 ± 0.2 ^a	0.70 ± 0.0 ^b	0.94 ± 0.0 ^a _x	0.54 ± 0.1 _y
14:1 ω 5	1.00 ± 0.1 ^a	0.44 ± 0.4 ^b	1.03 ± 0.0 ^a	0.60 ± 0.0 ^b _y	0.67 ± 0.0 _x
Iso or anteiso 15:0	1.0 ± 0.0 ^a	0.56 ± 0.0 ^b	1.03 ± 0.0 ^a	0.00 ± 0.0 ^c _y	0.83 ± 0.0 _x
15:0	1.19 ± 0.1 ^b	1.27 ± 0.0 ^{ab}	1.17 ± 0.0 ^b	1.35 ± 0.1 ^a _y	1.49 ± 0.0 _y
15:1	0.33 ± 0.1 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 ^b	0.00 ± 0.0 ^b _x	0.00 ± 0.0 _x
Iso or Ante iso16:0	1.48 ± 0.1 ^c	1.56 ± 0.7 ^b	1.59 ± 0.0 ^b	1.69 ± 0.0 ^a _x	1.26 ± 0.1 _y
16:0	62.41 ± 1.6 ^b	70.11 ± 2.6 ^a	65.33 ± 0.5 ^b	73.11 ± 3.8 ^a _y	80.34 ± 0.6 _y
16:1 ω 11	0.44 ± 0.0 ^b	0.48 ± 0.0 ^b	0.50 ± 0.0 ^a	0.00 ± 0.0 ^c _y	0.95 ± 0.0 _x
16:1 ω 9	1.07 ± 0.0 ^b	1.19 ± 0.0 ^b	1.15 ± 0.0 ^b	1.29 ± 0.0 ^a _x	0.95 ± 0.0 _y
16:1 ω 7	75.25 ± 2.5 ^b	82.47 ± 2.7 ^b	77.96 ± 0.6 ^c	89.44 ± 0.9 ^a _x	53.70 ± 0.5 _y
16:1 ω 5	2.03 ± 0.1 ^b	2.25 ± 0.1 ^b	2.20 ± 0.0 ^b	2.47 ± 0.1 ^a _x	1.71 ± 0.1 _y
Iso 17:0	0.73 ± 0.0 ^a	0.40 ± 0.0 ^b	0.82 ± 0.02 ^a	0.75 ± 0.3 ^b _x	0.00 ± 0.0 _y
Ante iso17:0	5.93 ± 0.1 ^c	6.75 ± 0.2 ^b	6.43 ± 0.1 ^b	7.32 ± 0.1 ^a _x	4.99 ± 0.2 _y
17:0	4.31 ± 0.1 ^c	4.91 ± 0.2 ^a	4.83 ± 0.1 ^a	5.42 ± 0.2 ^b _x	2.29 ± 0.1 _y
17:1 ω 9	0.61 ± 0.1 ^a	0.00 ± 0.0 ^b	0.68 ± 0.0 ^a	0.00 ± 0.0 ^b _y	0.91 ± 0.0 _x
Iso or Ante iso18:0	6.54 ± 1.6 ^c	8.53 ± 0.4 ^b	8.50 ± 0.3 ^b	9.51 ± 0.4 ^a _x	3.22 ± 0.2 _y
18:00	9.19 ± 0.6 ^c	10.08 ± 0.4 ^b	9.17 ± 0.1 ^c	10.69 ± 0.3 ^a _y	11.49 ± 0.3 _x
18:1 ω 9 <i>trans</i>	14.05 ± 3.4 ^c	16.49 ± 0.5 ^b	16.60 ± 0.9 ^b	18.46 ± 0.4 ^a _x	9.28 ± 0.8 _y
18:1 ω 9 <i>cis</i>	42.6 ± 7.3 ^c	51.97 ± 3.3 ^a	47.25 ± 1.6 ^b	53.57 ± 1.8 ^a _y	93.22 ± 2.3 _x
18:1 ω 7	29.20 ± 4.4 ^b	30.20 ± 1.6 ^a	27.45 ± 0.7 ^{ab}	31.97 ± 0.9 ^a _y	36.59 ± 0.5 _x
18:2 ω 6 <i>trans</i>	5.89 ± 5.2 ^b	3.94 ± 0.2 ^c	3.95 ± 0.1 ^c	4.36 ± 0.2 ^a _x	1.72 ± 0.1 _y
18:2 ω 6 <i>cis</i>	3.12 ± 0.1 ^b	3.39 ± 0.1 ^b	3.15 ± 0.0 ^b	3.66 ± 0.0 ^a	4.05 ± 0.1
18:3 ω 6	2.08 ± 0.3 ^a	2.53 ± 0.1 ^b	2.47 ± 0.2 ^b	2.63 ± 0.1 ^c _x	1.62 ± 0.1 _y
Unknown 2	1.03 ± 0.4 ^a	0.00 ± 0.0 ^d	0.67 ± 0.0 ^b	0.00 ± 0.0 ^d _x	0.00 ± 0.0 _x
18:3 ω 3	1.47 ± 0.1 ^b	1.40 ± 0.4 ^c	1.47 ± 0.0 ^b	1.66 ± 0.0 ^a _y	2.64 ± 0.1 _x
18:3 ω 4	7.01 ± 0.2 ^c	8.46 ± 0.2 ^{ab}	7.73 ± 0.2 ^b	9.20 ± 0.3 ^a _x	9.26 ± 0.4 _x
18:4 ω 3	1.96 ± 0.0 ^b	2.37 ± 0.1 ^b	2.28 ± 0.1 ^b	2.61 ± 0.1 ^a _x	1.30 ± 0.1 _y

Unknown 3	0.37 ± 0.0 ^b	0.41 ± 0.0 ^{ab}	0.44 ± 0.0 ^a	0.00 ± 0.0 ^c _x	0.00 ± 0.0 _x
20:0	0.93 ± 0.2 ^a	0.00 ± 0.0 ^b	0.85 ± 0.0 ^a	0.00 ± 0.0 ^b _x	0.00 ± 0.0 _x
20:1 ω 11	120.34 ± 4.8 ^c	128.56 ± 5.4 ^{bc}	133.03 ± 0.8 ^b	145.36 ± 5.4 ^a _x	48.8 ± 3.8 _y
20:1 ω 9	30.67 ± 1.0 ^a	32.52 ± 1.0 ^a	32.39 ± 0.2 ^a	36.71 ± 1.34 ^a _x	29.03 ± 2.6 _y
20:1 ω 7	2.00 ± 0.1 ^b	2.22 ± 0.1 ^a	2.05 ± 0.1 ^b	2.41 ± 0.1 ^a _x	1.52 ± 0.1 _y
20:1 ω 5	0.82 ± 0.0 ^a	0.17 ± 0.4 ^b	0.88 ± 0.0 ^a	0.00 ± 0.0 ^c _y	0.45 ± 0.3 _x
20:2 ω 6	0.90 ± 0.1 ^a	0.47 ± 0.0 ^b	0.83 ± 0.0 ^a	0.00 ± 0.00 ^c _y	1.08 ± 0.0 _x
Unknown 4	0.96 ± 0.1 ^a	0.00 ± 0.0 ^c	0.94 ± 0.0 ^a	0.42 ± 0.5 ^b _y	1.21 ± 0.0 _x
20:3 ω 3	0.11 ± 0.3 ^b	1.11 ± 0.0 ^a	0.00 ± 0.0 ^c	0.00 ± 0.0 ^c _x	0.00 ± 0.0 _x
20:4 ω 3	1.93 ± 0.2 ^c	2.21 ± 0.9 ^{ab}	2.00 ± 0.1 ^b	2.41 ± 0.1 ^a _x	2.78 ± 0.1 _y
20:5 ω 3 (EPA)	62.91 ± 3.3 ^d	75.36 ± 2.4 ^b	70.50 ± 1.7 ^c	81.07 ± 0.1 ^a _x	71.15 ± 1.2 _y
22:1 ω 11	102.04 ± 4.4 ^c	106.86 ± 3.8 ^b	109.38 ± 1.0 ^b	121.50 ± 5.5 ^a _x	61.05 ± 5.6 _y
22:1 ω 9	6.78 ± 0.3 ^a	6.94 ± 0.2 ^b	6.93 ± 0.1 ^b	7.91 ± 0.4 ^a _y	8.31 ± 0.6 _x
22:1 ω 7	2.01 ± 0.1 ^b	2.08 ± 0.1 ^b	1.99 ± 0.0 ^c	2.42 ± 0.1 ^a _x	1.40 ± 0.1 _y
22:2 ω 6	3.38 ± 0.2 ^c	3.93 ± 0.1 ^b	3.70 ± 0.1 ^b	4.27 ± 0.1 ^a	3.65 ± 0.1 _y
22:5 ω 3	4.82 ± 0.2 ^c	5.49 ± 0.2 ^b	5.37 ± 0.1 ^b	6.13 ± 0.2 ^a _x	5.17 ± 0.3 _y
22:6 ω 3 (DHA)	31.19 ± 2.1 ^d	36.65 ± 1.0 ^b	34.28 ± 0.1 ^b	40.84 ± 1.1 ^a	32.56 ± 1.4 _y
Unknown 6	1.70 ± 0.1 ^b	1.78 ± 0.0 ^b	1.84 ± 0.0 ^c	0.00 ± 0.0 _y	0.70 ± 0.5 _x
24:1 ω 9	2.55 ± 0.1 ^{ab}	2.51 ± 0.1 ^b	2.60 ± 0.0 ^a	2.90 ± 0.0 _y	3.36 ± 0.3 _x
Saponifiables	705.72 ± 9.94 ^c	754.70 ± 9.97 ^b	742.49 ± 5.28 ^b	841.08 ± 17.01 ^a _x	632.43 ± 14.5 _y
Σ SAT	116.44 ± 3.7 ^c	128.13 ± 4.5 ^b	122.79 ± 1.3 ^b	136.03 ± 6.5 ^a _x	130.76 ± 0.9 _y
Σ MUFA	439.11 ± 33.8 ^c	471.55 ± 19.7 ^b	467.34 ± 5.5 ^b	521.96 ± 17.2 ^a _x	351.03 ± 11.4 _y
Σ PUFA	121.79 ± 7.3 ^d	143.36 ± 4.8 ^b	134.73 ± 3.3 ^c	154.87 ± 3.0 ^a _x	138.15 ± 2.1 _y
Σ ω-3	104.33 ± 6.2 ^d	124.58 ± 4.2 ^b	115.91 ± 2.8 ^c	134.70 ± 2.0 ^a _x	115.57 ± 1.5 _y
Σ ω-6	10.45 ± 0.9 ^b	10.31 ± 0.37 ^b	11.09 ± 0.3 ^a	10.97 ± 0.7 ^a _x	13.32 ± 0.3 _x
P/S	1.10 ± 0.0 ^a	1.10 ± 0.3 ^a	1.10 ± 0.4 ^a	1.10 ± 0.0 ^a _x	0.98 ± 0.1
ω-3 / ω-6	10.0 ± 0.2 ^b	12.10 ± 0.1 ^a	10.50 ± 0.3 ^b	12.30 ± 0.1 ^a _x	8.72 ± 0.1 _y

F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min; SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids. Different superscript letters within a row indicate statistical differences due to rendering time and temperature P<0.05. Different subscript letters within a row indicate statistical differences due to season for oils extracted at 60 °C for 30 min (P<0.05).

Environmental contaminants

Table 16 shows the results of environmental contaminants analysis in pollock oils produced at sea. The levels of the 38 persistent organic pollutants (POPs) listed in Table 17 were determined at the ppm level. Results for all POPs reported are below levels of concern.

Table 16. Environmental contaminants of pollock and hake oils produced by the *F/T American Triumph* (ppm)

	FPO (n=1)	FPOAP (n=1)	FLO (n=1)	FPOAP (n=1)	Hake (n=1)
Org-P					
Diazinon	< 0.14	< 0.14	< 0.14	< 0.14	ND
Ethion	< 0.14	< 0.14	< 0.14	< 0.14	ND
Malathion	< 0.14	< 0.14	< 0.14	< 0.14	ND
Methyl Parathion	< 0.14	< 0.14	< 0.14	< 0.14	ND
Parathion	< 0.12	< 0.12	< 0.12	< 0.12	ND
Ronnel	< 0.13	< 0.13	< 0.13	< 0.13	ND
Carbophenothion (Trithion)	< 0.15	< 0.15	< 0.15	< 0.15	ND
Disulfoton	< 0.15	< 0.15	< 0.15	< 0.15	ND
Phorate (Thimet)	< 0.15	< 0.15	< 0.15	< 0.15	ND
PCB`s-Pest					

PCB-1016	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1221	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1232	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1242	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1248	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1254	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
PCB-1260	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Aldrin	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Alpha-BHC	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
2,4'-DDD [O,P-DDD]	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
4,4'-DDD	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
2,4'-DDE [O,P-DDE]	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
4,4'-DDE	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
2,4'-DDT [O,P-DDT]	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
4,4'-DDT	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
Dieldrin	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Endrin	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Heptachlor	< 0.01	< 0.01	< .01	< 0.01	< 0.01
Heptachlor Epoxide	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Hexachlorobenzene	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Gamma-BHC(Lindane)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Methoxychlor	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Mirex	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Toxaphene	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Endosulfan (Thiodan)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Beta-BHC	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Delta-BHC	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Alpha Chlordane	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Gamma Chlordane	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate; ND not determined.

Mineral profiles

Table 17 and Table 18 present the minerals in pollock oils produced at sea and in oils rendered in the laboratory, respectively. Most minerals are at very low abundance all oils except for boron and arsenic (Table 18). The two elements of concern for triggering lipid oxidation in fish oils, iron and copper, are lower than maximum levels suggested for crude fish oils (Table 1). Boron content in the *F/T American Triumph* Fall 08 oils and in hake oil were much higher than in Spring 09 oils, and this was also the case for Fall and Spring liver oils rendered in the laboratory. Boron is an essential marine algae nutrient (Carrano et al., 2009). As mentioned, during summer and early Fall pollock is feeding heavily on krill which in turn feeds on algae; and this is likely the source of boron in pollock oils. Arsenic was not detected in of the Fall oils (pollock and pollock liver oils), but significant amounts were found in Spring oils (pollock and pollock liver oils). Recent studies have shown that most arsenic found in seafood products is in organic forms, primarily as arsenobetaine and arsenocholine. Organic arsenic is much less toxic than inorganic arsenic and is generally not considered a threat to human health (Institute of Medicine of the National Academy of Sciences, 1991).

Table 17. Mineral profiles of pollock and hake oils produced by the *F/T American Triumph*

Unit	Minerals	FPO (n=1)	FPOAP (n=1)	FLO (n=1)	FLOAP (n=1)	SPO (n=1)	SPOAP (n=1)	Hake (n=1)
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%	N	< 0.01	< 0.01	< 0.01	< 0.01	0.03	< 0.01	< 0.01
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	K	< 0.01	< 0.01	0.02	< 0.01	< 0.01	0.01	0.01
	Ca	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Mg	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	S	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Ppm	Na	< 1	< 1	< 1	< 1	< 1	< 1	< 1
	Cu	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Zn	< 1	< 1	< 1	< 1	< 1	< 1	< 1
	Mn	< 1	< 1	< 1	< 1	< 1	< 1	< 1
	Fe	< 1	< 1	< 1	< 1	< 1	< 1	< 1
	Co	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
	Mo	< 0.15	< 0.15	< 0.15	< 0.15	0.31	0.44	< 0.15
	Se	< 0.40	< 0.40	< 0.40	< 0.40	< 0.40	< 0.40	< 0.40
	B	83.89	89.92	97.90	96.67	< 0.01	< 0.01	113.80
	As	0.0	0.0	0.0	0.0	3.72	5.27	0.0

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; SPO Spring pollock oil; SPOAP Spring pollock oil with ascorbyl palmitate

Table 18. Mineral profiles of pollock liver oils rendered in the laboratory

Units	Minerals	F50LO15` (n=1)	F50LO30` (n=1)	F60LO15` (n=1)	F60LO30` (n=1)	S60LO30` (n=1)
%	N	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	K	0.01	0.02	0.02	0.02	< 0.01
	Ca	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Mg	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	S	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Ppm	Na	< 1	< 1	< 1	< 1	< 1
	Cu	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Zn	< 1	< 1	< 1	< 1	< 1
	Mn	< 1	< 1	< 1	< 1	< 1
	Fe	< 1	5	< 1	< 1	< 1
	Co	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
	Mo	< 0.15	< 0.15	< 0.15	< 0.15	0.83
	Se	< 0.40	< 0.40	< 0.40	< 0.40	< 0.40
	B	73.62	106.82	77.35	69.32	< 0.01
	As	0.0	0.0	0.0	0.0	1.72

F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min

Fat-soluble vitamins

Table 19 presents the concentrations of fat-soluble vitamins A, D and E in oils produced at sea as determined by Warren Laboratories Inc.. These results were difficult to interpret are due to the low number of analysis, should be used carefully. There is no reasonable explanation for the observed differences in vitamin A values between identical oils with and without ascorbyl palmitate, especially for FPO and FPOAP samples. Hake oil had very high vitamin A content, and again the reason for this large difference in vitamin A content between oils from pollock and hake is unknown. Vitamin E results are easier to interpret because it is expected that AP, being an antioxidant, could help preserving vitamin E levels in fish oils. The levels of vitamin D were similar in the bulk part but do not provide a clear picture of the role AP plays in preserving this nutrient. Vitamin K was about twice the

abundance in hake oil of that found in any of the pollock oils, and this can only be explained by possible species-specific differences in composition of the byproducts. Overall, as pointed out one determination of fat soluble vitamin for each sample is insufficient to provide a good picture of the accurate values of these nutrients; however these analysis are costly and future studies should be conducted to carry out systematic sampling of pollock oils to accurately determine the ranges of each of the fat soluble vitamins of interest. Due to the difficulties in interpreting fat soluble vitamin levels as reported by Warren Laboratories, Dr. Peter Bechtel generously agreed to quantify, in his laboratory, two fat soluble vitamins (A and E) in several oil samples of interest for our study. The method used in his laboratory makes use of a liquid chromatographer coupled to a mass spectrometer (LC-MS) instead of a high performance liquid chromatographer coupled to a fluorescence or UV detector used by Warren Laboratories. The LC-MS is more accurate because the mass spectrum of each vitamin isomer is determined and purity is ascertained for each signal before quantification is attempted. On the other hand, an HPLC system makes use only of matching retention times of unknown peaks with that of known standards. Table 20 shows the results of vitamin analysis determined in Dr. Bechtel's laboratory, as an average of three determinations for each oil sample. Results are reported in $\mu\text{g/g}$ of oil and were converted to IU/ 100 g oil using the following standard conversion factors (National Institute of Health) for each of the fat soluble vitamins:

- Vitamin A (retinol): 1IU = 0.3 μg

(<http://ods.od.nih.gov/factsheets/vitamina.asp>;) - last accessed Dec 2009

- Vitamin E (tocopherols): 1 IU = 0.67 mg or 670 μg

(<http://dietary-supplements.info.nih.gov/factsheets/vitamine.asp>) - last accessed Dec 2009

Vitamin A values determined by LC-MS (Table 20) differ substantially from results in Table 19, while results for vitamin E are in relatively close agreement. The liver oils rendered in the laboratory were depleted from vitamin E, and this is likely due to the fact that these oils were rendered in an open system and air exposure oxidized this nutrient. Vitamin E has antioxidant properties and is highly susceptible to photo oxidation and thermal oxidation. There is no reasonable explanation for the discrepancy in vitamin A values observed between Tables 19 and 20 and further investigation needs to be conducted to solve this issue.

