processes

MDPI

Article

Effect of Pilot-Scale Decanter Centrifuge Processing Parameters on the Quality of Fish Meal Produced from Smoked Salmon Processing By-Products

Connor Neagle [1], Alexander Chouljenko [2], Greg Bolton [2], Sanazsadat Mirtalebi [2], Michael O. Frinsko [3], Steven G. Hall [4], Benjamin J. Reading [5] and Michael Joseph [1,*]

[1] Prestage Department of Poultry Science, North Carolina State University, Raleigh, NC 27695, USA; crneagle@ncsu.edu
[2] Department of Food, Bioprocessing and Nutrition Sciences, Center for Marine Sciences and Technology, North Carolina State University, Morehead City, NC 28557, USA; avchoulj@ncsu.edu (A.C.); gebolton@ncsu.edu (G.B.); smirtal@ncsu.edu (S.M.)
[3] Marine Aquaculture Research Center, North Carolina State University, Smyrna, NC 28579, USA; mofrinsk@ncsu.edu
[4] Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695, USA; shall5@ncsu.edu
[5] Department of Applied Ecology, North Carolina State University, Raleigh, NC 27695, USA; bjreadin@ncsu.edu
* Correspondence: mvjoseph@ncsu.edu

Abstract: Fish waste (FW) serves as an underutilized resource in agriculture, especially among small-scale processors. The trimmings and skins generated during the manufacturing of smoked salmon often end up in landfills due to insufficient quantities and logistical challenges to promote upcycling. An additional consideration is the high fat and mineral content in the smoked Atlantic salmon (*Salmo salar*) used for this study. We tested the feasibility of technology that small-scale processors can adapt to upcycle smoked salmon by-products into fish meal (FM) and fish oil (FO). A two-phase decanter centrifuge was optimized by manipulating acceleration, differential speed, flow rate, weir disc diameter, sample temperature, and the number of decanter runs. FW, processed through the decanter three times, produced FM with the least fat content compared to other trials. The optimized FM contained 74.09% protein, 8.56% fat, 15.41% ash, and 0.20% salt. FO production involved running a 9:1 water-to-by-product dilution through a three-phase clarifier centrifuge, followed by batch centrifugation and storage. Proximate, amino acid, and fatty acid profiles of the produced FM and FO aligned with industry standards. This study highlights a potentially sustainable solution for small-scale processors to transform FW into high-quality FM and FO, reducing waste and supporting sustainable resource recovery.

Keywords: seafood processing; fish waste; upcycling; aquaculture; animal feed; fish meal; fish oil; sustainability; decanter centrifuge; clarifier centrifuge

check for updates

Academic Editor: Dariusz Dziki

Received: 2 January 2025
Revised: 31 January 2025
Accepted: 7 February 2025
Published: 12 February 2025

Citation: Neagle, C.; Chouljenko, A.; Bolton, G.; Mirtalebi, S.; Frinsko, M.O.; Hall, S.G.; Reading, B.J.; Joseph, M. Effect of Pilot-Scale Decanter Centrifuge Processing Parameters on the Quality of Fish Meal Produced from Smoked Salmon Processing By-Products. *Processes* **2025**, *13*, 511. https://doi.org/10.3390/pr13020511

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Aquaculture is a global industry that is growing rapidly each year [1]. As such, more growth in the industry means more fish, and more fish means more availability of high-quality protein for higher numbers of people. Given that the majority of farmed marine fish are obligate carnivores [2], a stable and economic protein source must be provided for adequate feed manufacturing. Feed capture fisheries are fisheries that are commonly sourced for this protein supply in the form of fish meal (FM). Many of these fisheries are

near peak capacity; thus, utilization of current capture levels must be improved to remain sustainable [3]. FM is used for feeding land animals (pigs, chickens, companion animals) as well as fish [4]. Almost all the FM produced (97%) is used for feed applications, with 69% used for fish aquaculture, 23% to feed pigs, and 5% to poultry [5].

When looking at the demand for FM and fish oil (FO) globally, it is apparent that prices have been steadily increasing over the years. In 2013, the cost of FM was USD 1751/MT, which has since increased to the highest recorded price of USD 1815/MT as of 2023 [6]. FO in 2021 was valued at USD 3000 per ton, a USD 700 USD increase from 2020 [1]. This indicates that these products may no longer be regarded as low-value commodities [7]. Due to the combination of this and increased quota restrictions on capture fisheries associated with FM and FO, the economic incentive to utilize by-products for production is present. Such fisheries include the Peruvian Anchovy [8] and the Atlantic Menhaden [9]. To take some of the pressure off of these wild stocks, various methods have been employed. The most common is increasing the efficiency of feed usage to obtain aquaculture fish to market size [10]. Regardless, feeding fish is an expensive and labor-intensive endeavor due to the high frequency of feedings and the amount of feed and varying pellet sizes demanded by growing fish [11]. As estimated by Tacon and Metian [12], the majority of fish have a Fish In: Fish Out (FIFO) ratio of 3:1, thus demanding a large amount of feed to produce fish. As such, protein alternatives, such as by-products, for feed are of immense interest and highly investigated for usage in fish feed to further alleviate pressure on wild stocks [13]. Presently, studies looking at plant-based alternatives such as soybean meal and dried distiller grains with solubles (DDGSs) indicate these by-products as possible alternatives for FM [14,15]. Plant oils also serve as a similar alternative [16]. Insect meals are one of the more novel FM replacements [17].

One of the main methods used for the generation of FM and FO from the by-product of fish processing or 'fish waste' is the use of a tricanter centrifuge on the industrial scale. The name tricanter denotes three-phase separation in which there is a water phase, an oil emulsion phase, and solids (FM) that are generated. The tricanter works on the principle of using centrifugal force to settle out the solids from any given slurry. From there, an impeller applies pressure, which discharges the denser liquids while the less dense liquids flow without pressure through a different output. For FM production, raw material is caked and pressed. Any juices that come out of this press are fed through the tricanter centrifuge for three-phase separation, in which a solid phase, an oil-rich phase, and a water phase are all outputs. The water phase is evaporated, leaving behind dry soluble materials. These, along with the solid phase, are reincorporated into the initially pressed cake. This is then dried and is ultimately packaged and sold as FM [18]. Depending on the facility, the FO produced may or may not be retained through this process. This method is considered too costly in some instances, specifically in regard to at sea or artisanal fisheries [19]. As such, the initial press may be the only thing conducted with the FM cake being sold as is [20]. Due to the nature of processing fish in a timely manner, FM production plants are located on the coasts so as to quickly process and stabilize the highly perishable fish. The raw material input for these plants are the species that have little demand for direct human consumption, excess catch, and the fishing and processing residues. Ariyawansa [21] experimented with FM on a lab scale and found that through their methods of twin screw pressing, they were able to generate FM with crude protein percentages between 68 and 73% and crude fat percentages between 8.0 and 12.2%. These FMs spanned the use of three different species (herring, blue whiting, and capelin) as well. Skåra et al. [22] formulated FO from salmon by-product by means of decanter centrifuge, resulting in a free fatty acid (FFA) value of 26%. This value increased to 28% post use of an Alfa Laval separator. In addition, peroxide

values in this study were found to be 10.4 meq/kg by decanter centrifuge and 11.2 meq/kg by separator, respectively.

Small processors face the challenge of choosing which portions of the fish to utilize in order to make a profit. Often, this choice comes to choosing to maintain storage and processing space for the fish fillets over by-products, which hold less value in general. In 2018, waste produced from fish processing ranged from 25% to 70% depending on the processor in a year where 170 million metric tons of fish and shellfish were either captured or cultured worldwide [23]. These values represent a huge loss of potentially usable by-products. Therefore, our project sought to explore the potential uses of by-products from fish processing, which are generated by processors for FM and FO production. This work is driven by the hypothesis that a small-scale process for upcycling salmon by-products will yield a high-quality FM and FO that meets the quality and nutritional standards similar to that of a commercial FM and FO. Salmon was considered in this project because it is rich in protein and unsaturated fatty acids, and a smoked salmon processing facility is located in North Carolina. This company was generating by-products, 23,000 lbs (approximately 10,430 kg) of skins and 14,400 lbs (approximately 6530 kg) of trimmings per week, which were not being utilized to the fullest extent and were thus often destined to landfills. Therefore, this study would help them to be more sustainable in addition to improving their bottom-line income due to the value-addition of the by-products and not expending them for landfill tipping. This is particularly important to investigate for the value-addition of smoked salmon processing by-products, which are generated in small-scale operations for which there is little available research. This research will have local and global impact because it showcases the value-addition of fish processing by-products at a small-scale and would benefit fish processors who do not have large enough quantities to send to commercial FM and FO manufacturing facilities. The two-phase decanter equipment being used in this study is based on a few previous studies that used the same two-phase decanter centrifuge (Lemitec MD 80). They, respectively, processed proteins and fats using parameters and settings that were within range of 2000–4400$\times$ g acceleration, 10–50 rpm differential speed, 56–68 mm weir disc diameter, and 4–9 l/h flow rate [24] and 20–1000$\times$ g acceleration, 10 rpm differential speed, 64 mm weir disc diameter, and 7.4 l/h flow rate [25]. In order to achieve this, the following objectives were addressed: (1) conversion of smoked salmon processing by-products into FM and FO on a small scale, (2) optimization of the processing parameters to produce FM, and (3) characterization of the FM and FO.

