

Soy protein concentrates in salmonid diets

by

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**Table of Contents**

Executive Summary.....3

Introduction.....4

Soy Protein Concentrate in Diets Fed to Rainbow Trout.....6

    Summary.....16

Soy Protein Concentrate in Diets Fed to Atlantic Salmon.....17

    Summary.....21

Recommended SPC Inclusion Levels in Salmonid Diets.....22

Conclusions .....23

References.....24

Tables.....33

## **Executive Summary**

Aquacultural production of trout and salmon, collectively referred to as salmonids, is one of the largest global aquaculture industries and currently uses a disproportionately high amount of fish meal in dietary formulations. Sustainable production and growth in salmonid culture demands identification of alternative high-protein feed ingredients. The chemical composition of soy protein concentrate (SPC) suggests it has potential as an ingredient in diets fed to salmonids. There have been over 30 published studies of SPC use in diets for rainbow trout and Atlantic salmon. The data indicate small trout and salmon are more sensitive to SPC inclusion in diets than larger fish. SPC can provide up to 50% of the dietary crude protein in diets for small fish. Fish meal can be completely replaced in diets for larger fish. Results from digestibility studies indicate high nutrient availability from SPC. Methionine supplementation appears necessary for salmonids and taurine supplementation was recently identified as beneficial in SPC-based diets for trout. The form of phosphorus in SPC remains problematic, but incorporation of phytase or pretreatment of SPC with phytase improved phosphorus availability. Sensory characteristics of salmonid fillets fed SPC have been lighter in color than those from fish fed fish meal, but texture and flavor have not been adversely impacted. Several dietary formulations are available that have been tested in the target species. Ingredient cost hampered use of SPC in the 1990's and remains an issue in the 21<sup>st</sup> century. However, given the escalating price of fish meal and demand for that commodity, use of SPC in salmonid diets appears promising.

## **Introduction**

Aquacultural production of trouts and salmon, collectively referred to as salmonids, is one of the largest global fish production industries. Salmonids are typically raised in intensive aquaculture production systems and fed nutritionally complete formulated diets. Current salmonid diets contain fish meal as the primary source of crude protein and essential amino acids (EAA). While the global salmonid industry is approximately 13.7% of total production, the salmonid industry currently uses approximately 29.4% of the fish meal used in aquaculture (Tacon 2003). Global demand for fish meal is rapidly exceeding supply and new sources of crude protein and EAA are needed for sustained salmonid production.

Soybean meal (SBM) is the most commonly available soy ingredient for use in animal feeds; however, salmonid fishes do not grow as well when fed high levels of SBM in the diet. A typical salmonid diet will incorporate 10-30% SBM depending on species and feed manufacturer (Hardy 2002; Pillay and Kutty 2005). Antinutritional factors (ANF) and relatively high concentrations of carbohydrates are the primary factors limiting the amount of SBM fed to salmonids (Francis et al. 2001; Hardy 2002; Hart et al. 2007).

Because of these limitations, alternative soy ingredients with higher protein concentrations and reduced or negligible ANF concentrations would be more attractive fish meal replacements in salmonid diets. Soy protein concentrates (SPC) are made from SBM and typically have lower ANF concentrations and reduced concentrations of oligosaccharides (Russett 2002).

The majority of SPC is used for human consumption (Chajuss 2001); however, it has potential uses in animal feeds. Some of these potential uses include a protein and EAA source, a gelling/emulsifying agent in canned pet foods, and a fat binding agent in high fat pet and aquaculture feeds (Russett 2002). The most common method of manufacturing SPC is through aqueous alcohol extraction which reduces the carbohydrate fraction (Peisker 2001). Alcohol extracted SPC (referred to as SPC from this point forward) contains approximately 65% crude protein, 1% fat and 6% ash (Peisker 2001). Compared to SBM (~48% protein in solvent extracted, dehulled SBM), the protein content of SPC is more similar to that of fish meal, which typically ranges between 60-70% depending on the source species and efficiency of lipid extraction (NRC 1993). With the exception of methionine, and potentially lysine, the EAA content of SPC compares favorably with fish meal (Masumoto et al. 1996). SPC also contains lower levels of ANF; specifically trypsin inhibitors, lectins and oligosaccharides (Peisker 2001; Russett 2002). The lectin and trypsin inhibitor concentrations typically found in SPC are lower than the concentrations that have been shown to exert antinutritional effects on salmonid fishes (Peisker 2001; Russett 2002; Hart et al. 2007).