Table 19. Fat soluble vitamins of pollock and hake oils produced by the *F/T American Triumph* as determined by Warren Laboratories

	Vitamin A (IU/100g oil)	Vitamin E (IU/100g oil)	Vitamin D (IU/100g oil)	Vitamin K ($\mu\text{g}/100\text{g}$ oil)
FPO (n=1)	94,309	13.0	3,126.0	< 5.0
FPOAP (n=1)	58,264	21.0	3,852.0	< 5.0
FLO (n=1)	72,372	9.7	2,186.0	6.8
FLOAP (n=1)	81,994	13.2	1,962.0	6.0
Hake oil (n=1)	487,674	25.2	1,836.8	13.7

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate

Table 20. Fat soluble vitamins of pollock and hake oils produced by the *F/T American Triumph* and of pollock liver oils rendered in the laboratory

	$\mu\text{g/g}$ oil		IU/100g oil	
	Vitamin A (n=3)	Vitamin E (n=3)	Vitamin A (n=3)	Vitamin E (n=3)

FPO	17.76 ± 0.4	73.91 ± 0.2	5,920.0	11.0
FPOAP	2.95 ± 0.7	125.57 ± 0.8	983.3	18.7
FLO	10.07 ± 0.4	67.59 ± 1.4	3,356.7	10.1
FLOAP	14.46 ± 1.2	108.62 ± 8.9	4,820.0	16.2
Hake Oil	4.43 ± 0.3	67.32 ± 3.0	1,476.7	10.1
F50LO15 ^c	19.12 ± 1.5 ^b	0.00 ± 0.0	6,373.3	0
F50LO30 ^c	36.14 ± 0.5 ^a	0.00 ± 0.0	12,046.7	0
F60LO15 ^c	14.51 ± 2.4 ^c	0.00 ± 0.0	4,836.7	0
F60LO30 ^c	11.72 ± 2.8 ^d	0.00 ± 0.0	390.7	0

FPO Fall pollock oil; FLO Fall liver oil; FPOAP Fall pollock oil with ascorbyl palmitate; FLOAP Fall liver oil with ascorbyl palmitate; F50LO15^c Fall liver oil rendered at 50 °C for 15 min; F50LO30^c Fall liver oil rendered at 50 °C for 30 min; F60LO15^c Fall liver oil rendered at 60 °C for 15 min; F60LO30^c Fall liver oil rendered at 60 °C for 30 min; S60LO30^c Spring liver oil rendered at 60 °C for 30 min. Different superscript letters within a column indicate statistical differences between liver oils rendered in the laboratory ($P < 0.05$)

Free fatty acids values (%FFA)

Figure 9 shows the levels of free fatty acids of oils produced on board of the *F/T American Triumph* (Figure 9a) and of oils rendered in the laboratory (Figure 9b). The %FFA values were higher in oils produced in the laboratory than in oils produced at sea. Percent FFA ranged from 3-4% for crude oils from the *F/T American Triumph* and value of up to 5% are quite common for crude fish oils (Table 1; Bimbo, 1988). The %FFA reflects the degree of lipid hydrolysis in the raw material, mainly caused by enzymatic activity during storage of byproducts. During storage of the livers as frozen blocks or as liquid slurry, after tissue homogenization, it is likely that free fatty acids were formed as a result of hydrolysis of triacylglycerides. The byproducts used for the manufacturing of fish oils at sea are very fresh because limited storage space exists on board of catcher-processor vessels to hold large quantities of the byproduct stream. Therefore, little chance exists for byproducts used at sea for the manufacturing of fish oils to undergo lipid hydrolysis. Of note is the %FFA determined for liver oil produced at sea (FLO; FLOAP), which seems lower than the value determined for pollock oil derived from a mixture of pollock byproducts. A possible explanation for this difference is the high enzymatic activity in viscera tissue (high lipase activity), a component in the mixture of pollock byproducts used for the manufacturing of FPO, FPOAP, SPO and SPOAP.

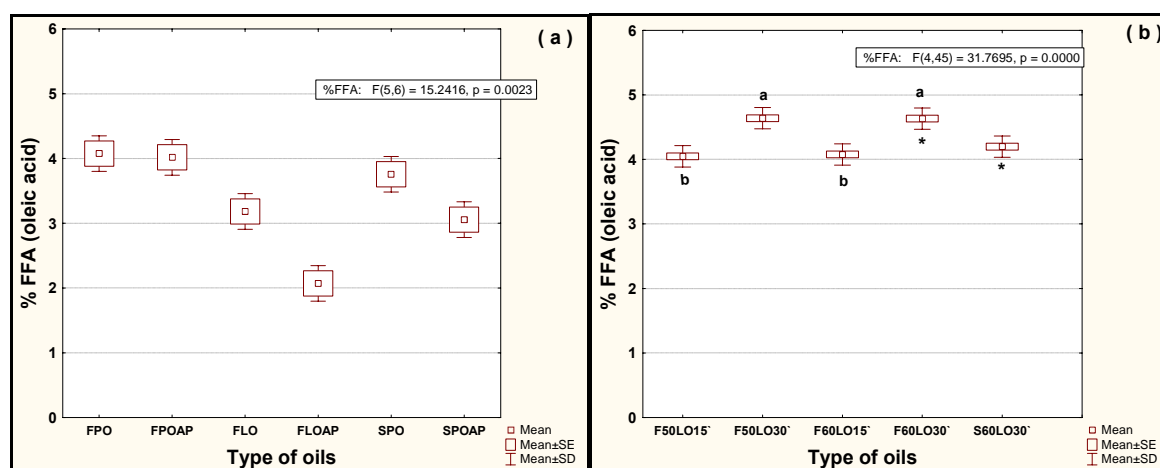


Figure 9. Free fatty acids content of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascorbyl palmitate; (b) Oils rendered in the laboratory: F50LO15^c Fall liver oil rendered at 50 °C for 15 min; F50LO30^c Fall liver oil rendered at 50 °C for 30 min; F60LO15^c Fall liver oil rendered at 60 °C for 15 min; F60LO30^c Fall liver oil rendered at 60 °C for 30 min; S60LO30^c Spring liver oil rendered at 60 °C for 30 min. Different letters

indicate statistical differences between Fall liver oils rendered in the laboratory ($P < 0.05$). * indicates statistical difference between Fall and Spring liver oils rendered at 60 °C for 30 min ($P < 0.05$)

Peroxide values (PV)

The PV values (Figure 10) reflect levels of primary products of lipid oxidation. The PV values of all oils produced at sea are in the lower range expected for crude fish oils (Table 1; Bimbo, 1988). On the other hand, the liver oils rendered in the laboratory are closer to the upper range of PV values expected for fish oils. The PV of oils rendered at lower temperature and shorter time (50 °C; 15 min) were significantly lower than the values for oils rendered at 60 °C for 30 min. This clearly shows the significance of rendering time, especially in an open system (Figure 5), in promoting lipid oxidation in fish oils. The *F/T American Triumph* oils were rendered at much higher temperatures (~90 °C) than the oils rendered in the laboratory; however, the Triumph's closed system combined with a very short processing time (~ 2 min) proved effective in preventing the formation of primary lipid oxidation products. These findings demystify the common belief that rendering fish oils at high temperatures triggers lipid oxidation. On the contrary, cooking time combined to oxygen (air) exposure seems to be more critical for formation of primary products of lipid oxidation than cooking temperature. On the whole, the PV values shown in Figure 10 are within the expected range for crude fish oils (3-20 meq/ Kg; Table 1), but with exception of FLAP all oils have higher PV than the maximum level of 5 meq/ Kg stipulated for edible fish oils. This shows the need to remove these impurities due to their potential detrimental effects to human health previously described.

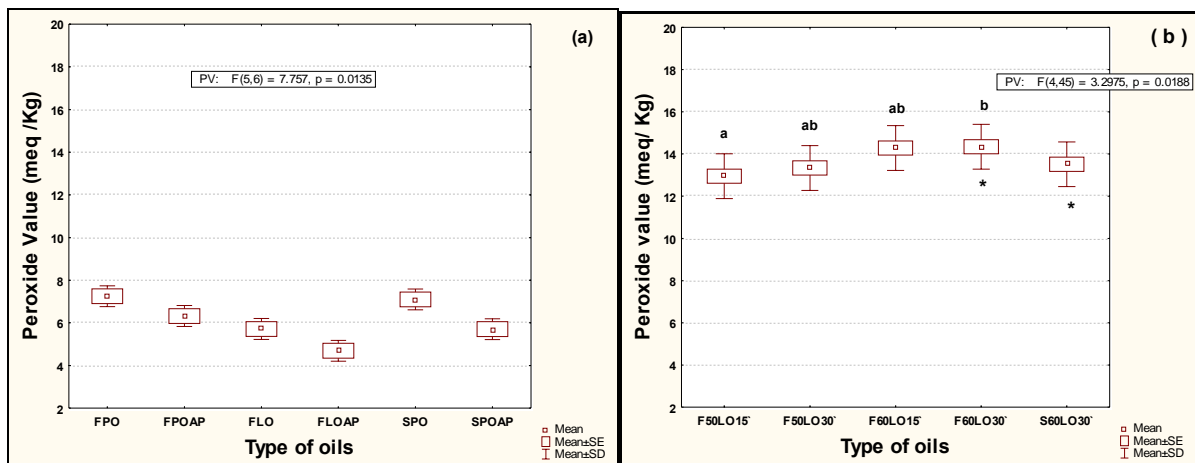


Figure 10. Peroxide values (meq/ Kg) of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascorbyl palmitate; (b) Oils rendered in the laboratory: F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min. Different letters indicate statistical differences between Fall liver oils rendered in the laboratory ($P < 0.05$). * indicates when a statistical difference between Fall and Spring liver oils rendered at 60°C for 30 min was determined ($P < 0.05$)

p-Anisidine values (*p*-AV)

Figure 11 depicts *p*-AV values for crude pollock oils. There was a trend of lower *p*-AV values in oils with ascorbyl palmitate (250 ppm) for oils produced onboard of the *F/T American Triumph*. This result is promising because ascorbyl palmitate is a GRAS substance and in this case seems effective in decreasing the rate of formation of secondary products of lipid oxidation during storage of pollock oils. For the liver oils rendered in the laboratory, the rendering temperature and process duration seem to influence the formation of secondary products of lipid oxidation in an open system. The *p*-AV was significantly higher in oils

rendered at 60 °C for 30 min when compared to oils rendered at lower temperature or for shorter time. Overall, the *p*-AV values of oils produced at sea were lower than the ones determined for liver oils rendered in the laboratory. These results are in line with results for PV. On the whole, the *p*-AV values for all oils depicted in Figure 11 are within the range expected for crude fish oils (Bimbo, 2009), but higher than the value (*p*-AV < 20) expected for edible fish oils (Table 1). This indicates the need to purify the oils to remove secondary products of lipid oxidation due to their potential detrimental effects to human health previously described.

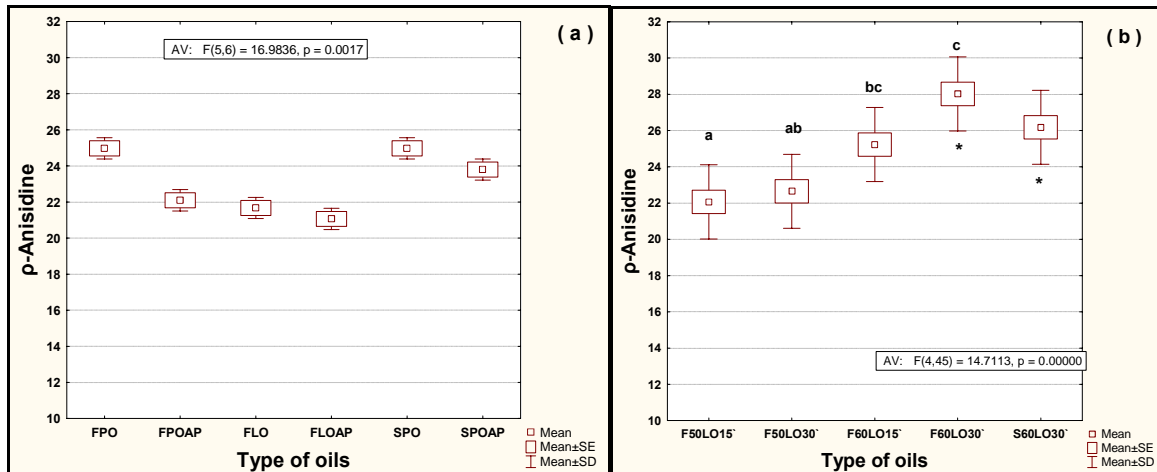


Figure 11. Anisidine values of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascorbyl palmitate; (b) Oils rendered in the laboratory: F50LO15' Fall liver oil rendered at 50 °C for 15 min; F50LO30' Fall liver oil rendered at 50 °C for 30 min; F60LO15' Fall liver oil rendered at 60 °C for 15 min; F60LO30' Fall liver oil rendered at 60 °C for 30 min; S60LO30' Spring liver oil rendered at 60 °C for 30 min. Different letters indicate statistical differences between Fall liver oils rendered in the laboratory ($P < 0.05$). * indicates when a statistical difference between Fall and Spring liver oils rendered at 60 °C for 30 min was determined ($P < 0.05$)

Thiobarbituric acid values (TBA)

Figure 12 shows the TBA values for crude pollock oils. Ascorbyl palmitate (AP) seem to decrease formation of secondary products of lipid oxidation in both Fall and Spring pollock oils, and this is in agreement with *p*-AV data above. Conversely, TBA values are similar for Fall liver oils with or without ascorbyl palmitate, while *p*-AV values seemed lower in liver oil produced at sea with antioxidant (AP). It is important to point out that FPO and SPO were rendered from a mixture of byproducts, where fish blood is found more abundantly than in a mixture of pollock livers. Iron, from hemoglobin, is a powerful oxidant and could have promoted formation of secondary lipid oxidation products during the rendering process. The addition of AP clearly reduced the TBA values and this additive because AP quenches free radicals, which trigger and propagate lipid oxidation in fish oils; thus, AP seemed to have improved the oxidative stability of the oils during transporting and storage. There are no set ranges for TBA values in either crude or refined fish oils and the main reason is the large number of analytical procedures available to determine TBA in foodstuff which make comparison of results difficult. In a previous study conducted by Oliveira and collaborators, oxidized fish oil had values above 1 mg MDA/ Kg of oil (unpublished data).

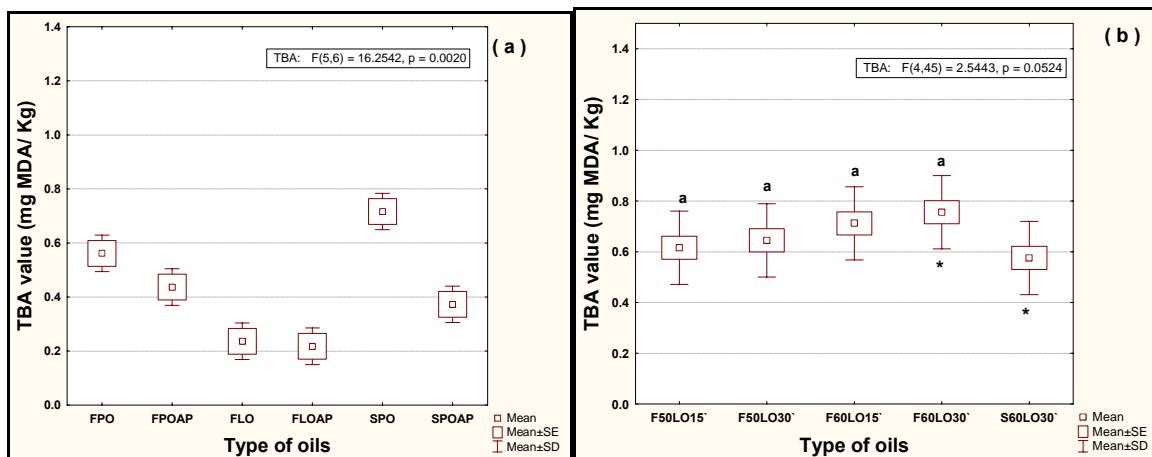


Figure 12. TBA value of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascobyl palmitate; (b) Oils rendered in the laboratory: F50LO15' Fall liver oil rendered at 50 °C for 15 min; F50LO30' Fall liver oil rendered at 50 °C for 30 min; F60LO15' Fall liver oil rendered at 60 °C for 15 min; F60LO30' Fall liver oil rendered at 60 °C for 30 min; S60LO30' Spring liver oil rendered at 60 °C for 30 min. Different letters indicate statistical differences between Fall liver oils rendered in the laboratory ($P < 0.05$). * indicates when a statistical difference between Fall and Spring liver oils rendered at 60 °C for 30 min was determined ($P < 0.05$)

Water activity

Water activity is seldom an analysis carried out in oils because fish oils tend to have very small quantities of water, which is considered an impurity (Table 1). Water activity is defined as the proportion of the water vapor pressure of the material to the vapor pressure of pure water at identical temperatures. Therefore, water activity is not directly correlated to the water content of a sample. The preferred method to measure small quantities of water present in fish oils is the Karl-Fisher method, but at the beginning of the study we encountered difficulties ordering one of the key reagents needed to conduct the method, which was in backorder for a period of 5 months. Therefore, water activity was used to provide general information about differences between fish oil produced at sea and fish oils rendered in the laboratory. The values of water activity of crude pollock oil samples are shown in Figure 13. Water activity was higher in Spring oils than in Fall oils for oils produced at sea, and similar differences ($P < 0.05$) were observed for oils rendered in the laboratory. This is likely due to the higher moisture content in Spring livers (Table 6). For oils rendered in the laboratory, it is clear that higher rendering temperature and longer time significantly decrease the water activity of Fall liver oils.

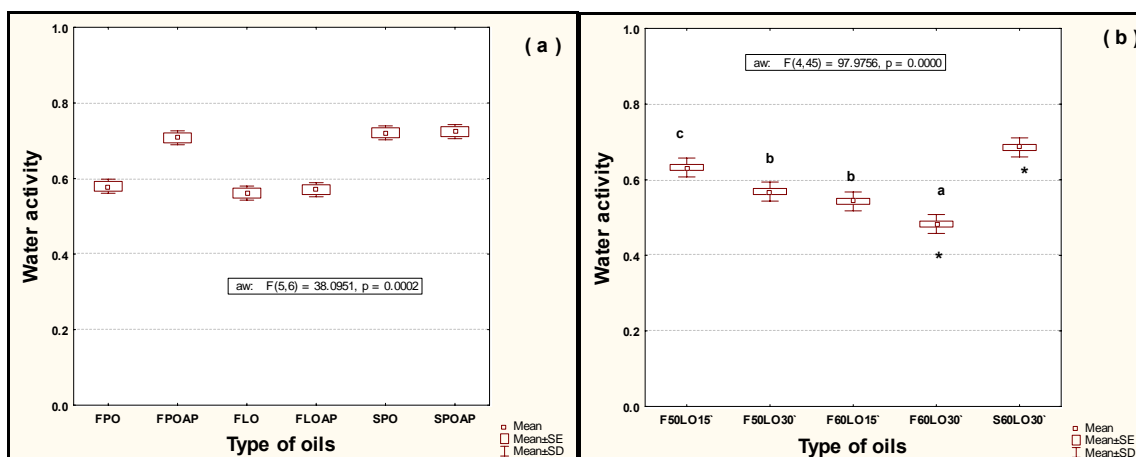


Figure 13. Water activity of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascobyl

palmitate; (b) Oils rendered in the laboratory: F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min. Different letters indicate statistical differences between Fall liver oils rendered in the laboratory (P<0.05). * indicates when a statistical difference between Fall and Spring liver oils rendered at 60 °C for 30 min was determined (P<0.05)

Phosphorus content

Phosphorus contents (ppm) of oils produced at sea and of liver oils rendered in the laboratory are shown in Figure 14. As shown in Table 1, the suggested range for this parameter in crude fish oils is quite wide varying from 5-100 ppm. Phosphorus contents of oils produced at sea are in the lower range of this set standard and did not exceed 10 ppm. For oils rendered in the laboratory, the means of phosphorus content ranged from 10 ppm to about 15 ppm. A significant difference was detected between oils rendered in the laboratory, with liver oils obtained 50°C for 15 min showing higher phosphorus content than all other oils. It is noteworthy to mention that high phosphorus content in oils can pose difficulties during distillation (SPD). As previously mentioned, the main source of phosphorus in fish oils are phospholipids and these compounds tend to solidify forming a viscous gel when oils rich in phospholipids are introduced in the evaporator under very low pressure conditions. Phosphorus content analysis is much more accurate than lipid classes analysis, for reasons already discusses in previous sections, and the results in Figure 14 are encouraging because with the exception of samples F50LO15`, all other oils show very low phosphorus content and this is a good indication that PL in oils are low and should not interfere in SPD purification.