2. Materials and Methods

2.1. Material

To carry out this study, a local fish processor, Acme-Smoked Fish (Wilmington, NC, USA), donated the raw material—fish skins and trimmings (Figure 1) from their cold-smoked aquacultured Atlantic salmon (*Salmo salar*) processing operations. The skins were the flanks of the fish without the filet, including some dermal flesh, skin, and scales. Trimmings or trims refers to a conglomerate of salmon parts that were not part of the saleable filet itself (i.e., gray meat, fat, membrane, and discolored parts). These were picked up in bulk from Acme-Smoked Fish and stored at North Carolina State University's Center for Marine and Sciences and Technology (CMAST) Seafood Lab (Morehead City, NC) in a freezer until further use.

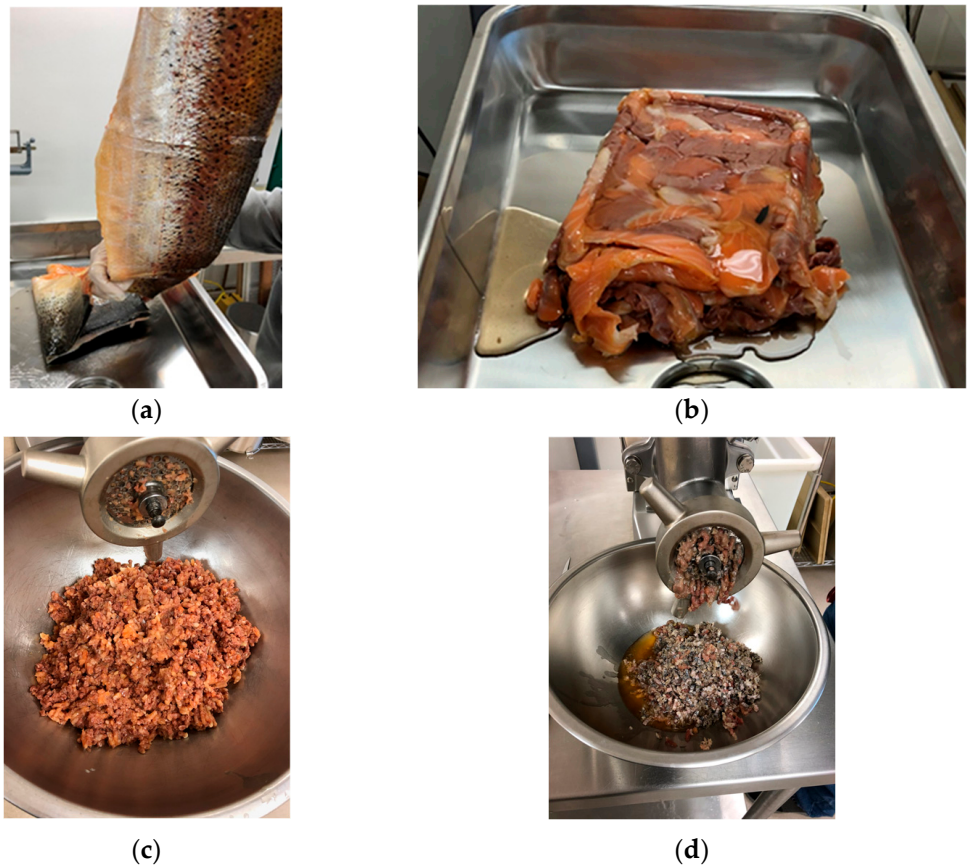


Figure 1. (**a**) Smoked salmon skin, (**b**) trimmings, (**c**) ground trimmings, (**d**) ground skins.

2.2. Equipment

For the purposes of this study, a pilot-scale decanter centrifuge (two-phase separation into solid and liquid) was used for producing FM. The Lemitec MD 80 Decanter Centrifuge (Lemitec, Berlin, Germany) is as shown in Figure 2. This is a two-phase separation decanter utilized to separate solid phase and liquid phase products. This occurs by means of differential rotation and acceleration of a bowl and scroll. The scroll is a steel screw that runs the length of the bowl and is responsible for conveying material through the decanter. Solid phase material is pushed toward the end of the scroll where it is ejected out of the bowl and into a sampling container. The liquid phase remains within the bowl. A weir disc is situated along the same side of the bowl as the liquid emulsion output. These discs are steel discs with a hole in the center and the diameter of which varies (Figure 3). The difference in these diameters determines the pond depth of the liquid phase found within the decanter. The smaller the diameter of the hole in the weir disc, the deeper the pond that develops within the bowl and vice-versa for wider diameters. The deeper the pond depth, the greater the residence time for separation. Once the pond depth spills over the weir height, it is ejected from the decanter and can be collected in another sampling container.

For the purposes of this project, the quality of the solid phase FM product derived from this equipment was optimized. An optimized solid phase in this case can be defined as FM that is (1) low in lipid content (<10%), (2) high in protein content (>70%), and (3) low in moisture content. These parameters were chosen due to the proximity in measurement to these same values in different FM, namely capelin, blue whiting, and herring [21]. The low crude fat and moisture content was shown to increase the shelf life of similar products and improve the extrusion process of feed. The FM produced by means of the decanter centrifuge would remain relatively moist (~65%); therefore, a dehydrator was used to generate a dry (<10% moisture) final FM product for later grinding and use.



Figure 2. Lemitec MD 80 Decanter Centrifuge in the pilot plant at North Carolina State University CMAST.



Figure 3. Various weir disc sizes for the Lemitec MD 80 Decanter Centrifuge.

For obtaining FO, an Alfa Laval Clara 20 (Lund, Sweden) pilot-scale centrifuge was utilized. This type of clarifier acts as a stage separation in which the sample is pumped via a peristaltic pump into a bowl that rotates as a centrifuge. This bowl will snap open for ejection of solid discharge and separate the oil emulsion from water while spinning under pressure. This separation results in three outlets. This equipment is not traditionally used as a tricanter centrifuge for oil production; instead, it is commonly found in the brewing industry [26].

2.3. Decanter Sample Preparation

When a sample was prepared for processing, trims and skins were run through a tabletop sausage grinder (Model M12H, Fleetwood Slicing Machines, Newark, NJ, USA) using a 9.5 mm hole diameter die to produce ground-smoked salmon by-products. These by-products were then placed within a 20-gallon (75.71 L) heating and mixing kettle (MKET20T, Cleveland Range, Cleveland, OH, USA) in a 2:1 ratio of skins to trims. This ratio was used because this is the ratio in which these by-products were being generated during the salmon processing. Reverse osmosis (RO) water was added in a 3:1 ratio of water to ground by-product. These were mixed within the kettle to form a slurry and heated until the temperature of the raw material within the kettle reached 75 °C due to operational limitations of the decanter centrifuge $\leq$80 °C. Once this target temperature was reached, the mixture was homogenized for 5 min using a Waring WSB Immersion Blender (Waring Commercial, Torrington, CT, USA). Sample slurry (3 kg) was measured

out for each run of the decanter and kept at 75 °C for the duration of each test run. A run constituted the complete processing of a sample slurry once through the decanter. The optimization runs had 4 different iterations, with each having one independent process parameter manipulated at a time. The combined flow chart of different optimization runs is presented in Figure 4.

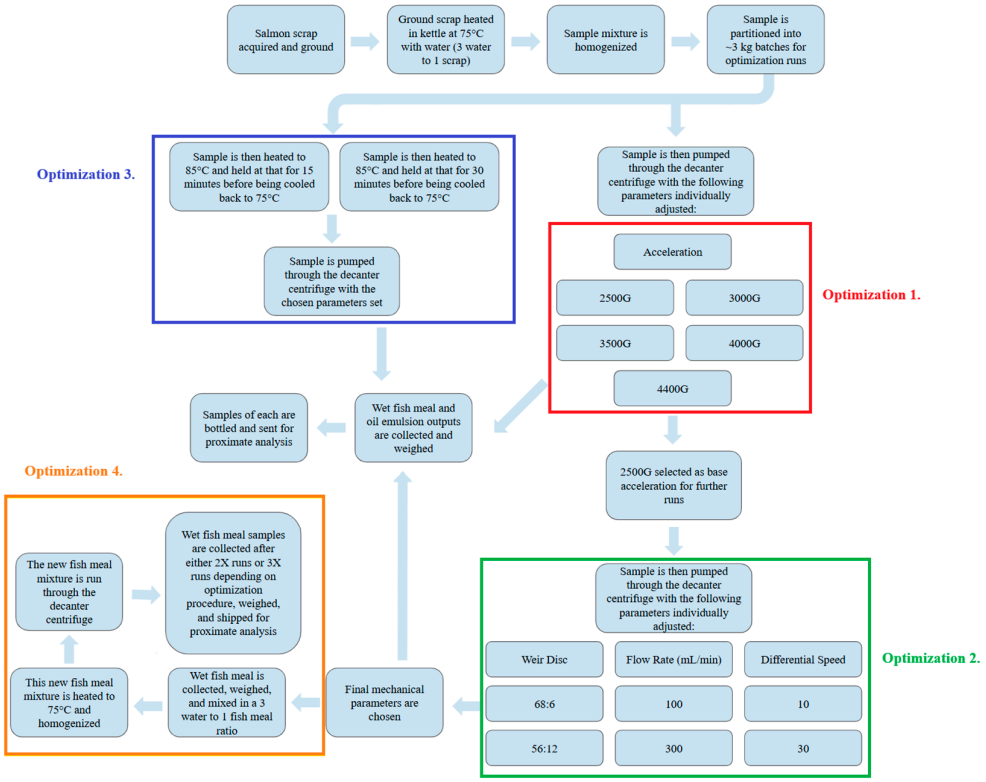


Figure 4. Flow chart showing all the different optimization runs with the aim of producing FM with <10% crude fat content.