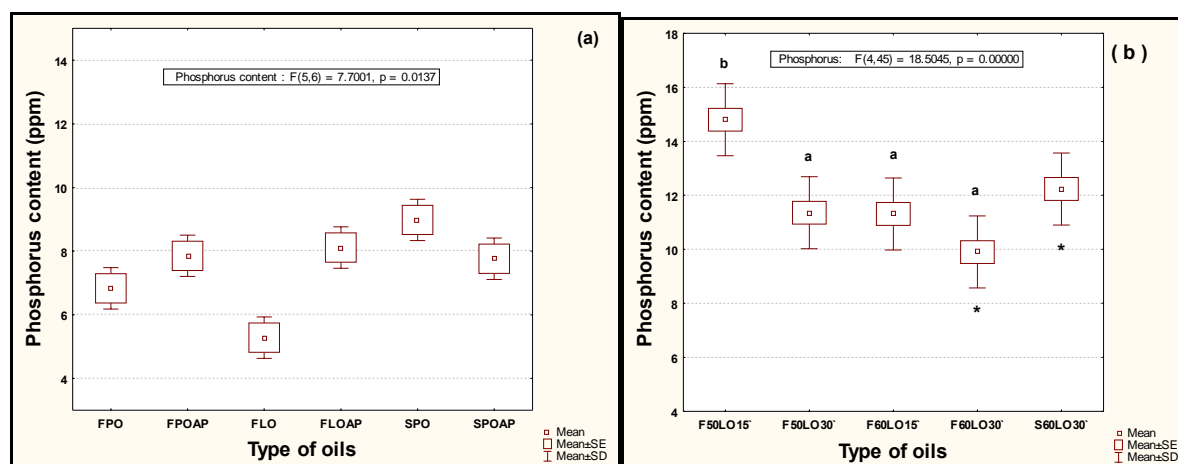


Figure 14. Phosphorus content of content of *F/T American Triumph* oils and liver oils rendered in the laboratory. (a) *F/T American Triumph* oils: FPO Fall pollock oil; FLO Fall pollock liver oil; SPO Spring pollock oil; AP ascobyl palmitate; (b) Oils rendered in the laboratory: F50LO15` Fall liver oil rendered at 50 °C for 15 min; F50LO30` Fall liver oil rendered at 50 °C for 30 min; F60LO15` Fall liver oil rendered at 60 °C for 15 min; F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min. Different letters indicate statistical differences between Fall liver oils rendered in the laboratory (P<0.05). * indicates statistical difference between Fall and Spring liver oils rendered at 60°C for 30 min (P<0.05)

Chemical and physical characterization of protein fractions

Proximate composition

Figure 15 depicts the freeze-dried pollock liver protein powders obtained from livers processed at different temperatures (50 °C and 60 °C) and times (15 min and 30 min). The protein powders (freeze-dried) produced at 60 °C for 30 min (F60PO30) was lighter in color than those produced at 50 °C for 15 and 30 min.

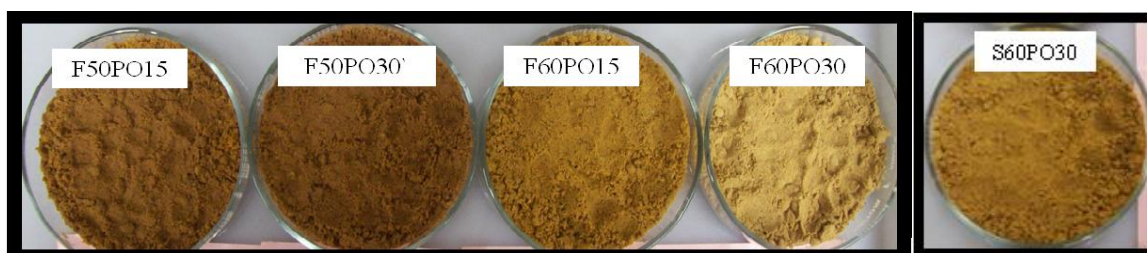


Figure 15. Picture of pollock liver protein powders recovered during processing in differences times. F50PO15 freeze dried protein powder from Fall pollock livers rendered at 50 °C for 15 min; F50PO30 freeze dried protein powder from Fall pollock livers rendered at 50 °C for 30 min; freeze dried protein powder from Fall pollock livers rendered at 60 °C for 15 min; freeze dried protein powder from Fall pollock livers rendered at 60 °C for 30 min; S60PO30 freeze dried protein powder from Spring livers rendered at 50 °C for 30 min

Table 21 shows the proximate composition of freeze dried liver protein powders. The percent of water loss of the protein pellets during freeze drying for samples F5015' (pellet recovered from Fall livers at 50 °C for 15 min) , F5030' (pellet recovered from Fall livers at 50 °C for 30 min), F6015' (pellet recovered from Fall livers at 60 °C for 15 min), F6030' (pellet recovered from Fall livers at 60 °C for 30 min), and S6030' (pellet recovered from Spring livers at 60 °C for 30 min) were 57.8%, 64.2%, 60.3%, 61.7%, and 77.2%, respectively. Using moisture values in Table 21, the total water content in the protein pellets prior to freeze drying can be estimated for F5015', F5030', F6015', F6030', and S6030' at 64.3%, 70.2%, 68.2%, 68.7%, and 83.6% respectively. This signifies that only 35.7% to 16.4% of the protein pellets removed for the liver mixture by centrifugation, after rendering, was composed of solids. The solids are mainly made of the insoluble protein fraction of the livers, the insoluble minerals and traces of lipids likely in the form of lipoproteins and phospholipids, not recovered in the oil fraction. Table 8 shows that the recoveries for the protein pellets ranged from 23.3 to 15.8% of the initial weight of liver tissue, with water being the major constituent of this material. Therefore, it can be concluded that the lipids in the protein pellets amounted to a very small percentage of the total lipid content in pollock livers. Protein content was significantly higher in Fall liver protein powders rendered for longer time (30 min) at either temperature. Liver powders obtained from rendering liver oils at 50 °C for 15 min had the lowest protein content. Conversely, the lipid content of the powders decreased as time and temperature of the rendering process increased. Only small differences in ash and moisture were observed with moisture values ranging from 7.9 to 6.0% and ash values ranging from 4.8 to 3.1%. Liver protein powders from Spring livers had the lowest lipid content and highest protein content. This is expected because pollock Spring livers had lower lipids and much higher moisture content. Water plays an important role in the separation of water and lipid phases after rendering for this reason some researchers suggest adding water to the raw material in order to improve oil and protein recovery (Sathivel, 2003). On the whole, the lipids in the protein powders correspond to about 3% of the lipids initially present in the livers and this is a relatively small amount of lipids that did not get recovered with the oil fraction separated by centrifugation.

Table 21. Proximate composition of freeze-dried liver powders (% wt./ wt.)

Sample	F5015'	F5030'	F6015'	F6030'	S6030'	
FD Protein powders	Protein	45.9 ± 0.8 ^c	48.1 ± 1.2 ^a	47.4 ± 2.3 ^b	49.8 ± 2.6 ^a _y	62.5 ± 1.9 _x
	Lipid	44.6 ± 0.8 ^a	42.0 ± 1.5 ^b	40.2 ± 1.5 ^{bc}	38.5 ± 2.4 ^c _x	26.3 ± 2.2 _y
	Moisture	6.5 ± 0.4 ^c	6.0 ± 0.7 ^b	7.9 ± 0.9 ^a	7.0 ± 0.7 ^b _x	6.4 ± 0.9 _x
	Ash	3.1 ± 0.3 ^c	3.9 ± 0.5 ^b	4.4 ± 1.2 ^{ab}	4.7 ± 0.7 ^a _x	4.8 ± 0.7 _x

F5015' protein powder recovered from rendering Fall livers at 50°C for 15 min; F5030' protein powder recovered from rendering Fall livers at 50°C for 30 min; F6015' protein powder recovered from rendering Fall

livers at 60 °C for 15 min; F6030* protein powder recovered from rendering Fall livers at 60 °C for 30 min; S6030* protein powder recovered from rendering Spring livers at 60 °C for 30 min; Different superscript letters within a row indicate statistical differences between Fall liver oils rendered in the laboratory (P<0.05); Different subscript letters within a row indicate statistical difference between Fall and Spring liver oils rendered at 60 °C for 30 min (P<0.05)

Figure 17 shows the free fatty acid content of the protein powders, and values are 1-2% higher than values determined for their fish oils counterparts (Figure 9b). This indicates that freeze drying may cause hydrolysis of lipids. Figure 18 presents the PV of the protein powders, and results indicate significant abundance of primary products of lipid oxidation in this fraction as compared to the fish oils (Figure 10b). Similarly, in Figure 19 the *p*-AV indicates also much higher abundance of secondary products of lipid oxidation in the protein powders than in the fish oils (Figure 11b). In light of these results, one would expect TBA values (Figure 20) in the protein powders to follow the same pattern, being much higher than in the fish oils (Figure 12b); however this is not the case. Again, these results show that TBA values lead to dubious results as pointed out previously. On the whole, it seems reasonable to state that the lipids in the liver protein powders have likely oxidized during freeze drying. Freeze drying is a very mild processing method to remove moisture from biological tissues that takes advantage of the sublimation properties of water. Freeze drying is often utilized to dry materials without affecting its nutrients and heat labile components, and this is the reason freeze drying was the drying method of choice in this study. Freeze drying is a costly drying process because of the high energy demand to operate the vacuum pump and the long processing times at low temperatures, and in an industrial setting it is unlikely that freeze drying would be cost effective to produce liver protein powders. Consequently, additional research is needed to investigate alternative methods to dry pollock liver protein fraction to produce edible powders that are free of harmful lipid oxidation products. Alternatively, this protein fraction could be added to fishmeal. As shown in Table 21, the solids in the protein pellets are a low ash material that could increase the protein content of fishmeal.

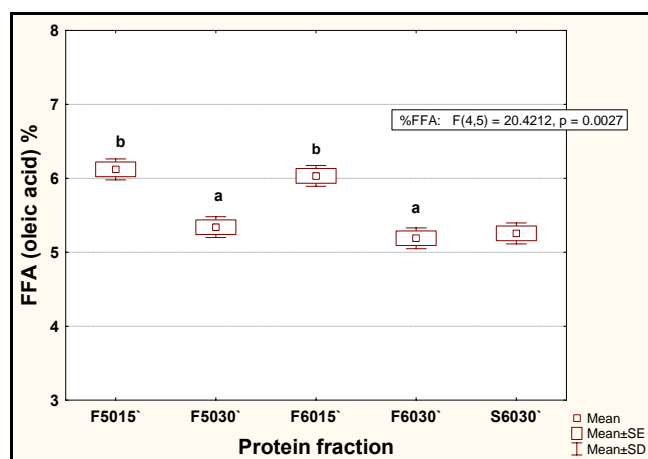


Figure 17. Free fatty acids content (%) in liver protein powders. Different letters indicate statistical differences between rendering conditions (P<0.05); * indicates when a statistical difference between Fall and Spring liver protein powders obtained at 60 °C for 30 min was determined (P<0.05)

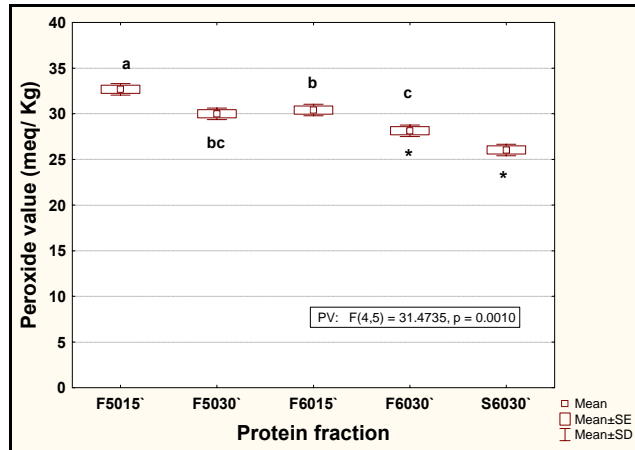


Figure 18. Peroxide values (meq/ Kg) in protein powders. Different letters indicate statistical differences between rendering conditions ($P < 0.05$); * indicates when a statistical difference between Fall and Spring liver protein powders obtained at 60 °C for 30 min was determined ($P < 0.05$)

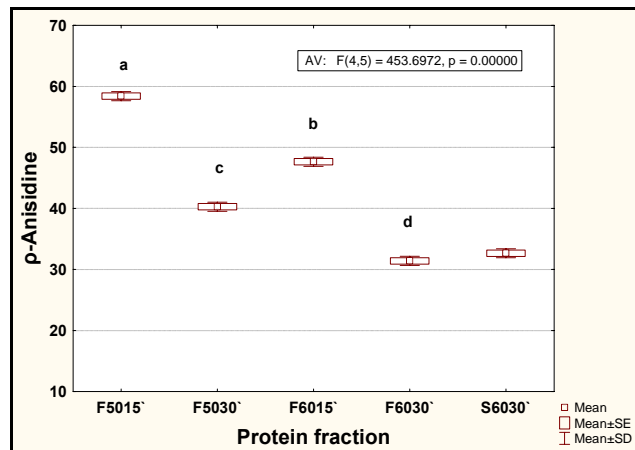


Figure 19. Anisidine values in protein powders. Different letters indicate statistical differences between rendering conditions ($P < 0.05$); * indicates when a statistical difference between Fall and Spring liver protein powder obtained at 60 °C for 30 min was determined ($P < 0.05$)

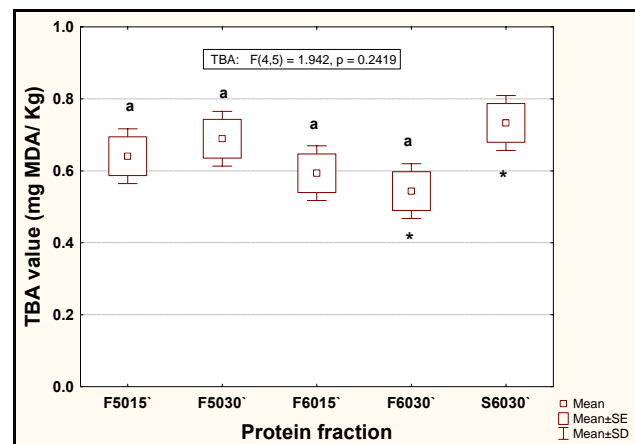


Figure 20. Thiobarbituric Acid (TBA) values in protein powders. Different letters indicate statistical differences between rendering conditions ($P < 0.05$); * indicates when a statistical difference between Fall and Spring liver protein powder obtained at 60 °C for 30 min was determined ($P < 0.05$)

Table 22 shows the amino acid composition of the liver protein powders. Significant differences in the amino acids composition were determined, but these are in general very small for Fall liver protein powders and reflect the precision of the measurements. The amino acid composition of male and female pollock livers from fish harvested in the Gulf of Alaska

were previously reported by Oliveira and Bechtel (2006b), and results of that study are similar to values shown in Table 22. Overall the protein powders show high values for total essential amino acids for infants (FAO/WHO, 1973), with Fall livers having 2% more TEAA than Spring livers. This signifies that pollock liver protein powders have high nutritional value and show potential for use as nutraceutical, a fast growing segment of the domestic food industry.

Table 22. Average amino acid profiles of liver oils rendered in the laboratory (% wt./ wt.)

Amino acids (AA)	F5015'	F5030'	F6015'	F6030'	S6030'
Alanine (ALA)	5.7 ± 0.0 ^b	5.6 ± 0.0 ^b	5.9 ± 0.2 ^{b^a}	5.5 ± 0.0 ^{b_y}	5.7 ± 0.0 _x
Arginine (ARG)	7.2 ± 0.0 ^a	6.9 ± 0.0 ^{ab}	6.6 ± 0.5 ^b	6.5 ± 0.2 ^{b_y}	7.1 ± 0.1 _x
Aspartic acid (ASP)	10.5 ± 0.0 ^b	10.6 ± 0.6 ^b	10.7 ± 0.1 ^b	11.5 ± 0.5 ^{a_y}	10.1 ± 0.3 _x
Glutamic acid (GLU)	13.8 ± 0.1 ^a	13.4 ± 0.8 ^a	13.6 ± 0.3 ^a	11.8 ± 0.9 ^b	14.1 ± 0.8 _x
Glycine (GLY)	4.8 ± 0.0 ^a	4.8 ± 0.0 ^a	4.8 ± 0.0 ^a	4.7 ± 0.0 ^{a_x}	4.8 ± 0.0 _x
Histidine (HIS) [†]	2.6 ± 0.0 ^b	2.8 ± 0.0 ^a	2.5 ± 0.0 ^b	2.8 ± 0.1 ^{a_y}	2.4 ± 0.1 _x
Isoleucine (ILE) [†]	5.1 ± 0.0 ^a	5.0 ± 0.0 ^a	5.2 ± 0.2 ^a	5.3 ± 0.1 ^{a_y}	4.8 ± 0.1 _x
Leucine (LEU) [†]	9.4 ± 0.0 ^a	9.3 ± 0.0 ^a	9.4 ± 0.3 ^a	9.4 ± 0.1 ^{a_x}	9.0 ± 0.1 _y
Lysine (LYS) [†]	8.8 ± 0.1 ^a	8.0 ± 0.0 ^b	8.7 ± 0.0 ^a	7.9 ± 0.2 ^{b_y}	8.4 ± 0.1 _x
Methionine (MET) [†]	3.4 ^{**}	3.3 ± 0.0	3.4 ^{**}	3.4 ± 0.1 _x	3.2 ± 0.0 _y
Phenylalanine (PHE) [†]	5.7 ± 0.0 ^a	5.7 ± 0.0 ^a	5.7 ± 0.1 ^a	5.6 ± 0.1 ^{a_y}	5.4 ± 0.0 _y
Proline (PRO)	3.9 ± 0.0 ^a	2.6 ± 0.1 ^b	4.0 ± 0.1 ^a	2.6 ± 0.4 ^{b_y}	4.1 ± 0.1 _x
Serine (SER)	4.9 ± 0.0 ^a	5.0 ± 0.1 ^a	5.1 ± 0.1 ^a	5.1 ± 0.1 ^{b_x}	4.8 ± 0.0 _y
Threonine (THR) [†]	5.4 ± 0.0 ^b	5.4 ± 0.1 ^b	5.6 ± 0.2 ^a	5.7 ± 0.1 ^{a_x}	5.3 ± 0.1 _y
Tyrosine (TYR)	4.9 ± 0.0 ^a	5.0 ± 0.1 ^a	4.6 ± 0.4 ^b	5.1 ± 0.0 ^{a_x}	4.2 ± 0.1 _y
Valine (VAL) [†]	6.8 ± 0.0 ^{ab}	6.6 ± 0.1 ^b	6.9 ± 0.2 ^{ab}	7.1 ± 0.2 ^{a_x}	6.6 ± 0.1 _y
TEAA (% total AA)	47.2	46.2	47.4	47.2	45.1

** Problems were encountered with MET values requiring additional analysis; however, there was only enough samples left for one determination; [†] TEAA = total essential amino acids for infant; Different superscript letters within a row indicate statistical differences between Fall liver protein powders (P<0.05); Different subscript letters within a row indicate statistical difference between Fall and Spring liver protein powders obtained at 60 °C for 30 min (P<0.05)

Characterization of purified oils

SPD experiments and variables

Table 23 summarizes the SPD variables tested for the oils samples purified. Test runs were conducted using FPOAP (Fall pollock oil with ascorbyl palmitate produced at sea) to determine the most adequate operating temperature of the evaporator (190 °C; 200 °C; 210 °C) and roller speed (500 rpm; 450 rpm). The oil flow in the bench-top SPD unit cannot be set for a specific value; however, in industrial scale SPD units, the oil flow is controlled. In the bench-top unit, flow was measured with a chronometer while observing the decrease in the volume of oil in the graduated feeding flask. Thus, the results shown in Table 23 for flow rate are not as accurate as these would be in an industrial scale SPD unit. The vacuum is only measured and cannot be controlled; vacuum pump and the diffusion pump have two operational modes 'on' and 'off'. The manufacturer suggests pressures lower than 0.5 mbar for degassing the oils (evaporator temperature set to 150°C), and pressures below 0.02 for removing oil impurities. If leak occurs, the system will not stabilize at a given pressure and will not reach pressures below 0.05 mbar. If a leak is detected the glass fitting joints need adjustment, or application of additional vacuum grease to seal the unit. The pressures reported in Table 23 were recorded using the electronic manometer depicted in Figure 6. After establishing the best conditions to operate the SPD unit using FPOAP samples the other four fish oil samples listed in Table 23 were also purified in triplicate.