2.4. Optimization of the Lemitec MD 80 Decanter Centrifuge

In order to optimize FM production with the decanter centrifuge, 4 setting parameters were identified to be adjusted throughout the study. These parameters were acceleration (quantified in G force), differential speed (difference in revolutions per minute between the bowl and the scroll), flow rate (rate at which material was pumped through the decanter centrifuge), and weir disc (varying diameters were selected). Optimization occurred in phases: Optimization 1 was used to adjust the independent variable of acceleration with no other variables being changed. The baseline variables used throughout this portion of the study were a weir disc with an inner diameter of 60 mm, a differential speed of 20, and a flow rate of 200 mL/min. These baseline parameters were chosen due to consistency in their operation, minor reduced energy consumption, and reduced high-intensity noise exposure to operators. Acceleration was tested at five different levels: 2500× g, 3000× g, 3500× g, 4000× g, and 4400× g. The maximum possible acceleration of the decanter centrifuge was 4400× g. To test acceleration, approximately 3 kg sample slurry was prepared for each test in triplicate. For each run, a 3 kg sample was kept in a glass beaker. The kettle was filled with water and heated to keep the sample at 75 °C in the beaker for the duration of the decanter run. The sample was placed on top of a metal cylinder within the kettle so as to keep the beaker from floating, and it was continuously mixed and held in place for pumping by hand for the duration of each test. This was the most efficient process found for holding the sample in place without spillage. The decanter centrifuge would then

be powered on, and error codes shown on the display of the decanter centrifuge would be cleared. Each time the decanter centrifuge was shut down (due to overload resulting from clogging of the centrifuge with solids), it showed an error code that stated "system shutdown", indicating that the power was off. The pump could be activated electronically via the decanter centrifuge once the decanter was powered on and the bowl acceleration achieved its targeted speed.

Once pumping was initiated, the electronic interface of the decanter that displayed and recorded the live feed of energy usage and the motor loads were monitored. A 100% motor load would shut down the equipment, and the process had to be restarted. The most common cause of this issue was overvoltage of the bowl, often caused by debris clog in the screw. Once the decanter was started, it was run all the way through until the sample became so viscous and shallow that it was no longer was able to be siphoned out of the beaker. When the sample stopped flowing, the machine was given a few minutes to empty the contents from the bowl and then shut down. All solid products were then weighed out separately to determine the yield of each run compared to the initial mass of the sample. This was recorded for each test. Solid and liquid phase samples were then collected.

Upon the completion of a test, the decanter centrifuge was dismantled, and all components were cleaned via hand scrubbing with dish soap. The components were then dried and reassembled in the opposite order they were disassembled. All the while, the next sample was heated and mixed in the kettle so the next run could be initiated post-assembly of the decanter centrifuge. The dismantling and reassembly took approximately 1 h in total.

2.5. Optimization 2

In the next steps of optimization, a variety of parameters were tested. Parameters were changed individually, with the others remaining the same along the baseline of 2500× *g* acceleration, 20 rpm differential speed, 200 mL/min flow rate, and 60 mm inner weir diameter. For example, if a test was addressing a change in differential speed, the parameters would be 2500× *g* acceleration, new differential speed (10 or 30 rpm), 200 mL/min flow rate, and 60 mm inner weir diameter. The same model would follow for any further parameter adjustments.

Samples were prepared in the same manner as for the acceleration trials. Once the slurry reached 75 °C, the mixing was halted and further homogenized by hand using a Waring WSB Immersion Blender (Conair LLC, Stamford, CT, USA). Homogenization lasted for 5 min, after which the solution was divided into 3 kg samples and stored separately for the tests ahead. After cleaning the kettle, it was filled with water and heated to 80 °C. A water temperature of 80 °C would ensure a 75 °C sample temperature due to heat transference across the glass beaker. The 3 kg sample was placed in the glass beaker as mentioned in Optimization 1 with continuous mixing of the sample within the beaker via a tabletop mixer until the sample was fully processed through the decanter centrifuge. After clearing any error codes present, the baseline settings for acceleration, differential speed, flow rate, and weir disc would then be set. One parameter would be changed for each test in Optimization 2. The run energy demand data were electronically collected on a memory card present in the decanter itself. Throughout the run, liquid and solid phase samples would be collected in different sampling containers and saved for later proximate analysis. Upon completion of the run, the decanter would be disassembled, cleaned, and reassembled as described previously. The process would then be restarted, and a new sample would be prepared.

For Optimization 2 tests, the differential speed was at 10 rpm and 30 rpm. These two values were considered as they were both 10 rpm away from the baseline differential speed of 20 rpm. After any shutdown during the running of the decanter, the decanter would be

turned back on, the error codes would be cleared, and the run would resume. Liquid would be removed from the decanter into a waste container, and the normal sample collection process would carry on as normal until the sample was depleted or the decanter shut down. Two shutdowns would result in a halt of the run in its entirety, and whatever samples could be salvaged would be used for proximate analysis.

The decanter centrifuge came with a series of weir discs to use during the operation of the decanter. Two additional weir discs were used during Optimization 2 (Figure 2). For the parameter of the weir disc, the individual discs are identified by two numbers. For example, the 60:10 weir disc used in Optimization 1. The 60 is representative of the internal diameter of the disc in mm, while the 10 is representative of the thickness of the disc in mm itself between the internal and external diameters. These weir discs were used to analyze their effect on the separation efficiency of the solid and liquid content of the sample.

All the runs were conducted in triplicate, and a total of 18 liquid and 18 solid (FM) samples were collected. The solid FM samples were analyzed for proximate composition, while the liquid samples were stored for potential later use. Any portion of the samples not collected for analysis was disposed of.

2.6. Optimization 3

After the above trials were completed and FM proximate composition data were collected, Optimization run 3 was undertaken to further increase the separation efficiency of the solid and liquid portions of the sample. Hilmarsdottir [27] reported that the raw materials are cooked at temperatures between 85 and 95 °C for 20 min in commercial production facilities. For these runs, the research team held the temperature of the sample at 85 °C for 15 min and 85 °C for 30 min after homogenization. A flow rate of 300 mL/min was used as opposed to 200 or 100 mL/min due to no significant difference being found in the quality of the FM yielded, while the higher flow rate results in faster processing of sampling. Optimization 3 was used to study the impact of crude fat separation from the FM, which has implications on the shelf life of the final desired product. This was achieved by heating water in a microwave and pouring the heated water into an insulated water bath. This water bath was kept at 85 °C, and the sample in a beaker was placed in it for the chosen duration of time. Once time at temperature was achieved for the sample, it was then placed in the kettle and cooled to 75 °C to run through the machine as normal. The temperature had to be reduced back to 75 °C due to the operational limitations of the decanter centrifuge, in which temperatures above 80 °C would overheat the equipment with potential metal/component warp from the combined heat of the raw material as well as the friction produced in operation.

After the time at which temperature trials were completed, solid and liquid yield was recorded, and samples were collected. Three solid and liquid samples were collected after each run, resulting in six solid samples and six liquid samples in total for this portion of Optimization 3. Again, the solid (FM) samples were analyzed for proximate composition, and the liquid samples were then retained for any potential later analysis.

2.7. Optimization 4

From all the above trials, the targeted crude fat values (<10%) in the FM could not be achieved. Therefore, FM was generated directly from the decanter centrifuge as previously described, then mixed and homogenized again at a 3:1 water to FM ratio in the kettle before passing through the decanter. It was processed like that an additional time, resulting in three decanter runs per FM batch. This created two more trial parameters to test, subsequently called 2X Decanter and 3X Decanter, indicating the number of times a sample would be run through the decanter centrifuge. The sample preparation and passage through the decanter

were performed as mentioned in Optimizations 1 and 2. The decanter would process the solution over a time period of 30 min per 3 kg solution. During the event of the engine starting to overload, the acceleration was reduced for the engine to level out and bring it up to speed again to ensure continuous processing of material. These were run at 2500× *g*, 20 rpm differential speed, 300 mL/min flow rate, and utilized a 60:10 weir disc. The liquid phase sample outlet was connected to a hose that would flow to the nearest drain. The solid phase (FM) final product was kept in sealed containers of varying sizes and stored in the refrigerator multiple times throughout the continuous run. At the end of the run, the decanter centrifuge was left to cool overnight prior to cleaning. This is due to the fact that the friction generated by the decanter over the course of the day would heat the metal to high temperatures deemed unsafe to handle. FM samples were collected in triplicate for each stage and preserved for proximate analysis.