Table 23. Short-path distillation variables measured experimentally for each test run

Type of oil	Pressure (mbar)	Flow rate (mL/min)	Speed (rpm)	Temperature (°C)	Replicate
FPOAP	0.114	10.0	500	150	A
FPOAP	0.182	6.7	500	150	B
FPOAP	0.133	8.3	500	150	C
FPOAP	0.011	6.2	500	190	A
FPOAP	0.017	7.5	500	190	B
FPOAP	0.015	7.0	500	190	C
FPOAP	0.016	6.2	500	200	A
FPOAP	0.017	7.5	500	200	B
FPOAP	0.015	7.0	500	200	C
FPOAP	0.018	6.2	500	210	A
FPOAP	0.018	7.5	500	210	B
FPOAP	0.015	7.0	500	210	C
FPOAP	0.220	8.0	450	150	A
FPOAP	0.295	10.0	450	150	B
FPOAP	0.345	10.0	450	150	C
FPOAP	0.015	6.1	450	210	A
FPOAP	0.018	9.0	450	210	B
FPOAP	0.015	6.2	450	210	C
SPOAP	0.057	10.0	450	150	A
SPOAP	0.047	10.3	450	150	B
SPOAP	0.502	10.0	450	150	C
SPOAP	0.013	8.6	450	210	A
SPOAP	0.012	6.0	450	210	B
SPOAP	0.012	10	450	210	C
LOAP	0.035	10.0	450	150	A
LOAP	0.024	10.2	450	150	B
LOAP	0.050	10.0	450	150	C
LOAP	0.012	7.6	450	210	A
LOAP	0.012	6.9	450	210	B
LOAP	0.012	7.0	450	210	C
F60LOAP30`	0.032	9.0	450	150	A
F60LOAP30`	0.037	9.5	450	150	B
F60LOAP30`	0.047	10.0	450	150	C
F60LOAP30`	0.016	8.0	450	210	A
F60LOAP30`	0.012	9.5	450	210	B
F60LOAP30`	0.019	8.0	450	210	C
S60LOAP30`	0.026	10.0	450	150	A
S60LOAP30`	0.037	10.0	450	150	B
S60LOAP30`	0.025	9.5	450	150	C
S60LOAP30`	0.011	9.0	450	210	A
S60LOAP30`	0.014	9.5	450	210	B
S60LOAP30`	0.014	9.0	450	210	C

FPOAP Fall pollock oil with ascorbyl palmitate (*F/T American Triumph*); FLOAP Fall liver oil with ascorbyl palmitate (*F/T American Triumph*); SPOAP Spring pollock oil with ascorbyl palmitate (*F/T American Triumph*); F60LO30` Fall liver oil rendered at 60 °C for 30 min; S60LO30` Spring liver oil rendered at 60 °C for 30 min.

Table 24 shows the SPD yields of Fall pollock oil (FPOAP) at each evaporator temperature and roller speed tested. As expected, increasing the evaporator temperature decreases the oil

recovery yield because higher temperature will remove more of the unwanted impurities. The roller speed significantly influence the results, and this was not expected. The rationale behind decreasing roller speed from 500 rpm to 450 rpm is solely to reduce stress in the mechanic parts of the wiper blades system. If the roller speed is too low, the residence time of the oil in the evaporator is shorter and would negatively influence the removal of impurities. The residence time of the oil in the evaporator (continuous flow mode) cannot be easily estimated in the SPD bench-top unit because a feed flow controller is not available for this model. It is possible that recovery yields can be optimized to values between 80-85%, but this will require further research work to scale-up the process for industrial application.

Table 24. Short-path distillation yields (%)

Sample code	N	Speed (rpm)	Temperature (°C)	Oil recovery (%)
FPOAP	3	500	190	89.0 ± 0.4 ^a
FPOAP	3	500	200	85.6 ± 1.1 ^b
FPOAP	3	500	210	77.2 ± 1.4 ^c
FPOAP	3	450	210	66.0 ± 0.8 ^d

FPOAP Fall pollock oil with ascorbyl palmitate (*F/T American Triumph*); FLOAP Fall liver oil with ascorbyl palmitate (*F/T American Triumph*); SPOAP Spring pollock oil with ascorbyl palmitate (*F/T American Triumph*); F60LO30 Fall liver oil rendered at 60 °C for 30 min; S60LO30 Spring liver oil rendered at 60 °C for 30 min; Different superscript letters within a row indicate statistical difference at P<0.05.

Table 25 shows the lipid classes results, and oils were comprised mostly of triacylglycerides, presenting only traces of phospholipids. The planar chromatography couple to flame ionization detection is not suitable for the determination of low levels of phospholipids, as previously discussed. The comparison of pollock purified oil and pollock crude oil (extracted from Table 8) showed that high temperature did not significantly influence the distribution of the lipids classes, except that SPD removed sterols, which in pollock oil are mainly in the form of cholesterol (Oliveira and Bechtel, 2006b). Interestingly, the ST peak is lower in the oils after degassing, decreasing further after the second pass. It would have been useful to quantify cholesterol in the oils. Oliveira and Bechtel determined in a previous study that pollock livers cholesterol averaged 620 mg/ 100 g oil in female pollock livers and 313 mg/ g oil in male pollock livers from fish harvested in Spring 2003 from Gulf of Alaska in water surrounding Kodiak Island (Oliveira and Bechtel, 2006b). Removing cholesterol with SPD is a benefit, because the product label of SPD purified fish oils would show that the product is free of cholesterol.

Table 25. Lipid classes analysis of crude and purified pollock oils produced at sea (*F/T American Triumph*)

Sample code	n	Speed (rpm)	Temperature (°C)	TAG	FFA	DAG/ST	MAG	PL
FPOAP (crude)				99.2	0	0.6	0	0.2
FPOAP	3	500	150	99.5	0.0	0.3	0.0	0.2
FPOAP	3	500	190	99.6	0.0	0.2	0.0	0.2
FPOAP	3	500	200	99.8	0.0	0.0	0.0	0.2
FPOAP	3	500	210	99.9	0.0	0.0	0.0	0.1
FPOAP	3	450	210	99.7	0.0	0.0	0.0	0.2

FPOAP Fall pollock oil with ascorbyl palmitate (*F/T American Triumph*); TAG triacylglycerides; FFA free fatty acids; DAG/ST diacylglycerols/sterols (co-eluting classes); MAG monoacylglycerides; PL phospholipids

Table 26 shows the GDC values of purified pollock oils color indexes. Oil color did not change during the process but the oil became less turbid after water an ascorbyl palmitate

were removed by distillation. The Gardner Delta Color Meter uses a back light that illuminates the oil sample; therefore, if more light passes through the sample the GDC value will decrease slightly as observed in the data presented in Table 26.

Table 26. Color of pollock oils produced at sea (*F/T American Triumph*) and of pollock liver oils rendered in the laboratory

Sample code	N	Temperature (°C)	GDC value
FPOAP	3	150	12
FPOAP	3	190	12
FPOAP	3	200	11
FPOAP	3	210	11
SPOAP	3	150	6
SPOAP	3	210	5
FLOAP	3	150	5
FLOAP	3	210	5
F60LOAP30` 150 °C	3	150	8
F60LOAP30` 210°C	3	210	10
S60LOAP30` 150 °C	3	150	9
S60LOAP30` 210°C	3	210	10

FPOAP Fall pollock oil with ascorbyl palmitate (*F/T American Triumph*); FLOAP Fall liver oil with ascorbyl palmitate (*F/T American Triumph*); SPOAP Spring pollock oil with ascorbyl palmitate (*F/T American Triumph*); GDC Garder Delta Color value

Table 27 and Table 28 show the FA profiles in mg/ g of oil and in % wt./ wt. of Fall pollock oil produced at sea and purified at different temperatures (190 °C, 200 °C and 210°C). The fatty acid composition did not change significantly from crude oil to degassed oil (150°C - data not shown). Losses of essential fatty acids due to the purification were not observed in oils purified at any of the temperatures tested. In the FA results reported in mg/ g of oil, it can be seen that an increase in the total saponifiables occurred after distillation when these are compared to values for the FPOAP crude oil (Table 13), and this is expected because SPD removes impurities. Overall, the results from fatty acid analysis are very encouraging because these demonstrate that it is possible to subject pollock oil to a temperature of 210°C under very low pressure (0.01 mbar) without observing significant losses in the fatty acid makeup.

Table 27. Fatty acid profiles of crude and purified Fall pollock oils produced at sea (*F/T American Triumph*) in % wt./ wt.

Fatty acids	FPOAP 190 °C n=3 500 rpm	FPOAP 200 °C n=3 500 rpm	FPOAP 210 °C n=3 500 rpm	FPOAP 210 °C n=3 450 rpm
14:0	4.67 ± 0.1 ^a	4.69 ± 0.1 ^a	4.76 ± 0.0 ^a _y	4.91 ± 0.0 _x
14:1ω7	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a _x	0.10 ± 0.0 _x
14:1ω5	0.11 ± 0.0 ^a	0.11 ± 0.0 ^a	0.10 ± 0.0 ^a _x	0.11 ± 0.0 _x
Iso or Ante iso 15:0	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a _x	0.10 ± 0.0 _x
15:0	0.18 ± 0.0 ^a	0.18 ± 0.0 ^a	0.17 ± 0.0 ^a _x	0.18 ± 0.0 _x
Iso or Anteiso 16:0	0.18 ± 0.0 ^a	0.13 ± 0.1 ^a	0.18 ± 0.0 ^a _x	0.18 ± 0.0 _x
16:0	8.29 ± 0.2 ^a	8.29 ± 0.1 ^a	8.37 ± 0.1 ^a _y	8.50 ± 0.0 _x
Unknown 1	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a _x	0.00 ± 0.0 _x
16:1ω11	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a _y	0.19 ± 0.0 _x
16:1ω9	0.18 ± 0.0 ^a	0.18 ± 0.0 ^a	0.19 ± 0.0 ^a _x	0.08 ± 0.0 _y
Unknown 2	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a _x	0.00 ± 0.0 _y
16:1ω7	9.64 ± 0.2 ^a	9.63 ± 0.1 ^a	9.71 ± 0.1 ^a _y	9.95 ± 0.1 _x
16:1ω5	0.29 ± 0.0 ^a	0.29 ± 0.0 ^a	0.29 ± 0.0 ^a _x	0.30 ± 0.0 _x

16:1 ω 4	0.14 \pm 0.0 ^a	0.14 \pm 0.0 ^a	0.14 \pm 0.0 ^a _x	0.14 \pm 0.0 _x
16:2 ω 4	0.09 \pm 0.0 ^a	0.09 \pm 0.0 ^a	0.09 \pm 0.0 ^a _x	0.09 \pm 0.0 _x
Iso 17:0	0.0 \pm 0.0	0.0 \pm 0.0	0.00 \pm 0.0 _y	0.04 \pm 0.0 _x
Ante iso 17:0	0.84 \pm 0.0 ^a	0.84 \pm 0.0 ^a	0.84 \pm 0.0 ^a _y	0.87 \pm 0.3 _x
17:0	0.57 \pm 0.0 ^a	0.57 \pm 0.0 ^a	0.58 \pm 0.0 ^a _x	0.59 \pm 0.2 _x
Unknown 3	0.42 \pm 0.0 ^a	0.42 \pm 0.0 ^a	0.45 \pm 0.0 ^a _x	0.42 \pm 0.0 _y
17:1 ω 11	0.09 \pm 0.0 ^a	0.09 \pm 0.0 ^a	0.0 \pm 0.0 ^a _y	0.09 \pm 0.0 _x
17:1 ω 9	0.00 \pm 0.0	0.00 \pm 0.0	0.00 \pm 0.0 _x	0.00 \pm 0.0 _x
17:1 ω 7	0.97 \pm 0.0 ^a	0.97 \pm 0.0 ^a	0.97 \pm 0.0 ^a _y	1.00 \pm 0.0 _x
18:0	1.37 \pm 0.0 ^a	1.37 \pm 0.0 ^a	1.36 \pm 0.0 ^a _x	1.37 \pm 0.0 _x
Unknown 3	0.0 \pm 0.0 ^b	0.0 \pm 0.0 ^b	0.0 \pm 0.0 ^b _x	0.00 \pm 0.0 _x
18:1 ω 9 <i>trans</i>	2.03 \pm 0.0 ^a	2.02 \pm 0 ^a	2.02 \pm 0.0 ^a _x	2.04 \pm 0.0 _x
18:1 ω 9 <i>cis</i>	5.31 \pm 0.0 ^a	5.30 \pm 0.0 ^a	5.31 \pm 0.0 ^a _x	5.34 \pm 0.0 _x
18:1 ω 7	3.21 \pm 0.0 ^a	3.20 \pm 0.0 ^a	3.22 \pm 0.0 ^a _x	3.23 \pm 0.0 _x
Unknown 4	0.54 \pm 0.0 ^a	0.54 \pm 0.0 ^a	0.54 \pm 0.0 _x	0.54 \pm 0.0 _x
C18:2 ω 6 <i>trans</i>	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0 _x	0.00 \pm 0.0 _x
18:2 ω 6 <i>cis</i>	0.57 \pm 0.0 ^a	0.56 \pm 0.0 ^a	0.56 \pm 0.0 ^a _x	0.57 \pm 0.0 _x
Unknown 5	0.00 \pm 0.0	0.00 \pm 0.0	0.00 \pm 0.0 _x	0.0 \pm 0.0 _x
18:3 ω 6	0.38 \pm 0.0 ^a	0.38 \pm 0.0 ^a	0.39 \pm 0.0 ^a _x	0.38 \pm 0.0 _x
Unknown 6	0.06 \pm 0.0 ^b	0.05 \pm 0.0 ^b	0.00 \pm 0.0 ^a _x	0.06 \pm 0.0 _x
18:3 ω 3	0.32 \pm 0.0 ^a	0.32 \pm 0.0 ^a	0.31 \pm 0.0 ^a _x	0.32 \pm 0.0 _x
18:4 ω 3	1.57 \pm 0.0 ^a	1.56 \pm 0.0 ^a	1.57 \pm 0.0 ^a _x	1.58 \pm 0.0 _x
Unknown 7	0.35 \pm 0.0 ^b	0.35 \pm 0.0 ^b	0.0 \pm 0.0 ^a _y	0.36 \pm 0.0 _x
Iso or anteiso 20:0	0.0 \pm 0.0	0.0 \pm 0.0	0.00 \pm 0.0 _y	0.06 \pm 0.0 _x
20:0	0.11 \pm 0.0 ^a	0.12 \pm 0.0 ^a	0.11 \pm 0.0 ^a _x	0.09 \pm 0.0 _x
20:1 ω 11	15.96 \pm 0.1 ^a	15.94 \pm 0.1 ^a	15.85 \pm 0.0 ^a _x	15.78 \pm 0.0 _y
20:1 ω 9	4.48 \pm 0.0 ^a	4.50 \pm 0.6 ^a	4.51 \pm 0.1 ^a _x	4.38 \pm 0.0 _y
20:1 ω 7	0.33 \pm 0.0 ^a	0.33 \pm 0.0 ^a	0.33 \pm 0.0 ^a _x	0.33 \pm 0.0 _x
20:1 ω 5	0.12 \pm 0.0 ^a	0.12 \pm 0.0 ^a	0.12 \pm 0.0 ^a _x	0.12 \pm 0.0 _x
20:2 ω 6	0.14 \pm 0.0 ^a	0.14 \pm 0.0 ^a	0.14 \pm 0.0 ^a _x	0.14 \pm 0.0 _x
21:0	0.07 \pm 0.0 ^a	0.07 \pm 0.0 ^a	0.07 \pm 0.0 ^a _x	0.07 \pm 0.0 _x
20:3 ω 6	0.15 \pm 0.0 ^a	0.15 \pm 0.0 ^a	0.14 \pm 0.0 ^a _x	0.15 \pm 0.0 _x
20:3 ω 3	0.00 \pm 0.0	0.00 \pm 0.0	0.00 \pm 0.0 _x	0.00 \pm 0.0 _x
Unknown 8	0.07 \pm 0.0 ^a	0.07 \pm 0.0 ^a	0.07 \pm 0.0 _x	0.07 \pm 0.0 _x
20:4 ω 3	0.39 \pm 0.0 ^a	0.39 \pm 0.0 ^a	0.38 \pm 0.0 ^a _x	0.39 \pm 0.0 _x
20:5 ω 3 (EPA)	10.25 \pm 0.1 ^a	10.21 \pm 0.6 ^a	10.19 \pm 0.0 _x	10.16 \pm 0.0 _x
22:0	0.00 \pm 0.0	0.00 \pm 0.0	0.00 \pm 0.0 _x	0.00 \pm 0.0 _x
22:1 ω 11	15.98 \pm 0.3 ^a	15.98 \pm 0.2 ^a	15.87 \pm 0.2 _x	15.45 \pm 0.1 _y
22:1 ω 9	1.13 \pm 0.0 ^a	1.13 \pm 0.0 ^a	1.12 \pm 0.0 ^a _y	1.08 \pm 0.0 _y
22:1 ω 7	0.37 \pm 0.0 ^a	0.38 \pm 0.0 ^a	0.37 \pm 0.0 ^a _x	0.36 \pm 0.0 _x
22:2 ω 6	0.53 \pm 0.0 ^a	0.54 \pm 0.0 ^a	0.53 \pm 0.0 ^a _x	0.52 \pm 0.0 _x
Unknown 9	0.00 \pm 0.0	0.00 \pm 0.0	0.00 \pm 0.0 _x	0.00 \pm 0.0 _x
22:5 ω 3	0.83 \pm 0.0 ^a	0.83 \pm 0.0 ^a	0.83 \pm 0.0 ^a _x	0.80 \pm 0.0 _x
22:6 ω 3 (DHA)	5.32 \pm 0.1 ^a	5.31 \pm 0.0 ^a	5.27 \pm 0.0 ^a _x	5.18 \pm 0.0 _y
Unknown 10	0.27 \pm 0.0 ^a	0.27 \pm 0.0 ^a	0.26 \pm 0.0 ^a _x	0.26 \pm 0.0 _x
24:1 ω 9	0.51 \pm 0.0 ^a	0.51 \pm 0.0 ^a	0.50 \pm 0.0 ^a _x	0.47 \pm 0.0 _x
Total fatty acids	100.00 \pm 0.0	100.00 \pm 0.0	100.0 \pm 0.0	100.0 \pm 0.0
Σ SAT	16.30 \pm 0.4 ^a	16.49 \pm 0.3 ^a	16.54 \pm 0.1 ^a _y	16.98 \pm 0.1 _x
Σ MUFA	61.88 \pm 0.2 ^a	60.98 \pm 0.2 ^b	60.90 \pm 0.12 ^b _x	60.86 \pm 0.1 _x
Σ PUFA	20.60 \pm 0.2 ^a	20.56 \pm 0.1 ^a	20.46 \pm 0.1 ^a _y	20.81 \pm 0.1 _x
Σ ω -3	18.89 \pm 0.2 ^a	18.69 \pm 0.1 ^a	18.62 \pm 0.6 ^a _x	18.43 \pm 0.1 _y
Σ ω -6	1.77 \pm 0.0 ^a	1.78 \pm 0.0 ^a	1.76 \pm 0.0 ^a _y	2.29 \pm 0.0 _x
P/S	1.26 \pm 0.0 ^a	1.25 \pm 0.2 ^a	1.24 \pm 0.0 ^a _x	1.23 \pm 0.0 _x
ω -3 / ω -6	10.70 \pm 0.2 ^a	10.50 \pm 3.2 ^a	10.58 \pm 0.0 ^a _x	8.06 \pm 0.0 _y

FPOAP pollock oil with ascorbyl palmitate (*F/T American Triumph*); SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids. Different superscript letters within a row indicate statistical difference at $P < 0.05$; * indicates statistical difference between FPOAP oils purified at 210 °C using different roller speeds ($P < 0.05$)

Table 28. Fatty acid profiles of crude and purified Fall pollock oils produced at sea (*F/T American Triumph*) in mg/ g oil