2.8. Clarifier Operation

The clarifier, as shown in Figure 5, is a piece of equipment that is another centrifuge commonly used in food and fermentation industries. It is a high-speed centrifuge that utilizes pressure for separation in order to separate heavy and light liquids while solids are ejected by centrifugal force. This equipment was used for producing FO due to its ability to separate the FO from water and solids in oil emulsions. The two-phase decanter centrifuge is ineffectual in such a separation of immiscible liquids. For this equipment, the raw material enters through the inlet provided at the top of the bowl. Once inside the bowl, the said material is separated by centrifugal force and through discs. Solids settle along the outside of the bowl while the separated liquid continuously pumps out of the sealed bowl through an outlet at the top of the separator by way of a system of piping. Solids in the bowl are discharged cyclically. While material is flowing, discharge is controlled essentially by water that opens and closes the sliding portion of the bowl, which subsequently opens and closes discharge outlets. All flows and pressures are monitored and metered by or on the equipment itself.



Figure 5. Alfa Laval Clara 20 in the pilot plant at NC State University CMAST.

It was found that a balance had to be achieved between the pressure and flow rate of material in order to reach the targeted oil clarity. As a result, the use of this machine for three-phase separation was further explored. This would have allowed for faster separation of the oil, water phase, and solids as compared to the decanter and its slower throughput.

The first explored operation of this machine was to clarify liquid samples obtained from the decanter into crude oil via two-phase separation of water and lipids. This was

initially found to be inefficient for high quantity yield in our process, and, due to time constraints, a second sample would be diluted for processing, which resulted in faster FO production necessary for the time constraints associated with this study. The 2:1 smoked salmon skins to trims mixture was initially prepared as described in Optimization 1–3, and this time, it was diluted 9:1 water to fish by-product. This diluted sample solution was heated to 75 °C while mixing in the kettle. Once this target temperature was achieved, the solution was homogenized for 10 min to ensure the breakdown of any large particles floating in the solution. The heated solution was continuously mixed at 75 °C for the duration of a run.

After powering up the clarifier, it underwent its warmup sequence. Once this automatic warmup sequence was completed, the machine was ready for sample intake via the siphon hose, which was connected to the pump and placed in the kettle. In order to start the clarifier without issue, the production mode settings on the clarifier and the pump were started at the same time. Oil phase, water phase, and solid phase samples were all collected in separate containers that were placed at each of the three corresponding outlets on the equipment. After the sample was fully processed through the clarifier, the clarifier entered standby mode again. The kettle would then be thoroughly cleaned and scrubbed. Both water phase and oil phase solutions would be recombined in the kettle and mixed. The collected solid phase solution was stored in the refrigerator for later processing through the decanter centrifuge.

The recombined solution in the kettle was run through the clarifier again to further separate the oil from the water. The collection containers were again placed at all three outlets of the equipment. Once the production mode was restarted, the clarifier's centrifuge started spinning at 7647 rpm. While the clarifier was running, the intake valve was adjusted to build up pressure of 0.5 to 1 bar. An orange colored oil containing residual water and non-fat solids was produced by the equipment and collected in a glass beaker. Simultaneously, the hose releasing the water phase solution was placed in the kettle to recycle the material, yielding as much oil as possible. Production was stopped when the machine's oil clarity output diminished. The remaining solution in the kettle was then disposed of. The collected oil was stored in the refrigerator at 4 °C for subsequent further clarification and analysis.

2.9. FM and FO Post-Processing

After FM was produced and collected, it was dispersed on stainless steel racks and dried at 70 °C for 24 h within a food dehydrator (EXC10EL, Excalibur, Sacramento, CA, USA). After it was successfully dried and cooled in a desiccator, the FM would then be ground via a small hammer mill (MF10, IKA, Wilmington, NC, USA) before being packaged in vacuum-sealed bags. The collected FO emulsion output produced by the Alfa Laval Clarifier is considered quite crude and was further clarified utilizing a tabletop centrifuge, followed by a Rotovapor R-300 (Buchi, Switzerland). The FO was centrifuged at 10,000$\times$ g for 10 min at 4 °C. After being centrifuged, the clear oil was moved to the Rotovapor where oil was processed at 160 rpm with a 50 °C heating bath and a 10 °C chiller. A spherical separation flask was used. The Rotovapor processed the FO over a course of 40 min to reduce water activity. The FO was stored in plastic 5-gallon buckets post-process.

2.9.1. Proximate Analysis and Amino Acid Profile of FM, Fatty Acid Profile, and FFA Content of FO

Proximate analysis was carried out by ATC Scientific (North Little Rock, Arkansas) for each run of FM in triplicate. Moisture, protein, ash, sodium, crude fat (by acid hydrolysis), and salt (calculated from sodium) were all tested for. In addition to proximate analysis, this lab also carried out an amino acid profile for the FM and a fatty acid profile for the FO. The protocols used were AOAC 930.15 for moisture content, AOAC 990.03 for crude protein,

AOCS Ba 6a-05 for crude fiber, AOAC 942.05 for ash, AOAC 2011.14 MOD for sodium, and AOAC 954.02 for crude fat. For the amino acid profile, the protocols used were AOAC 982.30, AOAC 994.12, and AOAC 988.15. For the fatty acid profile, the protocol used was AOCS Ce 2-66. Within the FO product, the fatty acid profile, especially the omega-3 fatty acid content, was of interest. Omega-3s are desired for inclusion in the diet of fish feed. Additionally, a pure FO product with a high omega-3 content has a large potential for economic value outside of the context of fish feed [18]. FO was analyzed for free fatty acids (FFAs) based on the procedures and methods of Ke et al. [28].

2.9.2. Statistical Analysis

All experiments were conducted in triplicate. The independent variables in this study were the process parameters of the decanter centrifuge. These are the acceleration (quantified as G force), differential speed, flow rate (of the raw materials), weir disc diameter, sample temperature, and the number of decanter runs. The dependent variables consisted of parameters analyzed in the proximate analysis—crude protein, crude fat, crude fiber, ash, moisture content, and salt. Data were analyzed in JMP Pro 16 by means of One-Way ANOVA and Tukey-Kramer HSD. Letter means tables were generated by output data detecting significant differences ($p < 0.05$) from Tukey-Kramer HSD.

3. Results

3.1. FM Proximate Analysis

The primary aim of the optimization processes was to achieve efficient separation of FM and FO. The proximate composition of fish skins and trims from Acme-Smoked Fish (Table 1) and the composition of FM after Optimization 1 (Table 2) are provided. Proximate composition data were converted to a dry weight basis in order to adequately assess potential differences in protein and lipid contents. Although there was no statistically significant difference ($p > 0.05$), the protein content ranged from 74.60% to 67.21%, with 2500× *g* presenting the highest value. Similarly, the crude fat content did not have any statistically significant differences ($p > 0.05$) between the different runs. The crude fat content ranged from 19.27% to 14.08%, with no significant differences detected. Ash content ranged from 12.43% at 3500× *g* and to 11.32% at 4400× *g*. As the raw materials had salt application during the processing of salmon fillets, sodium levels were also tested as a part of the chemical analysis of the FM. There was a statistically significant difference in sodium levels between the FMs produced at 2500× *g*, 3000× *g*, and 4400× *g* (Table 3).

Table 1. Proximate analysis of trims and skins from Acme-Smoked Fish.

Raw Material	Moisture Content on Wet Basis (%)	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Ash (%)	Salt (%)
Skins	36.66 ± 0.22	36.87 ± 10.12	48.72 ± 6.31	9.86 ± 0.88	3.00 ± 0.10
Trims	51.56 ± 0.38	41.81 ± 7.22	40.63 ± 4.89	8.66 ± 1.44	5.61 ± 0.43

Moisture content of Means ± SD expressed on a wet weight basis, whereas all other values are on a dry weight basis.

Table 2. Proximate analysis of FM for Optimization Group 1.

	Treatment	Number of Runs with Shutdowns	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Ash (%)
Optimization 1	2500× *g*	1	74.60 ± 0.66 ^{A}	17.03 ± 0.22 ^{A}	11.56 ± 2.80 ^{A}
	3000× *g*	2	67.21 ± 7.23 ^{A}	19.27 ± 3.66 ^{A}	12.27 ± 1.24 ^{A}
	3500× *g*	0	73.70 ± 5.14 ^{A}	17.33 ± 1.27 ^{A}	12.43 ± 1.53 ^{A}

Table 2. *Cont.*

Treatment	Number of Runs with Shutdowns	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Ash (%)
4000× *g*	2	68.48 ± 4.79 ^{A}	18.62 ± 4.08 ^{A}	11.93 ± 2.92 ^{A}
4400× *g*	0	71.35 ± 0.85 ^{A}	14.08 ± 3.33 ^{A}	11.32 ± 0.71 ^{A}

^{A} Means ± SD with a letter in common within the same column are not significantly different. Crude protein, crude fat by acid hydrolysis, and ash are expressed on a dry weight basis. The number of runs that experienced a full shutdown of the decanter centrifuge is also indicated by treatment.

Table 3. Moisture content, sodium, chloride, salt calculated from sodium, and salt calculated from chloride of FM for Optimization Groups (2–4), as well as the chosen baseline comparison run (2500× *g*) from Optimization 1.