Fatty acids	FPOAP 190 °C	FPOAP 200 °C	FPOAP 210 °C	FPOAP 210 °C
	n=3 500 rpm	n=3 500 rpm	n=3 500 rpm	n=3 450 rpm
14:0	39.99 ± 2.3 ^b	39.61 ± 1.1 ^b	43.52 ± 0.3 ^{a_y}	45.21 ± 1.8 ^x
Unknown 1	0.84 ± 0.0 ^{ab}	0.83 ± 0.0 ^b	0.90 ± 0.0 ^{a_y}	0.95 ± 0.0 ^x
14:1ω5	0.90 ± 0.1 ^a	0.90 ± 0.1 ^a	0.95 ± 0.0 ^{a_y}	0.99 ± 0.0 ^x
Iso or Ante iso 15:0	0.82 ± 0.0 ^b	0.81 ± 0.0 ^b	0.89 ± 0.0 ^a	0.92 ± 0.0 ^x
15:0	1.50 ± 0.1 ^b	1.49 ± 0.1 ^b	1.60 ± 0.0 ^{a_y}	1.65 ± 0.1 ^x
Iso or Anteiso 16:0	1.55 ± 0.1 ^b	1.11 ± 0.8 ^c	1.61 ± 0.0 ^{a_y}	1.67 ± 0.1 ^x
16:0	70.96 ± 3.5 ^b	69.97 ± 1.2 ^{bc}	76.56 ± 0.1 ^{a_y}	78.27 ± 2.5 ^x
Unknown 2	0.57 ± 0.0 ^a	0.57 ± 0.0 ^a	0.59 ± 0.0 ^{a_x}	0.00 ± 0.0 ^y
16:1ω11	1.57 ± 0.1 ^b	1.54 ± 0.0 ^c	1.68 ± 0.0 ^{a_y}	1.74 ± 0.1 ^x
16:1ω9	0.62 ± 0.0 ^b	0.62 ± 0.0 ^b	0.68 ± 0.0 ^{a_y}	0.71 ± 0.0 ^{ox}
16:1ω7	82.53 ± 4.0 ^b	81.26 ± 1.4 ^b	88.83 ± 0.0 ^{a_y}	91.58 ± 3.3 ^x
16:1ω5	2.49 ± 0.1 ^b	2.46 ± 0.0 ^b	2.69 ± 0.0 ^{a_y}	2.77 ± 0.1 ^x
16:1ω4	1.18 ± 0.1 ^b	1.16 ± 0.0 ^b	1.26 ± 0.0 ^{a_y}	1.30 ± 0.0 ^x
16:2ω4	0.75 ± 0.0 ^b	0.74 ± 0.0 ^b	0.81 ± 0.0 ^{a_x}	0.83 ± 0.0 ^x
Iso 17:0	0.10 ± 0.2 ^b	0.10 ± 0.0 ^b	0.32 ± 0.0 ^{a_x}	0.33 ± 0.0 ^x
Ante iso 17:0	7.20 ± 0.4 ^b	7.06 ± 0.16 ^b	7.78 ± 0.0 ^y	8.02 ± 0.3 ^x
17:0	4.92 ± 0.26 ^{ab}	4.83 ± 0.1 ^b	5.25 ± 0.0 ^{a_y}	5.41 ± 0.2 ^x
Unknown 3	3.57 ± 0.1 ^b	3.52 ± 0.0 ^b	3.97 ± 0.0 ^{a_x}	0.00 ± 0.0 ^y
17:1ω11	0.75 ± 0.1 ^b	0.76 ± 0.1 ^b	0.93 ± 0.0 ^{a_y}	3.91 ± 0.1 ^x
17:1ω9	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 ^{a_y}	0.11 ± 0.1 ^x
17:1ω7	8.29 ± 0.4 ^b	8.14 ± 0.2 ^c	8.94 ± 0.0 ^{a_y}	9.24 ± 0.3 ^x
18:0	11.76 ± 0.5 ^{ab}	11.55 ± 0.2 ^b	12.52 ± 0.0 ^{a_y}	12.57 ± 0.4 ^x
Unknown 4	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 ^{a_x}	0.00 ± 0.0 ^x
18:1ω9 <i>trans</i>	17.34 ± 0.8 ^b	17.06 ± 0.1 ^c	18.47 ± 0.0 ^{a_y}	18.81 ± 0.6 ^x
18:1ω9 <i>cis</i>	45.45 ± 2.0 ^b	44.73 ± 0.3 ^c	48.37 ± 0.1 ^{a_y}	49.16 ± 1.5 ^x
18:1ω7	27.45 ± 0.10 ^b	27.02 ± 0.2 ^b	29.27 ± 0.1 ^{a_y}	29.70 ± 0.9 ^x
Unknown 4	4.58 ± 0.16 ^b	4.53 ± 0.0 ^b	4.94 ± 0.0 ^{a_x}	0.00 ± 0.0 ^y
C18:2ω6 <i>trans</i>	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 ^{a_y}	4.98 ± 0.14 ^x
18:2ω6 <i>cis</i>	4.84 ± 0.2 ^b	4.75 ± 0.1 ^c	5.16 ± 0.0 ^{a_y}	5.26 ± 0.2 ^x
Unknown 5	0.00 ± 0.0 ^b	0.00 ± 0.0 ^b	0.42 ± 0.0 ^{a_x}	0.30 ± 0.3 ^x
18:3ω6	3.25 ± 0.2 ^b	3.23 ± 0.0 ^b	3.41 ± 0.0 ^{a_y}	3.46 ± 0.1 ^x
Unknown 6	0.47 ± 0.0 ^b	0.45 ± 0.17 ^b	0.50 ± 0.0 ^{a_x}	0.51 ± 0.0 ^x
18:3ω3	2.75 ± 0.2 ^{ab}	2.69 ± 0.1 ^b	2.87 ± 0.0 ^x	2.91 ± 0.1 ^x
18:4ω3	13.41 ± 0.6 ^{ab}	13.18 ± 0.2 ^b	14.24 ± 0.0 ^y	14.59 ± 0.4 ^x
Unknown 7	3.00 ± 0.2 ^b	2.98 ± 0.1 ^b	3.19 ± 0.0 ^a	3.33 ± 0.1 ^x
Iso or anteiso 20:0	0.45 ± 0.0 ^b	0.46 ± 0.0 ^a	0.47 ± 0.0 ^a	0.52 ± 0.0 ^x
20:0	0.96 ± 0.15 ^b	0.98 ± 0.1 ^a	0.95 ± 0.0 ^{b_x}	0.87 ± 0.0 ^y
20:1ω11	136.51 ± 4.2 ^b	134.47 ± 0.4 ^b	144.92 ± 0.0 ^{a_y}	145.26 ± 3.8 ^x
20:1ω9	38.32 ± 1.4 ^b	37.97 ± 0.4 ^b	40.35 ± 0.0 ^{a_x}	40.33 ± 1.1 ^x
20:1ω7	2.79 ± 0.1 ^b	2.77 ± 0.0 ^b	2.98 ± 0.0 ^{a_x}	0.00 ± 0.0 ^y
20:1ω5	1.03 ± 0.0 ^b	1.00 ± 0.0 ^b	1.11 ± 0.0 ^{a_x}	1.07 ± 0.0 ^x
20:2ω6	1.23 ± 0.1 ^b	1.21 ± 0.1 ^b	1.27 ± 0.0 ^{a_x}	1.27 ± 0.0 ^x
21:0	0.60 ± 0.1 ^a	0.60 ± 0.1 ^a	0.60 ± 0.0 ^{a_x}	0.62 ± 0.0 ^x
20:3ω6	1.28 ± 0.1 ^b	1.26 ± 0.1 ^b	1.32 ± 0.0 ^{a_x}	1.35 ± 0.0 ^x

20:3 ω 3	0.61 \pm 0.0 ^{ab}	0.59 \pm 0.0 ^b	0.65 \pm 0.0 ^a _x	0.00 \pm 0.0 _y
Unknown 8	0.00 \pm 0.0 ^a	0.00 \pm 0.0 ^a	0.0 \pm 0.0 ^a _y	0.63 \pm 0.0 _x
20:4 ω 3	3.35 \pm 0.10 ^b	3.27 \pm 0.0 ^c	3.57 \pm 0.0 ^a _x	3.55 \pm 0.1 _x
20:5 ω 3 (EPA)	87.66 \pm 3.0 ^b	86.19 \pm 0.2 ^b	92.62 \pm 0.2 ^a _y	93.55 \pm 2.4 _x
22:0	0.00 \pm 0.0 ^a	0.00 \pm 0.0 ^a	0.00 \pm 0.0 ^a _x	0.00 \pm 0.0 _x
22:1 ω 11	136.67 \pm 3.2 ^b	134.81 \pm 0.8 ^b	144.59 \pm 2.5 ^a _x	142.23 \pm 2.8 _y
22:1 ω 9	9.65 \pm 0.3 ^b	9.54 \pm 0.0 ^b	10.20 \pm 0.2 ^a _x	9.93 \pm 0.2 _y
22:1 ω 7	3.20 \pm 0.1 ^b	3.18 \pm 0.0 ^a	3.41 \pm 0.1 ^a _x	3.31 \pm 0.1 _y
22:2 ω 6	4.51 \pm 0.2 ^b	4.56 \pm 0.0 ^b	4.84 \pm 0.1 ^a _x	0.00 \pm 0.0 _y
Unknown 9	0.00 \pm 0.0 ^a	0.00 \pm 0.0 ^a	0.63 \pm 0.0 ^a _x	0.00 \pm 0.0 _y
22:5 ω 3	7.10 \pm 0.2 ^b	7.00 \pm 0.0 ^b	7.49 \pm 0.1 ^a _x	4.75 \pm 0.1 _y
22:6 ω 3 (DHA)	45.50 \pm 1.30 ^b	44.77 \pm 0.1 ^b	47.88 \pm 0.6 ^a _x	47.70 \pm 1.0 _x
Unknown 10	2.32 \pm 0.1 ^{ab}	2.27 \pm 0.0 ^b	2.46 \pm 0.1 ^a _x	2.40 \pm 0.0 _y
24:1 ω 9	4.33 \pm 0.1 ^b	4.28 \pm 0.1 ^c	4.56 \pm 0.1 ^a _x	4.34 \pm 0.1 _y
Saponifiables	855.56 \pm 31.0 ^b	843.68 \pm 4.1 ^c	913.56 \pm 4.6 ^a _y	920.63 \pm 24.3 _x
Σ SAT	139.49 \pm 7.9 ^b	139.17 \pm 3.4 ^b	152.35 \pm 0.15 ^a _y	156.33 \pm 5.4 _x
Σ MUFA	529.34 \pm 17.7 ^b	514.51 \pm 1.7 ^b	555.01 \pm 3.5 ^a _x	560.31 \pm 15.1 _x
Σ PUFA	176.25 \pm 6.1 ^b	173.44 \pm 0.4 ^b	186.13 \pm 1.1 ^a _y	191.59 \pm 4.7 _x
Σ ω -3	161.66 \pm 5.4 ^{ab}	157.69 \pm 0.32 ^b	169.32 \pm 1.0 ^a _x	169.7 \pm 4.1 _x
Σ ω -6	15.12 \pm 0.8 ^b	15.01 \pm 0.25 ^c	15.99 \pm 0.1 ^a _y	21.06 \pm 0.60 _x
P/S	1.26 \pm 0.0 ^a	1.25 \pm 0.1 ^a	1.22 \pm 0.0 ^a _x	1.23 \pm 0.6 _x
ω -3 / ω -6	10.7 \pm 0.2 ^a	10.50 \pm 1.3 ^a	10.59 \pm 0.0 ^a _x	8.06 \pm 0.0 _y

FPOAP pollock oil with ascorbyl palmitate (*F/T American Triumph*); SAT saturated fatty acids; MUFA monounsaturated fatty acids; PUFA polyunsaturated fatty acids. Different superscript letters within a row indicate statistical difference at $P < 0.05$; * indicates statistical difference between FPOAP oils purified at 210 °C using different roller speeds ($P < 0.05$)

Figure 21 presents the free fatty acid values in crude Fall pollock oil (*F/T American Triumph*) and in the SPD polished samples. All polished FPOAP oils presented very low %FFA, and these results show that SPD removed these impurities from Fall pollock crude oils (*F/T American Triumph*) when operated at any of the temperatures tested. Similarly, the PV values (Figure 22) decreased significantly in all polished oils, regardless of temperature. Edible fish oils should present a PV value of 5 or below (Table 1), and the purified Fall pollock oils had PV values under 1 meq/Kg. These results show that SPD effectively removed the primary products of lipid oxidation present in FPOAP. The p-AV values (Figure 23) of the polished Fall pollock oil samples showed the effect of temperature in the system's ability to remove secondary products of lipid oxidation. Secondary products of lipid oxidation are a mixture of odoriferous compounds, which impart off-odors and off-flavors to edible oils, primarily composed of saturated and unsaturated aldehydes and ketones. These compounds have a range of molecular weight and boiling points; thus, it is expected that evaporator temperature is a critical variable to ensure removal of these impurities. The p-AV values expected for edible oils should not exceed 20 (Table 1; Bimbo 2009); thus evaporator temperatures of 200 °C and 210 °C at roller speed of 500 rpm significantly decrease the p-AV to meet edible fish oils standards. There was a significant increase in p-AV between oils distilled at 210 °C with different roller speeds and this is expected because a lower roller speed decreases residency time of oil in the evaporator; thus decreasing the efficiency of the distillation. Nonetheless, the combination of 210 °C evaporator temperature and 450 rpm roller speed yielded purified oils with p-AV below 20. The TBA values of the crude and purified FPOAP samples are shown in Figure 24. Thiobarbituric acid values (TBA) do not have a set standard for fish oils, but this variable is often used by researchers to monitor lipid oxidation in edible oils. The increase in TBA values seems to contradict the results of the p-AV analysis except that the increase in TBA values is, despite statistically significant, very

small. A change of 0.1 units in TBA value does not indicate a significant increase in secondary lipid oxidation products, especially when the initial TBA value of the crude oil was already quite low.

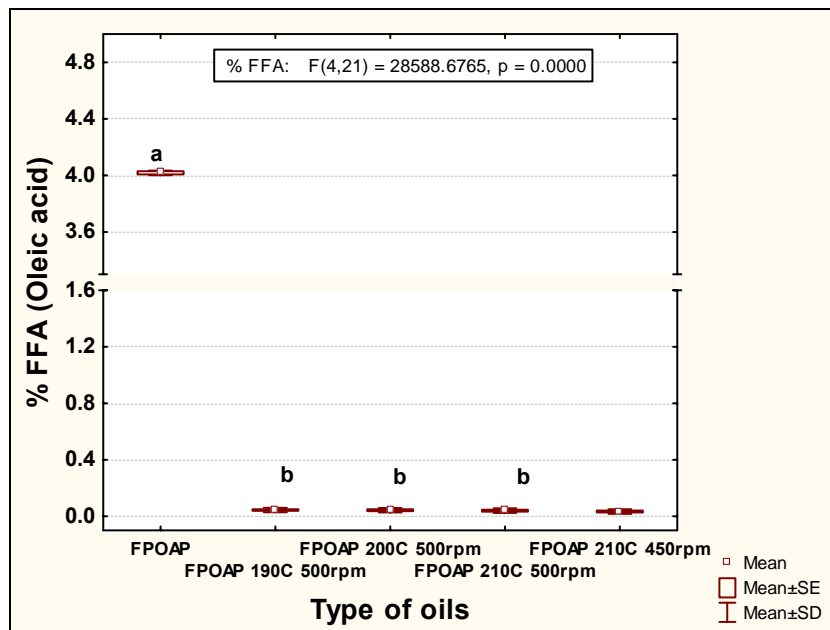


Figure 21. Free fatty acids content (%) of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P < 0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P < 0.05$)

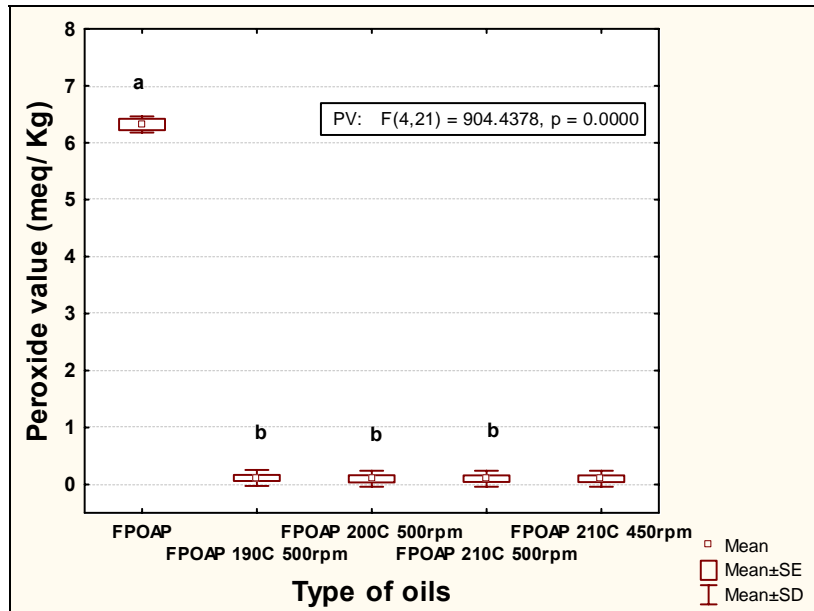


Figure 22. Peroxide value (meq/ Kg) of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P < 0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P < 0.05$)

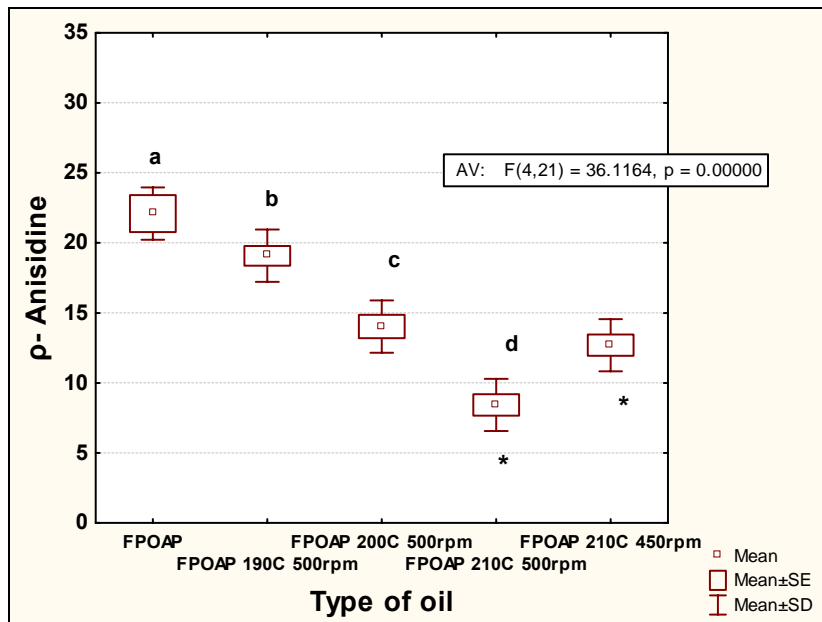


Figure 23. Anisidine value of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P < 0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P < 0.05$)

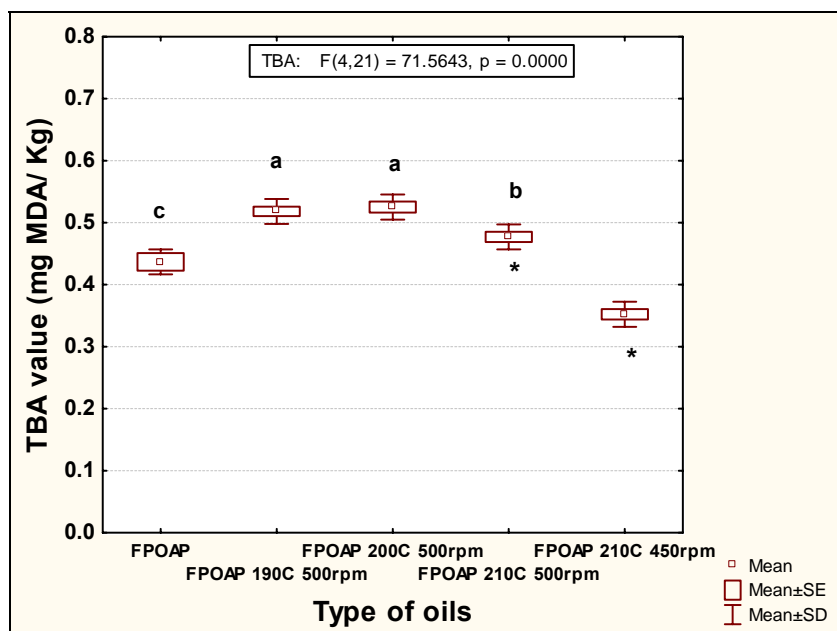


Figure 24. Thiobarbituric Acid (TBA) of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P < 0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P < 0.05$)

There was a significant decrease in water activity between crude and purified oils (Figure 25). Water activity of oils after degassing (150 °C) was in average 0.34; this demonstrates that water is mainly removed in the degassing stage, and that little change in water activity occurred between samples distilled at 150 °C and at higher temperatures. This is expected because of the water boiling point (100 °C), which is low when compared to the boiling points of saturated and unsaturated aldehydes and ketones resulting from lipid oxidation of

fish oils. Phosphorus content in the crude oil was very low and significant changes were neither expected nor observed (Figure 26).

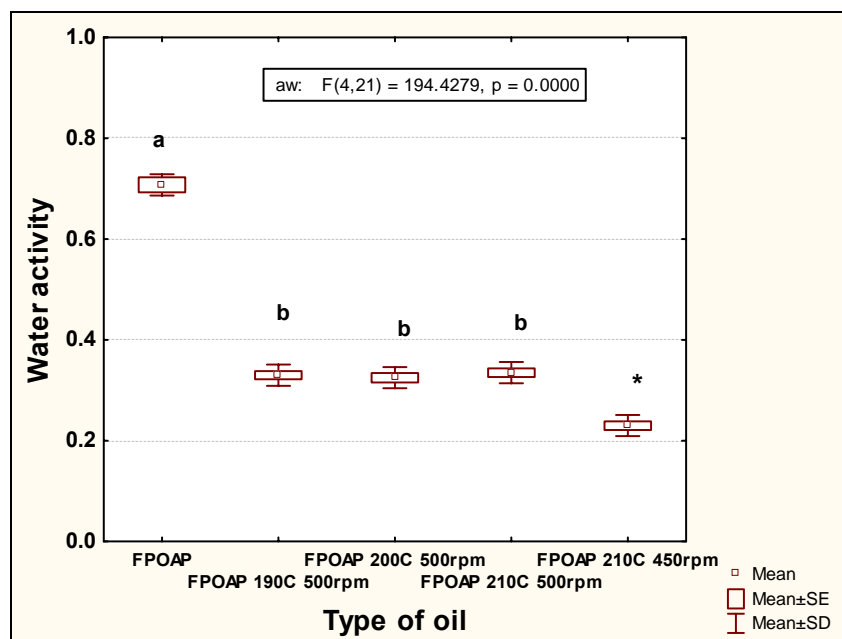


Figure 25. Water activity of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P<0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P<0.05$)

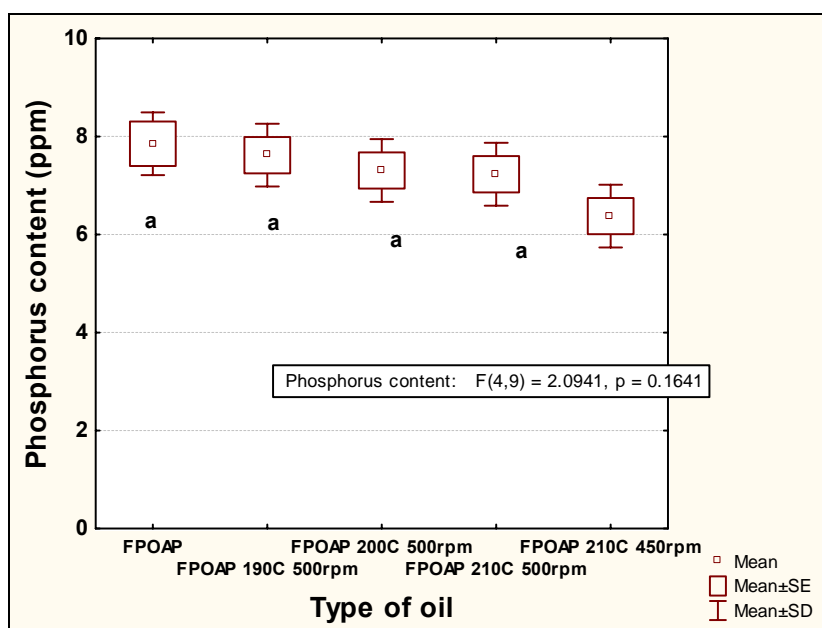


Figure 26. Phosphorus Content (ppm) of crude and purified Fall pollock oil with antioxidant (*F/T American Triumph*). Different letters indicate statistical differences ($P<0.05$) between crude oil and oils purified at different temperatures. * indicate when a statistical difference was detected between oils purified at 210 °C using different roller speed ($P<0.05$)

Table 29 shows the oil recovery yields for distilled oils at 210 °C. The range of oil recovery for FPOAP and SPOAP were low. These were the two first set of samples purified, after determining best optimal temperature and roller speed. Losses occurred during purification, lowering yields. Adjustments and continuous familiarization with the process lead to much higher yields for liver oils, which ranged from was 80 – 89% of the initial oil weight.

Recovery results for liver oil samples are very encouraging, and it seems that with routine operation of the SPD equipment, recoveries of 90% or more should not be difficult to achieve.

Table 29. SPD yields of purified pollock oils produced by the *F/T American Triumph* and of oils rendered in the laboratory

Sample code	N	Speed (rpm)	Temperature (°C)	Oil recovery (%)
FPOAP 210°C	3	450	210	66 ± 0.8 ^c
SPOAP 210°C	3	450	210	59.2 ± 3.8 ^d
FLOAP 210°C	3	450	210	81.2 ± 5.6 ^b
F60LOAP30` 210°C	3	450	210	89.4 ± 1.8 ^a
S60LOAP30` 210°C	3	450	210	88.2 ± 1.1 ^a

FPOAP Fall pollock oil with ascorbyl palmitate (*Americal Triumph*); SPOAP Spring pollock oil with ascorbyl palmitate (*Americal Triumph*); FPOAP Fall pollock liveir oil with ascorbyl palmitate (*Americal Triumph*); F60LOAP30` Fall liver oil (60 °C; 30 min); S60LOAP30` Spring liver oil (60 °C; 30 min)
Different letters within a column indicate statistical difference at P<0.05.

Table 30 shows the results for analysis of lipids class in purified pollock oils (*F/T American Triumph*). Oils were comprised mostly of triacylglycerides presenting only traces of phospholipids. The comparison of pollock purified oil and pollock crude oil (Table 8) showed that high temperature did not influence the lipids classes distribution, as seen for other FPOAP samples previously discussed. The major lipid class for all purified oils is TAG, as expected.

Table 30. Lipids classes of purified (210 °C; 450 rpm) pollock oils produced at sea (*F/T American Triumph*) and of oils rendered in the laboratory (% wt./ wt.)

	FPOAP 210 (n=3)	SPOAP 210 (n=3)	FLOAP 210 (n=3)	F60LOAP30` 210 °C (n=3)	S60LOAP30` 210 °C (n=3)
TAG	99.7 ± 0.0	99.8 ± 0.0	99.8 ± 0.0	99.3 ± 0.0	99.2 ± 0.0
FFA	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.00 ± 0.0	0.0 ± 0.0
DAG	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.00 ± 0.0	0.0 ± 0.0
ST	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.00 ± 0.0	0.0 ± 0.0
MAG	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.00 ± 0.0	0.0 ± 0.0
PL	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.7 ± 0.0	0.7 ± 0.0

FPOAP Fall pollock oil with ascorbyl palmitate (*Americal Triumph*); SPOAP Spring pollock oil with ascorbyl palmitate (*Americal Triumph*); FPOAP Fall pollock liveir oil with ascorbyl palmitate (*Americal Triumph*); F60LOAP30` Fall liver oil (60°C; 30 min); S60LOAP30` Spring liver oil (60°C; 30 min)

Table 31 and Table 32 shows the fatty acid (FA) profiles of crude and purified pollock oils (*F/T American Triumph*). Results indicated that SPD purification preserves the fatty acids composition of the crude oils. Due to removal of impurities, many of which are unsaponifiable compounds such as sterols, waxes ad hydrocarbons (Bimbo, 2009), the abundance of saponifiable matter increases.

Table 31. Fatty acid profiles of crude and purified pollock oils produced at sea (*F/T American Triumph*) in %wt/ wt.

Fatty acid	FPOAP Crude n=3	FPOAP 210 °C n=3 450 rpm	SPOAP crude n=3	SPOAP 210 °C n=3 450 rpm	LOAP crude n=3	LOAP210 °C n=3 450 rpm
14:0	4.97 ± 0.1 ^b	4.91 ± 0.0 ^a	4.45 ± 0.0 _a	4.28 ± 0.5 _b	5.40 ± 0.0*	5.33 ± 0.7
14:1ω7	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a	0.0 ± 0.0 _b	0.12 ± 0.0 _a	0.10 ± 0.0	0.09 ± 0.0

14:1ω5	0.11 ± 0.1 ^a	0.11 ± 0.0 ^a	0.12 ± 0.0 _a	0.11 ± 0.0 _a	0.14 ± 0.0	0.13 ± 0.0
Iso or Ante iso 15:0	0.10 ± 0.0 ^a	0.10 ± 0.0 ^a	0.14 ± 0.0 _a	0.13 ± 0.0 _a	0.09 ± 0.0	0.09 ± 0.0
15:0	0.19 ± 0.0 ^a	0.18 ± 0.0 ^a	0.24 ± 0.0 _a	0.23 ± 0.0 _a	0.19 ± 0.0	0.19 ± 0.0
Iso or Anteiso 16:0	0.19 ± 0.0 ^a	0.18 ± 0.0 ^a	0.19 ± 0.0 _b	0.21 ± 0.0 _a	0.19 ± 0.0	0.19 ± 0.0
16:0	8.54 ± 0.1 ^a	8.50 ± 0.0 ^b	10.6 ± 0.1 _a	10.39 ± 0.0 _a	9.93 ± 0.1*	9.86 ± 0.0
16:1ω11	0.07 ± 0.0 ^b	0.19 ± 0.0 ^a	0.15 ± 0.0 _a	0.15 ± 0.0 _a	0.14 ± 0.0	0.14 ± 0.0
16:1ω9	0.19 ± 0.0 ^a	0.08 ± 0.0 ^b	0.0 ± 0.0 ^b	0.13 ± 0.0 _a	0.07 ± 0.0	0.05 ± 0.0
Unknown 1	0.00 ± 0.0 ^a	0.0 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
16:1ω7	9.95 ± 0.1 ^a	9.95 ± 0.1 ^a	9.05 ± 0.0 _a	8.79 ± 0.0 _b	11.83±0.1*	11.70 ± 0.0
16:1ω5	0.30 ± 0.0 ^a	0.30 ± 0.0 ^b	0.31 ± 0.0 _a	0.30 ± 0.0 _b	0.29± 0.0	0.29 ± 0.0
16:1ω4	0.14 ± 0.0 ^a	0.14 ± 0.0 ^c	0.11 ± 0.0 _a	0.0 ± 0.0 _b	0.0 ± 0.0	0.0 ± 0.0
16:2ω4	0.09 ± 0.0 ^a	0.09 ± 0.0 ^a	0.89 ± 0.0 _a	0.0 ± 0.0 _b	0.12 ± 0.0	0.11± 0.0
Iso 17:0	0.0 ± 0.0 ^b	0.04 ± 0.0 ^a	0.11 ± 0.0 _a	0.11 ± 0.0 _a	0.08 ± 0.0	0.08 ± 0.0
Ante iso 17:0	0.86 ± 0.0 ^a	0.87 ± 0.3 ^a	0.89 ± 0.0 _a	0.87 ± 0.0 _a	0.94 ± 0.0	0.93 ± 0.0
17:0	0.59 ± 0.1 ^a	0.59 ± 0.2 ^a	0.45 ± 0.0 _a	0.44 ± 0.0 _a	0.63 ± 0.0	0.62 ± 0.0
Unknown 2	0.41 ± 0.0 ^a	0.42 ± 0.0 ^b	1.01 ± 0.1	0.99 ± 0.0 ^a	0.73 ± 0.0	0.71 ± 0.0
17:1ω11	0.09 ± 0.0 ^a	0.09 ± 0.0 ^a	0.15 ± 0.0 _a	0.14 ± 0.0 _a	0.10 ± 0.0	0.10 ± 0.0
17:1ω9	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
17:1ω7	0.99 ± 0.0 ^a	1.00 ± 0.0 ^a	0.65 ± 0.0 _a	0.62 ± 0.0 _b	1.02 ± 0.0	1.01 ± 0.0
18:0	1.31 ± 0.1 ^b	1.37 ± 0.0 ^a	1.43 ± 0.0 _b	1.52 ± 0.0 _a	1.60 ± 0.0	1.56 ± 0.1
Unknown 3	0.11 ± 0.0 ^a	0.0 ± 0.0 ^b	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
18:1ω9 <i>trans</i>	2.05 ± 0.0 ^a	2.04 ± 0.0 ^a	1.93 ± 0.0 _a	1.94 ± 0.0 _a	2.00 ± 0.0	1.99 ± 0.0
18:1ω9 <i>cis</i>	5.36 ± 0.0 ^b	5.34 ± 0.0 ^a	11.50 ± 0.0 _a	11.42 ± 0.0 _b	7.43 ± 0.0	7.41± 0.0
18:1ω7	3.23± 0.01 ^a	3.23 ± 0.0 ^a	4.65 ± 0.0 _a	4.63 ± 0.0 _a	4.42 ± 0.0	4.41 ± 0.0
Unknown 4	0.54 ± 0.0 ^b	0.00 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
C18:2ω6 <i>trans</i>	0.0 ± 0.0 ^a	0.54 ± 0.0 ^b	0.32 ± 0.0	0.32 ± 0.0 ^a	0.47 ± 0.0	0.47 ± 0.0
18:2ω6 <i>cis</i>	0.57 ± 0.0	0.57 ± 0.0 ^b	0.65 ± 0.0 _a	0.64 ± 0.0 _a	0.51 ± 0.0	0.50 ± 0.0
Unknown 5	0.0 ± 0.0 ^a	0.0 ± 0.0 ^a	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
18:3ω6	0.40 ± 0.0 ^a	0.38 ± 0.0 ^a	0.28 ± 0.0 _a	0.29 ± 0.0 _a	0.38 ± 0.0	0.38 ± 0.0
Unknown 6	0.0 ± 0.0 ^b	0.06 ± 0.0 ^a	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
18:3ω3	0.32 ± 0.0 ^a	0.32 ± 0.0 ^a	0.44 ± 0.0 _a	0.43 ± 0.0 _a	0.25 ± 0.0	0.24 ± 0.0
18:4ω3	1.58 ± 0.0 ^a	1.58 ± 0.0 ^a	1.52 ± 0.0 _a	1.51 ± 0.0 _a	1.25 ± 0.0	1.24 ± 0.0
Unknown 7	0.35 ± 0.0 ^a	0.36 ± 0.0 ^a	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
Iso or anteiso20:0	0.0 ± 0.0 ^b	0.06 ± 0.0 ^a	0.0 ± 0.0 _b	0.24 ± 0.0 _a	0.32 ± 0.0	0.31 ± 0.0
20:0	0.12 ± 0.0 ^a	0.09 ± 0.0 ^b	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0 ^a
20:1ω11	15.72 ± 0.0 ^b	15.78 ± 0.0 ^b	10.63 ± 0.0 _b	10.72 ± 0.0 _a	13.99 ± 0.0	14.14 ± 0.0*
20:1ω9	4.46 ± 0.0 ^b	4.38 ± 0.0 ^a	5.36 ± 0.0 _a	5.40 ± 0.0 _a	3.87 ± 0.0	3.90 ± 0.0
20:1ω7	0.32 ± 0.0 ^a	0.33 ± 0.0 ^b	0.25 ± 0.0 _a	0.29 ± 0.0 _a	0.32 ± 0.0	0.32 ± 0.0
20:1ω5	0.12 ± 0.0 ^a	0.12 ± 0.0 ^a	0.10 ± 0.0 _a	0.09 ± 0.0 _a	0.10 ± 0.0	0.10 ± 0.0
20:2ω6	0.14 ± 0.0 ^a	0.14 ± 0.0 ^a	0.16 ± 0.0 _a	0.17 ± 0.0 _a	0.13 ± 0.0	0.13 ± 0.0
21:0	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
20:3ω6	0.15 ± 0.0 ^a	0.15 ± 0.0 ^a	0.18 ± 0.0 _a	0.19 ± 0.0 _a	0.14 ± 0.0	0.15 ± 0.0
Unknown 8	0.07 ± 0.0 ^a	0.07 ± 0.0 ^a	0.0 ± 0.0 _a	0.0 ± 0.0 _a	0.0 ± 0.0	0.0 ± 0.0
20:4ω3	0.38 ± 0.0 ^a	0.39 ± 0.0 ^a	0.48 ± 0.0 _a	0.47 ± 0.0 _c	0.30 ± 0.0	0.30 ± 0.0
20:5ω3 (EPA)	10.12 ± 0.1 ^a	10.16 ± 0.0 ^a	10.0 ± 0.0 _a	10.04 ± 0.0 _a	10.64 ± 0.0	10.63 ± 0.0
22:0	0.27 ± 0.5 ^b	0.00 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
22:1ω11	15.52 ± 0.2 ^b	15.45 ± 0.1 ^a	12.2 ± 0.1 _b	12.50 ± 0.0 _a	12.20 ± 0.0	12.47 ± 0.0*
22:1ω9	1.10 ± 0.0 ^b	1.08 ± 0.0 ^a	1.40 ± 0.01 _a	1.42 ± 0.0 _a	0.91 ± 0.0	0.92 ± 0.0
22:1ω7	0.36 ± 0.0 ^a	0.36 ± 0.0 ^a	0.24 ± 0.0 _a	0.27 ± 0.0 _a	0.29 ± 0.0	0.29 ± 0.0
22:2ω6	0.54 ± 0.0 ^a	0.52 ± 0.0 ^a	0.51 ± 0.0 _a	0.52 ± 0.0 _a	0.53 ± 0.0	0.53 ± 0.0
22:5ω3	0.81 ± 0.0 ^a	0.80 ± 0.0 ^a	0.93 ± 0.0 _a	0.93 ± 0.0 _a	0.70 ± 0.0	0.70 ± 0.0
22:6ω3 (DHA)	5.16 ± 0.1 ^a	5.18 ± 0.0 ^a	5.15 ± 0.0 _a	5.21 ± 0.0 _a	4.70 ± 0.0	4.70 ± 0.0
Unknown 19	0.26 ± 0.0 ^a	0.26 ± 0.0 ^a	0.20 ± 0.0 _a	0.22 ± 0.0 _a	0.21 ± 0.0	0.21 ± 0.0
24:1ω9	0.49 ± 0.0 ^a	0.47 ± 0.0 ^a	0.58 ± 0.0 _a	0.61 ± 0.0 _a	0.35 ± 0.0	0.35 ± 0.0

Total fatty acids	100.00 ± 0.0	100.00 ± 0.0	100.00 ± 0.0	100.00 ± 0.0	100.00 ± 0.0	100.0 ± 0.0
Σ SAT	16.98 ± 0.3 ^a	16.98 ± 0.1 ^a	17.16 ± 0.1 _b	18.42 ± 0.0 _a	19.35 ± 0.1*	19.16 ± 0.1
Σ MUFA	60.68 ± 0.2 ^b	60.86 ± 0.1 ^a	57.92 ± 0.2 _b	60.53 ± 0.0 _a	60.43 ± 0.3	60.66 ± 0.0*
Σ PUFA	20.26 ± 0.1 ^b	20.81 ± 0.1 ^a	20.93 ± 0.1 _b	20.82 ± 0.0 _a	20.01 ± 0.2	19.97 ± 0.0
Σ ω-3	18.37 ± 0.1 ^b	18.43 ± 0.1 ^a	17.29 ± 0.0 _b	18.59 ± 0.0 _a	17.84 ± 0.2	17.80 ± 0.0
Σ ω-6	1.40 ± 0.0 ^a	2.29 ± 0.0 ^a	2.11 ± 0.0 _b	2.13 ± 0.0 _a	1.64 ± 0.0	2.17 ± 0.5*
P/S	1.12 ± 0.0 ^b	1.23 ± 0.0 ^b	1.22 ± 0.5 _a	1.13 ± 0.0 _a	1.03 ± 0.0	1.04 ± 0.5
ω-3 / ω-6	11.93 ± 0.36 ^a	8.06 ± 0.0 ^b	9.44 ± 0.15 _b	8.72 ± 0.0 _a	10.88 ± 0.0*	8.22 ± 0.0