	Treatment	Moisture Content on Wet Basis (%)	Sodium (%)	Chloride (%)	Salt-Calculated from Sodium (%)	Salt-Calculated from Chloride (%)
Optimization 1	2500× *g*	66.07 ± 1.74 ^{BCD}	0.90 ± 4.5^{A}	X	2.29 ± 0.03 ^{A}	X
Optimization 2	100 Flow	70.14 ± 0.43 ^{AB}	0.81 ± 0.0 ^{AB}	1.03 ± 0.05 ^{AB}	2.08 ± 0.08 ^{AB}	1.7 ± 0.09 ^{AB}
	300 Flow	66.46 ± 1.40 ^{ABCD}	0.75 ± 0.06 ^{AB}	0.84 ± 0.0 ^{AB}	1.89 ± 0.1 ^{BC}	1.39 ± 0.11 ^{AB}
	56:12 Weir	71.72 ± 4.50 ^{A}	0.88 ± 0.20 ^{A}	1.13 ± 0.28 ^{A}	2.13 ± 0.26 ^{AB}	1.86 ± 0.46 ^{A}
	68:6 Weir	66.13 ± 1.74 ^{BCD}	0.78 ± 0.06 ^{AB}	0.95 ± 0.08 ^{AB}	1.97 ± 0.17 ^{ABC}	1.56 ± 0.12 ^{AB}
	DS 10	62.02 ± 0.76 ^{D}	0.66 ± 0.01 ^{B}	0.75 ± 0.04 ^{B}	1.68 ± 0.04 ^{C}	1.22 ± 0.07 ^{B}
	DS 30	69.54 ± 0.35 ^{ABC}	0.80 ± 0.03 ^{AB}	0.98 ± 0.02 ^{AB}	2.04 ± 0.04 ^{ABC}	1.62 ± 0.03 ^{AB}
Optimization 3	85 °C, 15 Min.	64.89 ± 2.98 ^{BCD}	0.86 ± 0.06 ^{A}	0.89 ± 0.18 ^{AB}	2.16 ± 0.14 ^{AB}	1.48 ± 0.30 ^{AB}
	85 °C, 30 Min.	64.38 ± 0.98 ^{CD}	0.84 ± 0.01 ^{AB}	0.84 ± 0.05 ^{AB}	2.16 ± 0.02 ^{AB}	1.39 ± 0.08 ^{AB}
Optimization 4	2X Decanter	64.62 ± 1.43 ^{CD}	0.33 ± 0.02 ^{C}	0.11 ± 0.02 ^{C}	X	0.18 ± 0.04 ^{C}
	3X Decanter	69.04 ± 0.82 ^{ABC}	0.26 ± 0.010 ^{C}	0.12 ± 0.07 ^{C}	X	0.20 ± 0.12 ^{C}

$^{A–D}$ Means ± SD with no letter in common within the same column are significantly different. Moisture content is expressed on a wet weight basis, and sodium, chloride, and salt contents are expressed on a dry weight basis. DS = differential speed; Flow = flow rate (mL/min); Weir = weir disc; X = not analyzed.

Due to the lack of any statistical difference in both crude protein and crude fat values among runs, the parameters used during the 2500× *g* (2500× *g*, 60:10 weir diameter, 200 mL/min flow rate, 20 differential speed) treatment were selected as the baseline acceleration for all subsequent trials because these conditions were optimal from the equipment operation point of view—less shutdowns and lower load on the equipment. Additional proximate data can be seen for analytes such as ash and sodium (Table 3); however, these data were largely inconsequential when deciding optimal FM for the purposes of this study. One factor that was considered with the optimization aspect of the decanter centrifuge was how many shutdowns the equipment experienced when running a sample. If a run yielded optimal FM but shut down more frequently than the others, the run would be considered suboptimal due to the time invested in disassembling and reassembling the equipment. The first optimization run showed that running the equipment at different speed settings did not have a significant impact on the proximate values of FM solids.

For Optimization 2, the data were compared to the baseline results from Optimization 1. The parameters tested in Optimization 2 are summarized in Table 4.

Statistically significant differences for crude fat were found using a 56:12 weir disc and a differential speed of 30, while no other significant differences were detected throughout the main parameters of interest (crude fat and crude protein). Significant differences were also witnessed between ash values at 100 Flow and 300 Flow, sodium values at 56:12 weir disc and differential speed of 10, and salt calculated from chloride at 56:12 weir disc

and differential speed of 10. The majority of statistically significant differences seen in Optimization 2 were in salt values calculated from sodium, with all but 68:6 weir and a differential speed of 30 having statistical significance. Crude fat was not within the desired parameter of less than 10%.

Within Optimization 3, keeping the raw material at a higher temperature for both 15 and 30 min showed a statistically significant difference between 2500× *g* data from Optimization 1 in crude protein, with it being relatively reduced. There were no additional statistically significant differences within Optimization 3. The optimization parameters are presented in Table 5.

Table 4. Proximate analysis of FM for Optimization Group 2, as well as the chosen baseline comparison run (2500× *g*) from Optimization 1.

	Treatment	Number of Runs with Shutdowns	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Crude Fiber (%)	Ash (%)
Optimization 1	2500× *g*	1	74.60 ± 0.66 ^{A}	17.03 ± 0.22 ^{B}	X	11.56 ± 2.80 ^{AB}
Optimization 2	100 Flow	3	73.37 ± 8.78 ^{A}	18.98 ± 1.12 ^{AB}	0.81 ± 2.00 ^{A}	9.67 ± 3.74 ^{B}
	300 Flow	1	69.69 ± 0.60 ^{A}	19.47 ± 1.04 ^{AB}	0.75 ± 1.63 ^{A}	15.47 ± 0.85 ^{A}
	56:12 Weir	2	70.82 ± 3.11 ^{A}	23.57 ± 4.22 ^{A}	0.88 ± 0.32 ^{A}	12.52 ± 1.84 ^{AB}
	68:6 Weir	2	71.48 ± 1.62 ^{A}	19.29 ± 0.73 ^{AB}	0.78 ± 0.02 ^{A}	13.93 ± 1.57 ^{AB}
	DS 10	0	64.58 ± 5.60 ^{A}	20.99 ± 0.78 ^{AB}	0.66 ± 0.01 ^{A}	13.63 ± 1.04 ^{AB}
	DS 30	3	76.39 ± 5.62 ^{A}	17.59 ± 1.66 ^{B}	0.80 ± 0.003 ^{A}	13.44 ± 0.65 ^{AB}

^{A,B} Means ± SD with no letter in common within the same column are significantly different. Crude protein, crude fat by acid hydrolysis, crude fiber, and ash are expressed on a dry weight basis. The number of runs that experienced a full shutdown of the decanter centrifuge is also indicated by treatment. DS = differential speed; Flow = flow rate (mL/min); Weir = weir disc; X = not analyzed.

Table 5. Proximate analysis of FM for Optimization Group 3, as well as the chosen baseline comparison run (2500× *g*) from Optimization 1.

	Treatment	Number of Runs with Shutdowns	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Crude Fiber (%)	Ash (%)
Optimization 1	2500× *g*	1	74.60 ± 0.66 ^{A}	17.03 ± 0.22 ^{A}	X	11.56 ± 2.80 ^{A}
Optimization 3	85 °C, 15 Min.	1	63.66 ± 3.76 ^{B}	24.69 ± 5.6 ^{A}	0.59 ± 0.34 ^{A}	13.92 ± 2.11 ^{A}
	85 °C, 30 Min.	3	68.23 ± 0.55 ^{B}	21.68 ± 2.04 ^{A}	0.28 ± 0.01 ^{A}	13.26 ± 3.06 ^{A}

^{A,B} Means ± SD with no letter in common within the same column are significantly different. Crude protein, crude fat by acid hydrolysis, crude fiber, and ash are expressed on a dry weight basis. The number of runs that experienced a full shutdown of the decanter centrifuge is also indicated by treatment. X = not analyzed.

Significant differences between Optimization 4 and Optimization 1 were only seen for sodium (Table 3) and crude fat (Table 6), with the values for each decreasing with each decanter rerun. Sodium was reduced from 0.90% to 0.26% in 3X Decanter. The desired crude fat target parameter of less than 10% was achieved by 3X Decanter as well at 8.56%. All optimization trials were compared to one another, and it was found that the 3X Decanter run was optimal at reducing fat below the desired threshold when compared to all other trial runs in Optimizations 2, 3, and 4. As such, the 3X Decanter together with parameters of 2500× *g*, 20 differential speed, 300 mL/min flow rate, and 60:10 weir disc were used to produce the final FM product. The subsequent proximate analysis of that final FM can be seen in Table 7. The average solid yield after Optimization 4 is approximately 22% and is within the range described for commercial operations, 16–25% [29] (Table 8).

Table 6. Proximate analysis of FM for Optimization Group 4, as well as the chosen baseline comparison run (2500× *g*) from Optimization 1, showing that further runs lowered the fat content.