FPOAP Fall pollock oil with ascorbyl palmitate; SPOAP Spring pollock oil with ascorbyl palmitate; FPOAP Fall pollock liveir oil with ascorbyl palmitate; Different subscript letters indicate differences between crude and purified Fall and Spring pollock oils (P<0.05); * indicated significant differences between crude a purified pollock liver oils (P<0.05)

Table 32. Fatty acid profiles of crude and purified pollock oils produced at sea (*F/T American Triumph*) in mg/ g oil

Fatty acid	FPOAP Crude	FPOAP 210 °C	SPOAP crude	SPOAP 210 °C	LOAP crude	LOAP210 °C
	n=3	n=3 450 rpm	n=3	n=3 450 rpm	n=3	n=3 450 rpm
14:0	38.46 ± 1.5 ^b	45.21 ± 1.8 ^a	40.15 ± 0.2 _a	39.76 ± 0.5 _b	46.71 ± 0.3	49.10 ± 0.7*
14:1ω7	0.80 ± 0.2 ^b	0.95 ± 0.0 ^a	0.00 ± 0.0 _b	1.07 ± 0.0 _a	0.84 ± 0.0	0.86 ± 0.0
14:1ω5	0.88 ± 0.1 ^b	0.99 ± 0.0 ^a	1.06 ± 0.0 _a	1.06 ± 0.0 _a	1.18 ± 0.0	1.24 ± 0.0*
Iso or Ante iso 15:0	0.77 ± 0.0 ^b	0.92 ± 0.0 ^a	1.24 ± 0.0 _a	1.25 ± 0.0 _a	0.76 ± 0.0	0.80 ± 0.0
15:0	1.44 ± 0.1 ^b	1.65 ± 0.1 ^a	2.12 ± 0.0 _a	2.13 ± 0.0 _a	1.64 ± 0.0	1.73 ± 0.0*
Iso or Anteiso 16:0	1.45 ± 0.0 ^b	1.67 ± 0.1 ^a	1.72 ± 0.2 _b	1.95 ± 0.0 _a	1.62 ± 0.1	1.77 ± 0.0*
16:0	66.12 ± 2.0 ^b	78.27 ± 2.5 ^a	95.42 ± 0.6 _b	96.58 ± 1.1 _a	85.91 ± 0.4	90.92 ± 1.7*
16:1ω11	0.56 ± 0.0 ^b	1.74 ± 0.1 ^a	1.32 ± 0.0 _a	1.35 ± 0.1 _a	1.18 ± 0.0	1.29 ± 0.1*
16:1ω9	1.46 ± 0.0 ^b	0.71 ± 0.0 ^a	0.00 ± 0.0 _b	1.19 ± 0.1 _a	0.63 ± 0.0*	0.47 ± 0.4
Unknown 1	0.56 ± 0.0 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
16:1ω7	77.04 ± 2.4 ^b	91.58 ± 3.3 ^a	81.50 ± 0.2 _a	81.69 ± 1.1 _a	102.34 ± 0.6	107.90 ± 2.0*
16:1ω5	2.32 ± 0.0 ^b	2.77 ± 0.1 ^a	2.75 ± 0.0 _a	2.80 ± 0.0 _a	2.55 ± 0.0	2.69 ± 0.1*
16:1ω4	1.05 ± 0.1 ^a	1.30 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	1.00 ± 0.0	1.04 ± 0.1
16:2ω4	0.68 ± 0.0 ^b	0.83 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
Iso 17:0	0.00 ± 0.0 ^b	0.33 ± 0.0 ^a	0.95 ± 0.0 _b	1.05 ± 0.1 _a	0.68 ± 0.0	0.71 ± 0.1
Ante iso 17:0	6.66 ± 0.2 ^b	8.02 ± 0.3 ^a	8.03 ± 0.1 _a	8.07 ± 0.1 _a	8.10 ± 0.0	8.56 ± 0.2*
17:0	4.60 ± 0.2 ^b	5.41 ± 0.2 ^a	4.03 ± 0.0 _a	4.06 ± 0.1 _a	5.46 ± 0.0	5.76 ± 0.1*
Unknown 2	3.21 ± 0.1 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
17:1ω11	0.69 ± 0.1 ^b	3.91 ± 0.1 ^a	9.11 ± 0.4 _a	9.17 ± 0.1 _a	6.30 ± 0.1	6.57 ± 0.1*
17:1ω9	0.00 ± 0.0 ^a	0.0 ± 0.1 ^a	1.33 ± 0.0 _a	1.34 ± 0.0 _a	0.84 ± 0.0	0.88 ± 0.0*
17:1ω7	7.68 ± 0.3 ^b	9.24 ± 0.3 ^a	5.80 ± 0.0 _a	5.76 ± 0.1 _a	8.87 ± 0.1	9.36 ± 0.2*
18:0	10.16 ± 0.7 ^b	12.57 ± 0.4 ^a	12.85 ± 0.1 _b	14.10 ± 0.1 _a	13.84 ± 0.1	14.36 ± 1.0*
Unknown 3	5.93 ± 8.8 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
18:1ω9 ^{trans}	15.88 ± 0.9 ^b	18.81 ± 0.6 ^a	17.37 ± 0.0 _b	18.07 ± 0.2 _a	17.31 ± 0.1	18.31 ± 0.5*
18:1ω9 ^{cis}	41.47 ± 0.3 ^b	49.16 ± 1.5 ^a	103.62 ± 0.5 _b	106.10 ± 1.2 _a	64.31 ± 0.3	68.34 ± 1.4*
18:1ω7	24.72 ± 0.5 ^b	29.70 ± 0.92 ^a	41.88 ± 0.2 _b	42.98 ± 0.5 _a	38.28 ± 0.2	40.66 ± 0.8
Unknown 4	4.15 ± 0.2 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
C18:2ω6 ^{trans}	0.0 ± 0.0 ^b	4.98 ± 0.14 ^a	2.91 ± 0.0 _a	3.00 ± 0.6 _a	4.11 ± 0.0	4.37 ± 0.1*
18:2ω6 ^{cis}	4.3 ± 0.1 ^b	5.26 ± 0.2 ^a	5.86 ± 0.0 _b	5.97 ± 0.1 _a	4.38 ± 0.0	4.64 ± 0.1*
Unknown 5	0.0 ± 0.0 ^b	0.30 ± 0.3 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
18:3ω6	3.09 ± 0.1 ^b	3.46 ± 0.1 ^a	2.54 ± 0.0 _b	2.65 ± 0.0 _a	3.33 ± 0.0	3.53 ± 0.1*
Unknown 6	0.0 ± 0.0 ^b	0.51 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
18:3ω3	2.51 ± 0.1 ^b	2.91 ± 0.1 ^a	3.93 ± 0.0 _a	3.98 ± 0.0 _b	2.12 ± 0.0	2.25 ± 0.0*
18:4ω3	12.2 ± 1.6 ^b	14.59 ± 0.4 ^a	13.73 ± 0.0 _a	14.05 ± 0.2 _a	10.78 ± 0.1	11.45 ± 0.2*
Unknown 7	2.74 ± 0.3 ^b	3.33 ± 0.1 ^a	0.00 ± 0.0 _b	2.27 ± 0.0 _a	2.74 ± 0.0	2.90 ± 0.1*

Iso or anteiso 20:0	0.0 ± 0.0 _b	0.52 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0 ^a
20:0	0.93 ± 0.2 ^b	0.87 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0 ^a
20:1ω11	121.67 ± 2.4 ^b	145.26 ± 3.8 ^a	95.72 ± 0.4 _b	99.61 ± 1.0 _a	121.09 ± 1.6	130.40 ± 2.7*
20:1ω9	34.53 ± 0.4 ^b	40.33 ± 1.1 ^a	48.30 ± 0.2 _b	50.15 ± 0.5 _a	33.50 ± 0.2	35.97 ± 0.7*
20:1ω7	2.46 ± 0.0 ^a	0.00 ± 0.0 ^b	2.28 ± 0.0 _b	2.73 ± 0.0 _a	2.79 ± 0.0	2.98 ± 0.1*
20:1ω5	0.90 ± 0.0 ^b	1.07 ± 0.0 ^a	0.90 ± 0.0 _a	0.88 ± 0.0 _a	0.89 ± 0.0	0.94 ± 0.0*
20:2ω6	1.11 ± 0.1 ^b	1.27 ± 0.0 ^a	1.49 ± 0.0 _b	1.59 ± 0.0 _a	1.12 ± 0.0	1.22 ± 0.0*
21:0	0.54 ± 0.1 ^b	0.62 ± 0.0 ^a	0.00 ± 0.0	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
20:3ω6	1.15 ± 0.1 ^b	1.35 ± 0.0 ^a	1.65 ± 0.0 _b	1.73 ± 0.0 _a	1.25 ± 0.0	1.34 ± 0.0*
Unknown 8	0.52 ± 0.0 ^b	0.63 ± 0.0 ^a	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
20:4ω3	2.95 ± 0.1 ^b	3.55 ± 0.1 ^a	4.31 ± 0.0 _a	4.35 ± 0.1 _a	2.61 ± 0.0	2.74 ± 0.0*
20:5ω3 (EPA)	78.30 ± 1.2 ^b	93.55 ± 2.4 ^a	90.37 ± 0.3 _a	93.29 ± 0.1 _b	92.08 ± 0.6	97.96 ± 2.3*
22:0	0.27 ± 0.5 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
22:1ω11	120.05 ± 1.2 ^b	142.23 ± 2.8 ^a	110.04 ± 0.7 _a	116.12 ± 0.1 ₀	105.61 ± 2.8	115.0 ± 2.4*
22:1ω9	8.55 ± 0.17 ^b	9.93 ± 0.2 ^a	12.56 ± 0.1 _b	13.20 ± 0.1 _a	7.90 ± 0.0	8.48 ± 0.2*
22:1ω7	2.82 ± 0.0 ^b	3.31 ± 0.1 ^a	2.16 ± 0.0 _a	2.55 ± 0.0 _a	2.51 ± 0.0	2.66 ± 0.0*
22:2ω6	4.21 ± 0.2 ^a	0.00 ± 0.0 ^b	0.00 ± 0.0 _a	0.00 ± 0.0 _a	0.00 ± 0.0	0.00 ± 0.0
22:5ω3	6.27 ± 0.1 ^a	4.75 ± 0.1 ^b	4.60 ± 0.0 _b	4.86 ± 0.0 _a	4.56 ± 0.0	4.87 ± 0.1*
22:6ω3 (DHA)	39.96 ± 0.4 ^b	47.70 ± 1.0 ^a	46.41 ± 0.1 _b	48.46 ± 0.5 _a	40.68 ± 0.3	43.29 ± 1.0*
Unknown 9	1.99 ± 0.1 ^b	2.40 ± 0.0 ^a	1.77 ± 0.1 _b	2.07 ± 0.0 _a	1.86 ± 0.0	1.98 ± 0.1*
24:1ω9	3.77 ± 0.1 ^b	4.34 ± 0.1 ^a	5.18 ± 0.0 _b	5.65 ± 0.0 _a	3.00 ± 0.0	3.23 ± 0.1*
Saponifiables	864.98 ± 6.8 ^b	920.44 ± 25.6 ^a	902.0 ± 5.1 _b	929.35 ± 10.0 _a	850.26 ± 2.6	922.01 ± 19.7*
Σ SAT	131.51 ± 5.1 ^b	156.33 ± 5.4 ^a	154.57 ± 1.0 _b	171.22 ± 2.0 _a	167.46 ± 0.7	176.62 ± 3.8*
Σ MUFA	465.58 ± 8.8 ^b	560.31 ± 15.1 ^a	522.76 ± 2.4 _a	562.58 ± 5.9 _a	522.90 ± 4.3	559.28 ± 1.7*
Σ PUFA	157.75 ± 2.7 ^b	191.59 ± 4.7 ^a	187.01 ± 0.7 _b	193.48 ± 2.0 _a	173.12 ± 1.0	184.13 ± 4.2*
Σ ω-3	142.24 ± 2.1 ^b	169.7 ± 4.1 ^a	155.72 ± 0.6 _b	172.79 ± 1.8 _a	154.37 ± 1.0	164.16 ± 3.8*
Σ ω-6	11.92 ± 0.4 ^b	21.06 ± 0.60 ^a	16.50 ± 0.1 _b	19.81 ± 0.2 _a	14.19 ± 0.0	19.97 ± 0.5*
P/S	1.12 ± 0.0 ^a	1.23 ± 0.6 ^a	1.22 ± 0.7 _a	1.13 ± 0.0 _b	1.03 ± 0.0	1.04 ± 0.0
ω-3 / ω-6	11.93 ± 0.4 ^a	8.06 ± 0.0 ^b	9.44 ± 0.2 _a	8.72 ± 0.0 _b	10.88 ± 0.0*	8.22 ± 0.0

FPOAP Fall pollock oil with ascorbyl palmitate; SPOAP Spring pollock oil with ascorbyl palmitate; FPOAP Fall pollock liver oil with ascorbyl palmitate; Different subscript letters indicate differences between crude and purified Fall and Spring pollock oils (P<0.05); * indicated significant differences between crude and purified pollock liver oils (P<0.05)

Figure 27 shows the abundance of free fatty acids in crude and purified pollock oils produced at sea (evaporator temperature = 210 °C). There was a significant decrease in %FFA, and these results demonstrate that SPD is an effective purification method to remove free fatty acids from pollock oils. In Figure 28, the PV values for these oils are shown, and in all three types of oils there was a significant decrease in the abundance of primary products of lipid oxidation. The PV values of edible oils were very low and meet specifications for edible oils shown in Table 1. Similarly, the *p*-AV (Figure 29) values of purified oils produced were below 20, ranging in average from 12 to 15, being below the specification for edible oils shown in Table 1. Thiobarbituric acid values (TBA) were also very low in all oils (Figure 30). Water activity of oils produced at sea decreased after purification (Figure 31), and phosphorus content was also low for all oils. Results shown from Figure 27 to Figure 31 demonstrate the successful application of SPD to produce edible pollock oils from crude oils produced at sea.

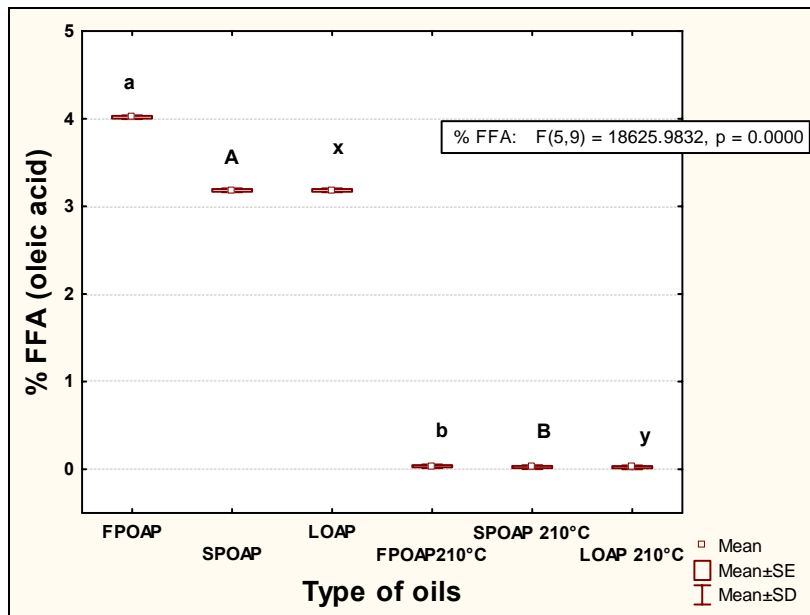


Figure 27. Free fatty acids content (%) of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

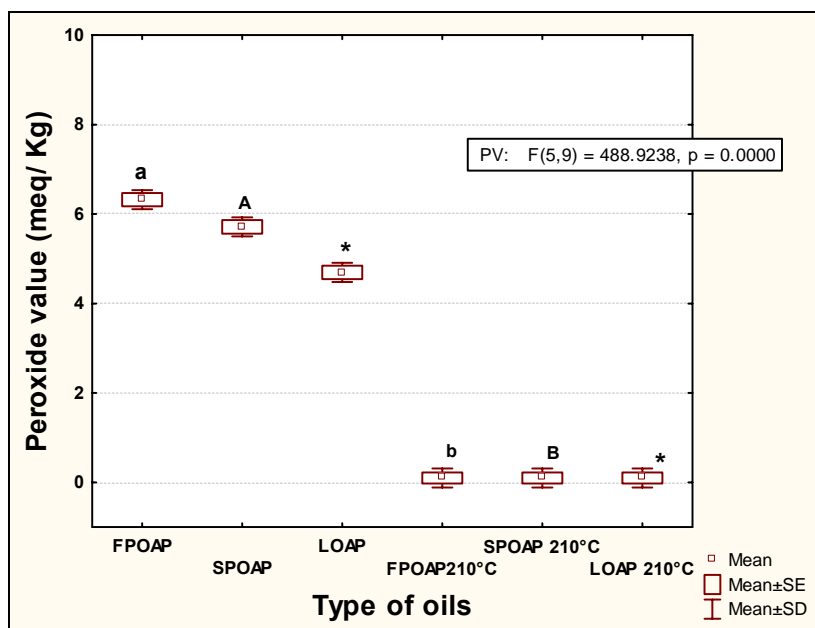


Figure 28. Peroxide value (meq/ Kg) of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

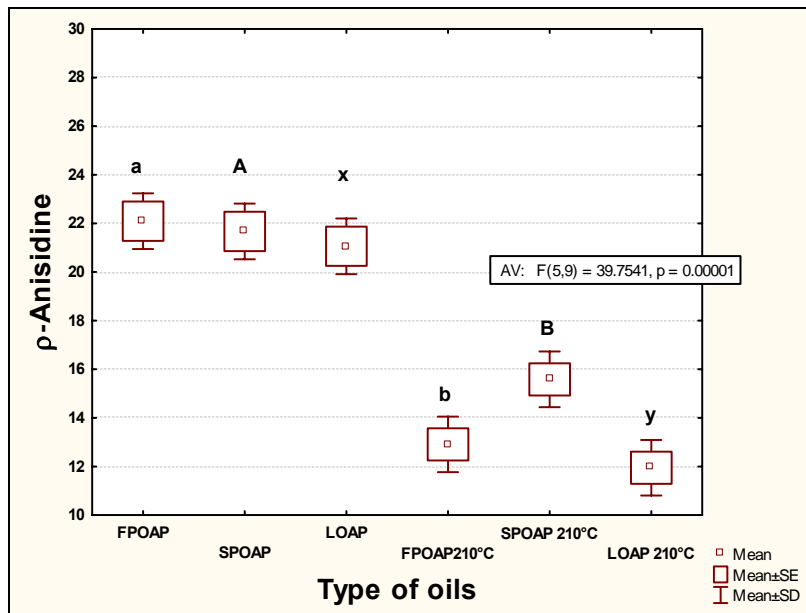


Figure 29. Anisidine value of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

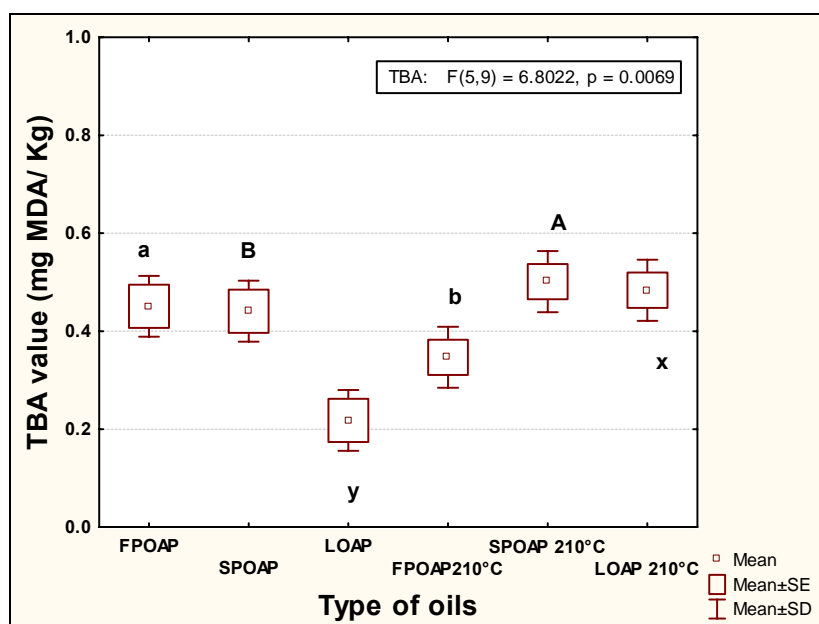


Figure 30. Thiobarbituric Acid (TBA) of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

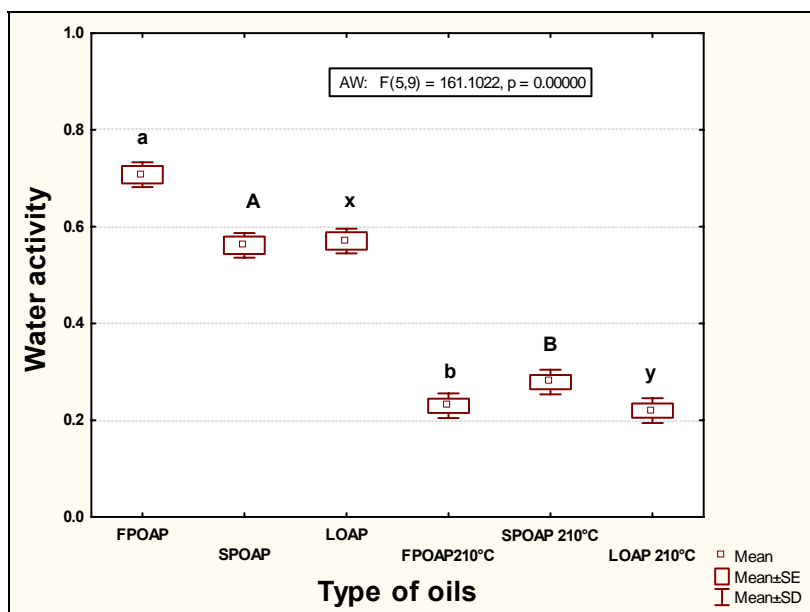


Figure 31. Water activity of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

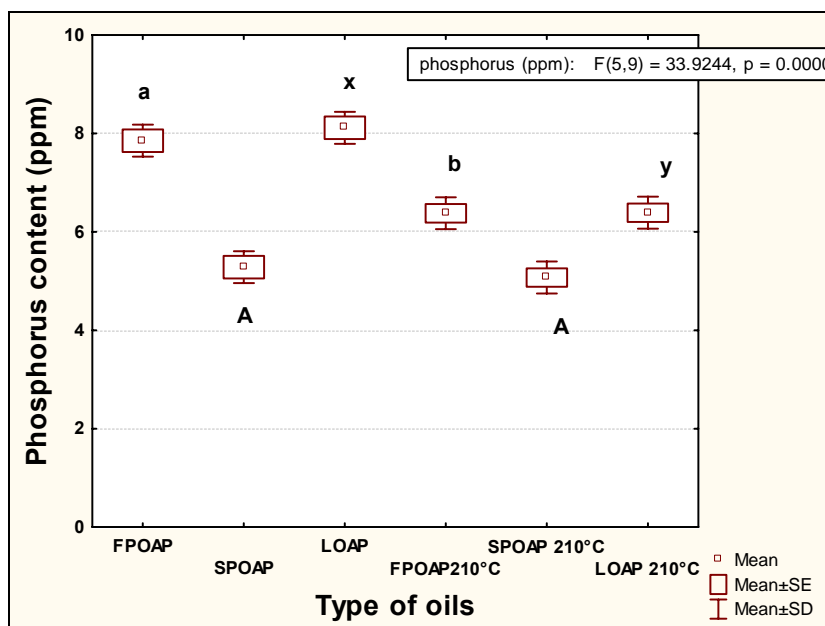


Figure 32. Phosphorus content of crude and purified pollock oils produced onboard of the *F/T American Triumph*. Different small caption letters (a, b) indicate statistical difference between crude and purified Fall pollock oils at $P < 0.05$; Different small caption letters (x, y) indicate statistical difference between crude and purified Fall pollock liver oils at $P < 0.05$; All caption letters (A, B) indicate statistical difference between crude and purified Spring pollock oils at $P < 0.05$

Figures 33 shows the abundance of free fatty acids in crude and purified pollock liver oils produced in the laboratory (evaporator temperature = 210 °C). There was a significant decrease in %FFA, and these results demonstrate that SPD is an effective purification method to remove free fatty acids from pollock liver oils rendered under laboratory conditions. In Figure 34, the PV values for these oils are shown, and a significant decrease in primary products of lipid oxidation was observed after oils were distilled. The p -AV (Figure 35)

values were surprising low for these purified samples, but are in agreement with the low values determined in the TBA analysis (Figure 36). Figure 36 shows a significant decrease in water activity occurred in the oils after distillation and Figure 37 shows a significant decrease in phosphorus content; however, this value was already low in the crude oils and did not interfere in the SPD purification. Results shown in Figure 33 to Figure 37 are in line with the results determined for SPD purified pollock oils produced at sea.

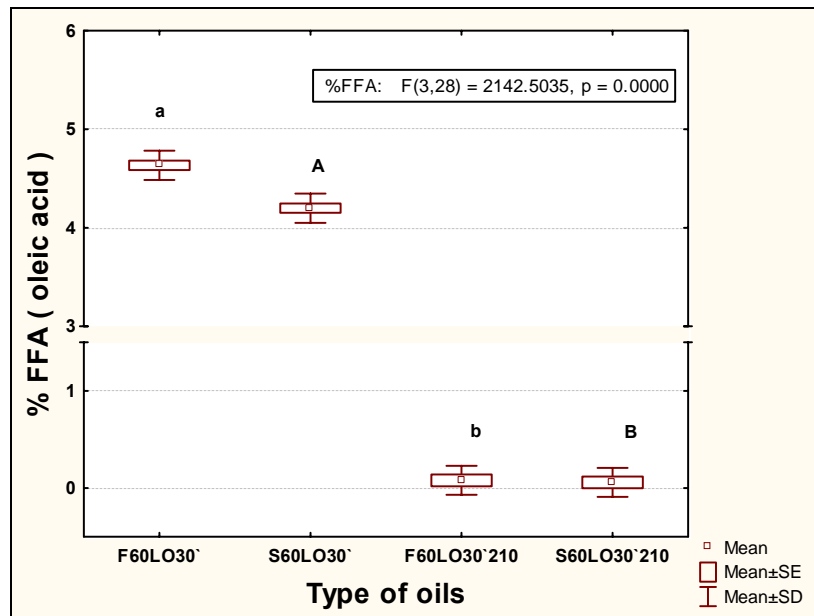


Figure 33. Free fatty acids content (%) of crude and purified liver oils rendered in the laboratory with antioxidant from Fall and Spring season extracted and purified by SPD. Different small caption letters indicate statistical difference between crude and purified Fall pollock liver oils (60 °C; 30 min) at $P < 0.05$; All caption letters indicate statistical difference between crude and purified Spring pollock liver oils (60 °C; 30 min) at $P < 0.05$

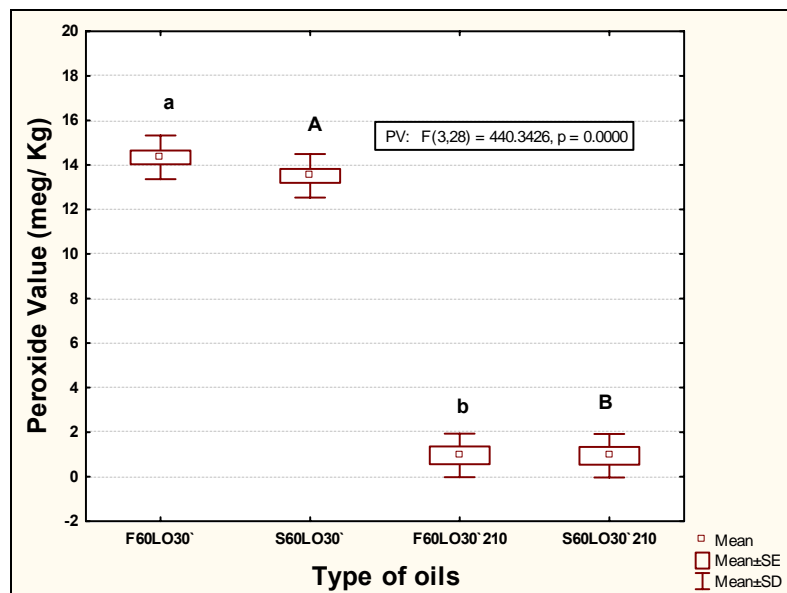


Figure 34. Peroxide value of crude and purified pollock liver oils rendered in the laboratory. Different small caption letters indicate statistical difference between Fall oils at $P < 0.05$; All caption letters indicate statistical difference between Spring oils (60 °C; 30 min) at $P < 0.05$

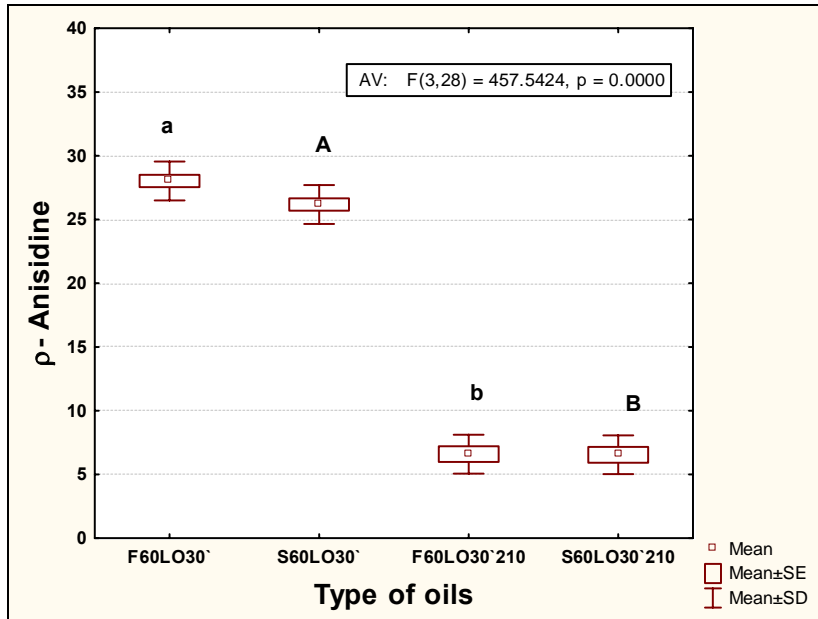


Figure 35. Anisidine value of crude and purified pollock liver oils rendered in the laboratory. Different small caption letters indicate statistical difference between Fall oils at $P < 0.05$; All caption letters indicate statistical difference between Spring oils (60°C ; 30 min) at $P < 0.05$

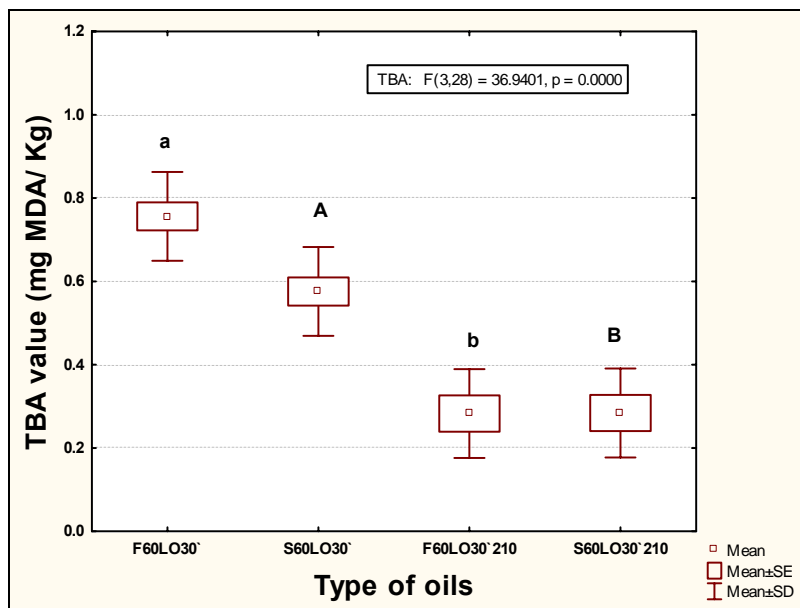


Figure 36. Thiobarbituric Acid (TBA) of crude and purified pollock liver oils rendered in the laboratory. Different small caption letters indicate statistical difference between Fall oils at $P < 0.05$; All caption letters indicate statistical difference between Spring oils (60°C ; 30 min) at $P < 0.05$

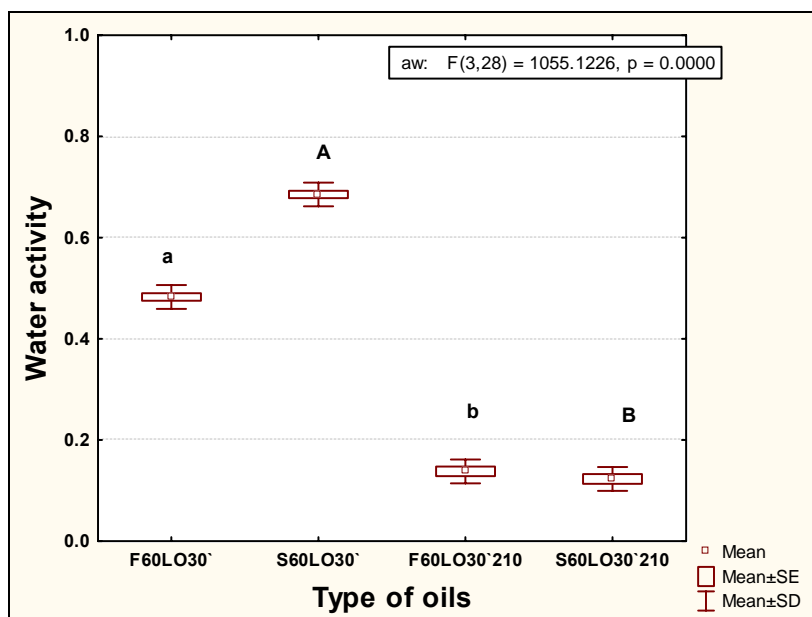


Figure 37. Water activity of crude and purified pollock liver oils rendered in the laboratory. Different small caption letters indicate statistical difference between Fall oils at $P < 0.05$; All caption letters indicate statistical difference between Spring oils (60 °C; 30 min) at $P < 0.05$

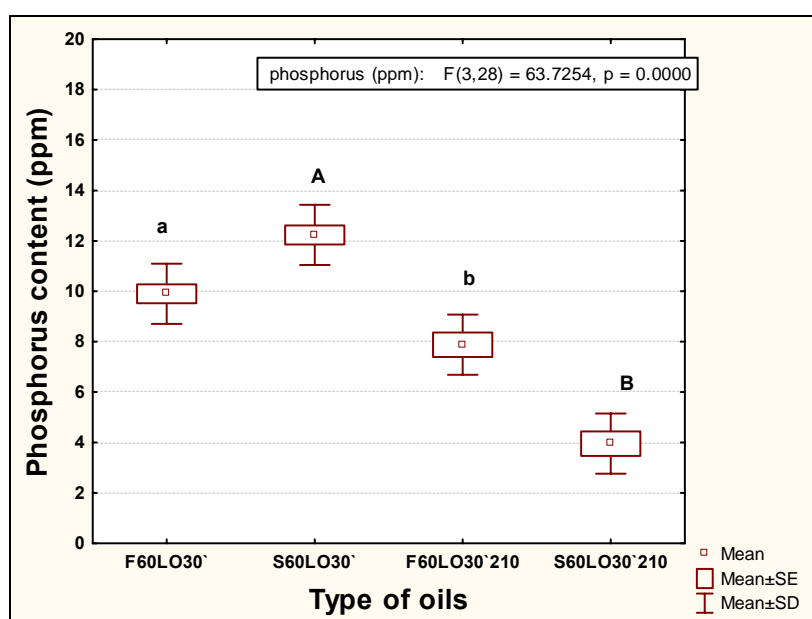


Figure 38. Phosphorus content of crude and purified pollock liver oils rendered in the laboratory. Different small caption letters indicate statistical difference between Fall oils at $P < 0.05$; All caption letters indicate statistical difference between Spring oils (60 °C; 30 min) at $P < 0.05$

CONCLUSIONS

1. Crude pollock oils and crude pollock liver oil produced at sea were of better quality than pollock liver oils produced under laboratory conditions (50 °C or 60 °C) despite the fact that oils produced at sea were rendered at much higher temperature (90 °C);
2. Ascorbyl palmitate, a GRAS substance, proved to be a very good additive (250 ppm) to stabilize pollock oils produced at sea. This additive improved the oxidative stability of Fall and Spring pollock oils produced from a mixture of byproducts and Fall pollock liver oil (*F/T American Triumph*);

3. Pollock liver oil produced during Fall 2008 at sea (trial run) was of higher quality than oils produced from a mixture of pollock byproducts from either Fall 2008 or Spring 2009. This oil, especially when stabilized with 250 ppm of ascorbyl palmitate, had lower levels of free fatty, and of primary and secondary products of lipid oxidation;
4. All crude pollock oils characterized during the course of this study need to be refined to meet edible fish oil specifications;
5. Pollock oils from either a mixture of byproducts or from segregated livers had lower ω -3 FA, EPA and DHA contents than the values for these fatty acids determined for either hake oil or cod liver oils. Additionally, pollock oils have higher content of ω -11 monounsaturated fatty acids of 20 and 22 carbon chains. In order to produce oil with a more favorable fatty acid profile, it is recommended that pollock oil is blended to cod liver oils and/or hake oils to produce an oil blend of "Bering Sea Whitefish Oil". Cod livers are presently underutilized in the Bering Sea fisheries, and this byproduct could be frozen in 7.5 Kg blocks at sea and utilized for the manufacturing of cod liver oil at a shore facility. An oil blend could be produced and then polished to meet edible fish oils specifications. The fatty acid profile of the oil blend would have higher ω -3 FA, EPA and DHA contents and lower ω -11 monounsaturated fatty acids than pure pollock oil;
6. Results showed that all pollock oils investigated could be refined using short-path distillation. Free fatty acids, primary and secondary products of lipid oxidation and sterols were effectively removed from pollock oils with SPD. The refined oils met all quality standards for edible fish oils;
7. Traditional fish oil purification is a multi-step process that utilizes chemical treatments and subsequent deodorization by vapor distillation, producing effluents that require treatment for discharge. Short-path distillation refines and deodorizes fish oils in a chemical-free single-step process.

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PRODUCTS OF THE STUDY

- 1) Oliveira ACM*, Ribeiro VA, Popp TA, Prentice C, Draves R and Bechtel PJ. **2010**. Application of short path distillation to produce human-grade pollock oil. Accepted for oral presentation. Pacific Fisheries Technologists Meeting. Seattle, WA. Feb 21st-24th.
- 2) Oliveira ACM*, Prentice C, Ribeiro VA, Popp TA, Draves R and Bechtel PJ. **2010**. Application of short-path distillation to refine Alaska pollock oils for nutraceutical use. Accepted for poster presentation. Institute of Food Technologists Annual Meeting. Chicago, IL. July 17th-20th.
- 3) Ribeiro VA, Oliveira ACM*, Bechtel PJ and Prentice C. **2009**. Low temperature rendering and characterization of edible fish oil from walleye pollock livers. Poster presentation. Institute of Food Technologist Annual Meeting. Anaheim, CA. Abstract #119-41. Book of abstracts p.140.

Two manuscripts will be submitted to peer-review journals reporting the findings of this study under the following titles:

- A. Low temperature rendering and characterization of walleye pollock livers oils
- B. Application of short-path distillation to refine Alaska pollock oils for nutraceutical use