	Treatment	Number of Runs with Shutdowns	Crude Protein (%)	Crude Fat by Acid Hydrolysis (%)	Crude Fiber (%)	Ash (%)
Optimization 1	2500× *g*	1	74.60 ± 0.66 ^{A}	17.03 ± 0.22 ^{A}	X	11.56 ± 2.80 ^{A}
Optimization 4	2X Decanter	0	74.78 ± 2.90 ^{A}	10.97 ± 0.50 ^{B}	1.06 ± 0.15 ^{A}	15.00 ± 1.65 ^{A}
	3X Decanter	2	74.09 ± 1.94 ^{A}	8.56 ± 0.42 ^{C}	1.51 ± 0.41 ^{A}	15.41 ± 0.33 ^{A}

$^{A–C}$ Means ± SD with no letter in common within the same column are significantly different. Crude protein, crude fat by acid hydrolysis, crude fiber, and ash are expressed on a dry weight basis. The number of runs that experienced a full shutdown of the decanter centrifuge is also indicated by treatment. X = not analyzed.

Table 7. Comparison of proximate analysis of the final selected FM product with that of a commercial FM on a dry weight basis.

Proximate Analyte	Mean ± SD (%)	Commercial Whitefish FM (%) *
Protein	74.09 ± 1.94	74.0
Crude Fat	8.56 ± 0.42	7.25
Crude Fiber	1.51 ± 0.41	0.39
Ash	15.41 ± 0.33	17.6
Sodium	0.26 ± 0.010	0.47
Chloride	0.12 ± 0.07	---
Salt	0.20 ± 0.12	1.19

* FM = fish meal, the analytical values for the commercial FM were provided by the FM manufacturer.

Table 8. Sample size, solid yield, and liquid yield for Optimization Groups 1–3 and 3X Decanter of Optimization 4.

	Treatment	3:1 Diluted Sample (kg)	Solid Yield (%)	Liquid Yield (%)
Optimization 1	2500× *g*	2.99 ± 0.02 ^{A}	10.00 ± 0.41 ^{BC}	67.60 ± 0.69 ^{A}
	3000× *g*	3.14 ± 0.28 ^{A}	12.74 ± 0.23 ^{B}	65.41 ± 5.64 ^{A}
	3500× *g*	3.04 ± 0.03 ^{A}	9.90 ± 0.40 ^{BC}	72.31 ± 0.35 ^{A}
	4000× *g*	3.55 ± 1.00 ^{A}	9.74 ± 3.50 ^{BC}	71.25 ± 2.76 ^{A}
	4400× *g*	3.02 ± 0.03 ^{A}	12.09 ± 0.47 ^{B}	70.29 ± 1.52 ^{A}
Optimization 2	100 Flow	3.03 ± 0.01 ^{A}	1.76 ± 0.61 ^{E}	15.65 ± 4.76 ^{C}
	300 Flow	3.01 ± 0.01 ^{A}	8.83 ± 0.19 ^{BCD}	73.32 ± 2.93 ^{A}
	56:12 Weir	3.03 ± 0.05 ^{A}	4.31 ± 2.67 ^{DE}	17.86 ± 12.44 ^{BC}
	68:6 Weir	3.02 ± 0.01 ^{A}	6.20 ± 3.74 ^{CDE}	53.97 ± 30.38 ^{AB}
	DS 10	3.02 ± 0.01 ^{A}	8.35 ± 0.33 ^{BCD}	77.43 ± 2.54 ^{A}
	DS 30	3.02 ± 0.03 ^{A}	1.85 ± 0.40 ^{E}	22.81 ± 3.42 ^{BC}
Optimization 3	85 °C, 15 Min.	3.03 ± 0.04 ^{A}	10.92 ± 1.20 ^{BC}	71.50 ± 1.41 ^{A}
	85 °C, 30 Min.	3.07 ± 0.04 ^{A}	5.87 ± 3.02 ^{CDE}	51.41 ± 23.90 ^{ABC}
Optimization 4	3X Decanter	3.10 ± 0.13 ^{A}	22.45 ± 0.47 ^{A}	70.97 ± 30.14 ^{A*}

$^{A–E}$ Means ± SD with no letter in common within the same column are significantly different. Significant differences were compared between all groups (Optimizations 1–3 and 3X Decanter). DS = differential speed; Flow = flow rate (mL/min); Weir = weir disc, * = liquid yield for Optimization 4 is presented in duplicate.

3.2. FM Amino Acid Profile

In addition to the proximate analysis of the final FM, the amino acid profile was also analyzed and is presented in Figure 6. Of the amino acids, the three highest contents were glutamic acid (3.19 ± 0.32%), aspartic acid (2.36 ± 0.10%), and glycine (2.25 ± 0.28%). The amino acid taurine was found to be the lowest at 0.002 ± 0.003%. The amino acids hydroxyproline and lanthionine did not show up in the amino acid profile in any quantity. Due to differences in the conversion factor of protein between the trim (conversion factor

6.25) and skins (conversion factor 5.40 [30]), there are chances that the crude protein content may be overestimated during the proximate analysis. In order to verify the same, we found that the cumulative sum of all the amino acids (75.60% dry basis) showed that both values were comparable.

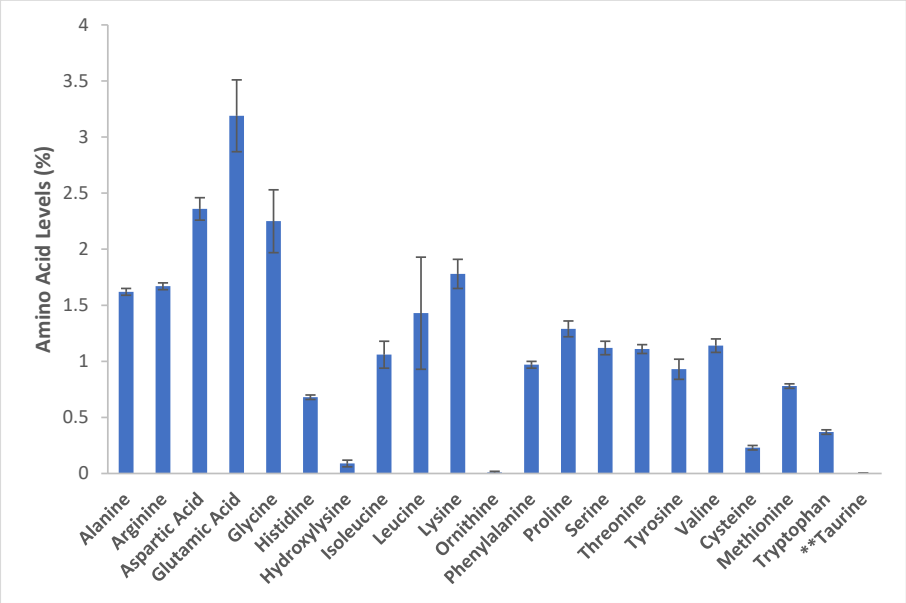


Figure 6. Amino acid composition of the final selected FM product on a wet weight basis. ** Taurine content was the least at 0.002%.

3.3. FO Fatty Acid Profile

FO was analyzed for a fatty acid profile (Figure 7). Monounsaturated fats comprised the majority of the fat content by percentage within the FO, followed by polyunsaturated fats and lastly by saturated fats. Trans fats were less than a 10th of a percent of the FO. Omega-9 fatty acids were 44.48% of the monounsaturated fats. Within the polyunsaturated fats, 22.12% were omega-6 fatty acids and 9.46% were omega-3 fatty acids. Additional major players within the fatty acid profile included oleic acid (36.42%), linoleic acid (20.06%), and palmitic acid (12.06%). Other fatty acids presented themselves in smaller quantities throughout the fatty acid profile.

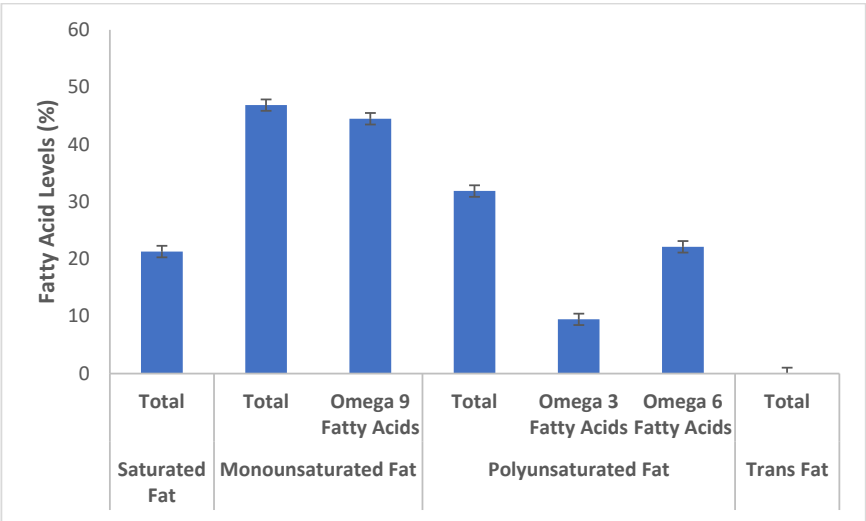


Figure 7. FO fatty acid profile of major fat types and relative concentrations of omega 3, 6, and 9 fatty acids found within these fat types. Trans Fat was found to be 0.01%.

4. Discussion

4.1. FM Production and Proximate Analysis

One of the major hurdles encountered in the operation of the Lemitec MD 80 Decanter Centrifuge was the ease with which either engine (bowl or scroll) could be overloaded, causing the equipment to shut down. What was noted in preliminary exploration with the equipment was that while capable of a greater differential speed, the combination of that and the viscosity of our sample would lead to a shutdown of the decanter centrifuge, usually when raised above 20 rpm. As such, the differential speed was kept low. Other parameters had apparent influences on product consistency and equipment operation as well. An increase in flow rate reduces residence time within the decanter centrifuge, making each run faster with the increased rate. The faster the flow rate, however, the more wet a product came out because of the lower time available for the separation of solids and liquids. Additionally, the likelihood of a clog increased due to material bridging. Weir disc size had similar influences as flow rate in terms of residence time, where a thicker weir disc size would increase the pond depth. The greater the pond depth, the greater the residence time of the material, which was found to result in better separation of solids in other studies [24].

During Optimization 1, no significant differences were found in the primary constituents of the FM, the crude protein, and crude fat content. The FM output had a moisture content of approximately 65% across all the runs (Table 3). This meant that the separation efficiency of solid and liquid components from the raw material was not affected by the different levels of accelerations used in this study. This was probably because the diluted samples run through the equipment had a moisture content of 86%, or in other words, the solids concentration was 14%. The range of accelerations used in this study probably does not affect such a low level of solids content circulating through the equipment. In a study conducted by Róbertsdóttir [31] on designing a pelagic fish meal processing line, they used the raw material input into the decanter with 20.8% of dry matter or solids.

It should be brought to the forefront that the results discussed here are based on two settings of equipment due to operational issues leading to frequent stoppages during running the tests. Optimization 2 tested the other parameters of decanter operation, such as the flow rate, different weir disc diameters, and varying differential speeds between the scroll and the bowl. Changing flow rates did not result in any significant difference in the crude protein and crude fat content of the FM. This could be due to the flow rates of a dilute input not affecting the separation efficiency of the equipment. It was observed that the lower flow rate of 100 mL/min caused more equipment shutdowns. This may be due to the higher residence time of the material inside the equipment, which clogs the outlet of the scroll due to not having enough flow rate to keep the material flowing from it to the bowl. Between the two discs used during this run, there was no significant difference between the crude protein and crude fat content of the FM. Though the 56:12 weir disc created a deeper pond and had a higher residence time, which should lead to better separation or in other words higher crude protein content and lower crude fat content, that was not the case: a higher residence time also creates a wetter output, so, the solids may have been coated/bathed in oil-rich liquid more and thus had higher crude fat content [24]. As observed in the previous two parameters that were tested, there were no significant differences in the crude protein and crude fat content for the differential speeds. Theoretically, lower differential speeds increase the residence time of solids inside the decanter and vice versa. It also ensures better dehydration of the FM output. However, the results were just the opposite, with higher differential speed showing higher crude protein content and lower crude fat content. Again, these results may have been impacted

by higher residence time with lower differential speed, causing oil to be coated onto the protein/solids. The higher differential speed also caused more shutdowns.

The Optimization 3 consisted of heating the raw material to 85 °C and holding it for two time periods of 15 min and 30 min. The purpose of heating and holding was to improve the efficiency of oil separation from the fish mass. Heating helps in coagulating the proteins, which aids in better removal of oil and water during subsequent processing [27]. However, the heating protocols used did not provide the intended results; the crude protein content was lower and the crude fat content was higher in the FM than in the preceding optimization runs (Table 5). Probably, the temperature used was higher or not optimal, which reduced the efficiency of separation of solids and liquid components, and thereby, the FM produced was not of good quality in terms of the crude protein and fat content.

Based on the different optimization runs, it was found that the FM produced was high in crude fat content, which was not desirable. Therefore, Optimization 4 consisted of a double and triple pass of the same raw material through the decanter. The multiple separation steps helped lower the fat content in the FM, and the three runs produced the FM with the target crude fat content of <10% (Table 6). Multiple passes at the Optimization 1 settings had an additive effect on the separation efficiency of the FM produced at each step.

In a study conducted by Atanasoff et al. [32] looking at the proximate composition of Atlantic salmon (*Salmo salar*), it was found that the mean crude protein content on a dry basis was 68.69% and the mean crude fat content on a dry basis was 4.67%. Now, this was found to be within the salmon product itself and not FM. For studies addressing FM, Ween et al. [33] looked at the proximate composition of FM produced from fresh by-products of cod (*Gadus morhua* L.) and saithe (*Pollachius virens*). These were collectively labeled as whitefish fish meal (WFM) and were found to have a crude protein content of 61.9 ± 1.8% and a crude fat content of 8.9 ± 1.1% on a dry basis. When comparing this to the dry basis crude protein (74.09 ± 1.94%) and crude fat (8.56 ± 0.42%) found for Atlantic salmon FM from skins and trim meat in this study (Table 7), the proportion of protein is similar while the crude fat content is slightly higher (but below 10%) to that of these industry FM. Similarly, glutamic acid was the highest concentration in both WFM and the FM of this study; however, the concentration of glutamic acid in WFM was more than double that of our smoked salmon by-product FM at 8.19% compared to 3.20% [33]. The amino acid profile also proved similar, with the next two highest being aspartic acid and glycine in the WFM at 5.84% and 4.56%, respectively. Overall, the amino acid quantities were higher in WFM as opposed to what was found in the smoked salmon FM of this study. Hassan et al. [34] conducted a feeding trial study looking at protein substitutes in fish feed. One such substitute was smoked fish waste meal, on which proximate analysis was conducted. When looking at crude protein, the smoked fish waste meal was 40.03%, while the crude fat was 25.40%. Comparatively, the smoked salmon FM meal yielded in this study was both higher in crude protein (74.09%) and lower in crude fat (8.56%).

4.2. FO Fatty Acid Profile

In a study that evaluated the fatty acid profile of Atlantic salmon oil, it was found that salmon oil contained 19.80 ± 0.20% saturated fats, 44.20 ± 0.42% monounsaturated fats, and 33.72 ± 0.62% polyunsaturated fats [35]. In comparison, the FO from the present study was found to have 21.29 ± 0.36% saturated fats, 46.86 ± 0.59% monounsaturated fats, and 31.86 ± 0.23% polyunsaturated fats, making it on par with market salmon oil. For the same study, omega-3 was found to be 14.33 ± 0.58% and omega-6 was 19.36 ± 0.17% [35]. This contrasts from the study performed here, with omega-3 found to be lower at 9.46 ± 0.42% and omega-6 found to be higher at 22.12 ± 0.11%. Percentages of oleic acid, linoleic acid,

and palmitic acid were similar between both studies. The differences in the omega-3 and omega-9 fatty acids were due to the fish used in this study being aquacultured.

Overall, the quality of FM and FO yielded from the Lemitec MD 80 Decanter Centrifuge and the Alfa Laval Clara 20 was on par with commercial salmon and whitefish meal and oils. This indicates that the process conducted in this study has great potential to be a means for small-scale producers to utilize and retain economically valuable resources (FM and FO) from smoked salmon, with potential applications to other varieties of fish by-products as well. Specifically, with regard to FO, the quantity of desired omega-3s opens windows to potential uses of FO from by-products in human-centric products in the future [36]. The use of such fish waste in the form of by-products is a means to alleviate pressure on wild-caught fisheries as well. As of 2014, 17% of all wild-caught fish were utilized for FM production [18]. This does not include the waste found from convenience food products such as ready-packaged fish filets. Sequestering the waste from these convenience food products and using them for by-product manufacture is an avenue that has the capacity to alleviate pressure on already imperiled fisheries under strict quotas. This study offers a means for incentivizing the use of fish waste in a way that is potentially both economically profitable and environmentally sustainable for producers.

5. Conclusions

Addressing the objectives of the study, the adopted process was successful in utilizing smoked salmon processing by-products to produce FM and FO. This process was optimized for small-scale production of FM through the usage of a Lemitec MD 80 decanter centrifuge. The Alfa Laval Clara 20 centrifuge was used to generate FO. These products were then characterized by way of proximate analysis, amino acid profile, and fatty acid profile. The model used in this study may work well for small-scale manufacturing; however, it differs from the industrial equipment commonly used for this kind of production.

The use of FW from smoked fish processing operations has the potential to be a valuable source for FM and FO production in aquaculture. Smoked Atlantic salmon (*Salmo salar*) skins and trimmings from aquacultured fish demonstrated the ability to be processed into high-quality products with FM that is high in crude protein and low in crude fat, and FO has a fatty acid profile demonstrating substantial concentrations of desired omega-3s, omega-6s, and omega-9s. How these skins and trims are processed by way of a decanter centrifuge is important for FM quality; however, in order to dramatically reduce the crude fat percentage of the FM, processing the FM through the decanter centrifuge 3 times proved optimal for lowering crude fat content to desired levels. On a pilot scale, equipment is prone to shut down due to clogs from scales and skin; however, this issue seems to be avoided in industry scale decanter centrifuge operations. The products yielded from smoked salmon by-products were of sufficient quality in proximate analysis, amino acid profile, and fatty acid profile to be considered as high-value ingredients in feed manufacturing for aquaculture while enhancing the sustainability of both the processing and aquaculture industries. Further studies are needed to optimize production of FO and FM on a small scale where decanter and clarifier centrifuges are employed sequentially rather than separately. This can include testing the equipment process parameters beyond the two settings for each parameter used in this study.

Author Contributions: Conceptualization, A.C., M.J., S.G.H., B.J.R. and M.O.F.; methodology, M.J. and A.C.; software, C.N. and S.M.; formal analysis, C.N., A.C. and M.J.; investigation, C.N., A.C. and G.B.; resources, A.C. and M.J.; data curation, M.J.; writing—original draft preparation, C.N.; writing—review and editing, S.M., A.C., M.J., S.G.H., B.J.R. and M.O.F.; visualization, S.M.; supervision, A.C. and M.J.; project administration, M.J. and A.C.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Oceanic and Atmospheric Administration (NOAA) via grant number NA21NMF4270352.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FAO. *International Markets for Fisheries and Aquaculture Products*; Globefish Highlights: Rome, Italy, 2022; p. 4.
2. Froehlich, H.E.; Gentry, R.R.; Halpern, B.S. Synthesis and comparative analysis of physiological tolerance and life-history growth traits of marine aquaculture species. *Aquaculture* **2016**, *460*, 75–82. [CrossRef]
3. Morrissey, M.T.; Sylvia, G. Intrinsic and extrinsic factors affecting efficient utilization of marine resources. *Dev. Food Sci.* **2004**, *42*, 37–43.
4. Ramírez, A. Innovative uses of fisheries by-products. *Globefish Res. Programme* **2013**, *110*, 1–53.
5. Boyd, C.E.; McNevin, A.A. Overview of aquaculture feeds: Global impacts of ingredientt production, manufacturing, and use. In *Feed and Feeding Practices in Aquaculture*, 2nd ed.; Woodhead Publishing: Cambridge, UK, 2022; pp. 3–28.
6. World Bank Pink Sheets. Available online: https://thedocs.worldbank.org/en/doc/5d903e848db1d1b83e0ec8f744e55570-0350012021/related/CMO-Historical-Data-Annual.xlsx (accessed on 4 September 2024).
7. Tacon, A.G.J.; Hasan, M.R.; Metian, M. Demand and supply of feed ingredients for farmed fish and crustaceans: Trends and prospects. *FAO Fish. Tech. Pap.* **2011**, *564*, 71–87.
8. Vizurraga, A. Peru's Fishmeal Industry: Its Societal and Environmental Impact. Master's Thesis, City University of New York, New York, NY, USA, 2022.
9. Anstead, K.A.; Drew, K.; Chagaris, D.; Schueller, A.M.; McNamee, J.E.; Buchheister, A.; Nesslage, G.; Uphoff, J.R.J.H.; Wilberg, M.J.; Sharov, A.; et al. The path to an ecosystem approach for forage fish management: A case study of Atlantic menhaden. *Front. Mar. Sci.* **2021**, *8*, 607657. [CrossRef]
10. Hancz, C. Feed efficiency, nutrient sensing and feeding stimulation in aquaculture: A review. *Acta Agrar. Kaposváriensis* **2020**, *24*, 35–54. [CrossRef]
11. Craig, S.R.; Louis, A.H.; David, K.; Michael, H.S. *Understanding Fish Nutrition, Feeds, and Feeding*; Virginia Cooperative Extension, Virginia Tech University: Blacksburg, VA, USA, 2017.
12. Tacon, A.G.J.; Metian, M. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* **2008**, *285*, 146–158. [CrossRef]
13. Arvanitoyannis, I.S.; Kassaveti, A. Fish industry waste: Treatments, environmental impacts, current and potential uses. *Int. J. Food Sci. Technol.* **2008**, *43*, 726–745. [CrossRef]
14. Chevanan, N.; Muthukumarappan, K.; Rosentrater, K.A.; Julson, J.L. Effect of die dimensions on extrusion processing parameters and properties of DDGS-based aquaculture feeds. *Cereal Chem.* **2007**, *84*, 389–398. [CrossRef]
15. Magbanua, T.O.; Ragaza, J.A. Selected dietary plant-based proteins for growth and health response of Nile tilapia *Oreochromis niloticus*. *Aquac. Fish.* **2024**, *9*, 3–19. [CrossRef]
16. Hansen, A.C.; Hemre, G.I. Effects of replacing fish meal and oil with plant resources in on-growing diets for Atlantic cod *Gadus morhua* L. *Aquac. Nutr.* **2013**, *19*, 641–650. [CrossRef]
17. Hua, K. A meta-analysis of the effects of replacing fish meals with insect meals on growth performance of fish. *Aquaculture* **2021**, *530*, 735732. [CrossRef]
18. Olsen, R.L.; Toppe, J.; Karunasagar, I. Challenges and realistic opportunities in the use of by-products from processing of fish and shellfish. *Trends Food Sci. Technol.* **2014**, *36*, 144–151. [CrossRef]
19. Rustad, T.; Storrø, I.; Slizyte, R. Possibilities for the utilisation of marine by-products. *Int. J. Food Sci. Technol.* **2011**, *46*, 2001–2014. [CrossRef]
20. Gamarro, E.G.; Orawattanamateekul, W.; Sentina, J.; Gopal, T.S. By-products of tuna processing. *Globefish Res. Programme* **2013**, *112*, 1–48.
21. Ariyawansa, S. *The Evaluation of Functional Properties of Fish Meal*; Fisheries Training Programme, Project Final, Sri Lanka; United Nations University: Reykjavik, Iceland, 2000.
22. Skåra, T.; Sivertsvik, M.; Birkeland, S. Production of salmon oil from filleting byproducts—Effects of storage conditions on lipid oxidation and content of ω-3 polyunsaturated fatty acids. *J. Food Sci.* **2004**, *69*, 417–421. [CrossRef]
23. Caruso, G.; Floris, R.; Serangeli, C.; Di Paola, L. Fishery wastes as a yet undiscovered treasure from the sea: Biomolecules sources, extraction methods and valorization. *Mar. Drugs* **2020**, *18*, 622. [CrossRef]
24. Schubert, T.; Meric, A.; Boom, R.; Hinrichs, J.; Atamer, Z. Application of a decanter centrifuge for casein fractionation on pilot scale: Effect of operational parameters on total solid, purity and yield in solid discharge. *Int. Dairy J.* **2018**, *84*, 6–14. [CrossRef]

25. Kyrimlidou, M.; Terstegen, T.A.; Parisi, A.; Wagner, L.; Rudolph-Flöter, S.E.J.; Flöter, E. Fractionation of edible fats: Separation of fat-covered particles by decanter centrifuge. *Eur. J. Lipid Sci. Technol.* **2024**, *126*, 2300111. [CrossRef]
26. Freeman, G.J. Separation technologies in brewing. In *Separation, Extraction and Concentration Processes in the Food, Beverage and Nutraceutical Industries*; Woodhead Publishing: Cambridge, UK, 2013; pp. 430–449.
27. Hilmarsdottir, G.S.; Ogmundarson, Ó.; Arason, S.; Gudjónsdóttir, M. The effects of varying heat treatments on lipid composition during pelagic fishmeal production. *Processes* **2020**, *8*, 1142. [CrossRef]
28. Ke, P.J.; Woyewoda, A.; Ackman, R. An improved titrimetric method for determination of free fatty acid in fish oils. In *Fisheries and Marine Service: New Series Circular 61*; Environment Canada: Gatineau, QC, Canada, 1976.
29. Majluf, P.; Matthews, K.; Pauly, D.; Skerritt, D.J.; Palomares, M.L.D. A review of the global use of fishmeal and fish oil and the Fish In: Fish Out metric. *Sci. Adv.* **2024**, *10*, eadn5650. [CrossRef] [PubMed]
30. Blanco, M.; Vázquez, J.A.; Pérez-Martín, R.I.; Sotelo, C.G. Hydrolysates of fish skin collagen: An opportunity for valorizing fish industry byproducts. *Mar. Drugs* **2017**, *15*, 131. [CrossRef]
31. Róbertsdóttir, K. Redesign of Pelagic Fish Meal Processing Line. Master's Thesis, University of Iceland, Reykjavík, Iceland, 2018.
32. Atanasoff, A.; Nikolov, G.; Staykov, Y.; Zhelyazkov, G.; Sirakov, I. Proximate and mineral analysis of Atlantic salmon (*Salmo salar*) cultivated in Bulgaria. *Biotechnol. Anim. Husb.* **2013**, *29*, 571–579. [CrossRef]
33. Ween, O.; Stangeland, J.K.; Fylling, T.S.; Aas, G.H. Nutritional and functional properties of fishmeal produced from fresh by-products of cod (*Gadus morhua* L.) and saithe (*Pollachius virens*). *Heliyon* **2017**, *3*, e00343. [CrossRef]
34. Hassan, A.S.; Seden, M.E.; Amer, T.N.; El-Tawil, N.E. Substituting fish meal with smoked fish waste meal in diets African catfish (*Gariepinus*). *Abbassa Int. J. Aqua.* **2013**, *6*, 302–318.
35. Cascant, M.M.; Breil, C.; Fabiano-Tixier, A.S.; Chemat, F.; Garrigues, S.; de la Guardia, M. Determination of fatty acids and lipid classes in salmon oil by near infrared spectroscopy. *Food Chem.* **2018**, *239*, 865–871. [CrossRef]
36. Šimat, V.; Vlahovic, J.; Soldo, B.; Skroza, D.; Ljubenkov, I.; Mekinic, I.G. Production and refinement of omega-3 rich oils from processing by-products of farmed fish species. *Foods* **2019**, *8*, 125. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.