Because of the higher protein content and lower ANF levels, SPC has garnered interest as a fish meal replacement in fish feeds. To date, approximately 50 studies have been published in peer-reviewed journals in which SPC has been fed to a variety of fish species. The purpose of this paper is to review the published literature on the effects of SPC inclusion in diets fed to rainbow trout and Atlantic salmon.

## **Soy Protein Concentrate in Diets fed to Rainbow Trout**

The major findings from studies examining use of SPC in diets fed to rainbow trout have been summarized in Table 1. Apparent digestibility or availability values of macro- and micronutrients from SPC have been summarized in Table 2.

Rumsey et al. (1993) published one of the earliest studies in which various soy protein ingredients, including SPC, were fed to rainbow trout. SPC was made by washing conventional SBM with ethanol at 50-78°C for 40 minutes. Diets were formulated with 33% of this SPC (accounting for approximately 50% of the dietary protein) and fed to fingerling rainbow trout (initial weight ~ 5 g). They also fed a fish meal control and four other test diets in which several varieties of SBM were supplied as the primary source of crude protein. Rainbow trout fed the 33% SPC diet gained 10% less weight than the fish fed the control, but feed conversion ratio was equal between both treatments. Rumsey et al. (1993) also conducted a metabolism trial with 200-300 g rainbow trout and reported that apparent digestibility of nitrogen in the SPC-based diet (81.6%) was 10% lower than for the fish meal control (90.0%). The authors concluded that the oligosaccharide content of SBM was not the only limiting factor in rainbow trout diets. They theorized that an antigenic factor in SBM may be limiting its use by causing an allergic reaction in the intestinal tract of rainbow trout, thus causing a reduction in nutrient absorption. These conclusions were supported by a separate study in which the authors reported an increase in serological non-specific disease defense mechanisms in rainbow trout fed a diet containing SBM as 100% of the protein source. The antigenic response was not observed

in fish fed a diet containing SPC as the protein source (Rumsey et al. 1994). However, in both of these studies trout still exhibited reduced growth when fed the SPC-based diets compared to fish fed a fish meal-based diet (Rumsey et al. 1993; Rumsey et al. 1994). The SPC used by Rumsey et al. (1993) was not processed in the same way as commercially available SPC. Commercially available SPC is extracted with an alcohol/water concentration of 60-70% alcohol (Chajuss 2001) as opposed to 43% alcohol by weight used by Rumsey et al. (1993). The crude fiber and oligosaccharide contents (6.3 and 4.9%, respectively) of the SPC used by Rumsey et al. (1993) were higher than reported concentrations (3-5 and 3%, respectively) in commercial SPC (Chajuss 2001; Russett 2002). The processing technique employed by Rumsey et al. (1993) may also have left higher concentrations of other ANF, such as lectins, which have been shown to cause a reduction in growth performance when fed to rainbow trout (Hart et al. 2007). The SPC used by Rumsey et al. (1994) was a commercially available variety; however, in this study the reduced growth may have been the result of an essential amino acid deficiency as no supplemental methionine was added to the diet.

Olli and Krogdahl (1994) fed four levels of SPC to rainbow trout (9.4, 18.8, 28.2 and 37.6% of the diet) in which SPC accounted for as much as 56% of the dietary protein. The SPC diets were supplemented with methionine. Growth of rainbow trout fed SPC was similar to fish fed a fish meal control, even at the highest inclusion levels. There are several possibilities that could explain the differences between this study and those of Rumsey et al. (1993, 1994). Methionine supplementation was incorporated in the studies of Olli and Krogdahl (1994). The initial weight of rainbow trout used by Olli and

Krogdahl (1994) was 70 g, compared to 5 g (Rumsey et al. 1993). The smaller fish may not have been able to utilize the SPC as effectively. Another possibility that could explain the difference in results is the nutritional characteristics of the two SPC products. Olli and Krogdahl (1994) used a commercially available SPC as opposed to processing their own. Finally, strains of trout used were different. Individual strains of rainbow trout have been shown to exhibit differences in growth rate, feed conversion, protein retention and immune response when fed a standard commercial diet (Smith et al. 1988; Overturf et al. 2003).

Kaushik et al. (1995) fed 83 g rainbow trout diets in which 33 to 100% of the fish meal was replaced with SPC. Diets with the highest level of SPC inclusion (replacing 66 and 100% of the fish meal) were supplemented with L-methionine. Final weight gain, daily growth coefficient, feed efficiency and protein efficiency ratio were not significantly different in fish fed all SPC diets and the fish meal control. Some sensory characteristics of the fillets were significantly affected by SPC inclusion in diets. Fillets from fish fed the control diet were redder in color than those fed the highest SPC inclusion level. These differences were observed in both raw and cooked fillets. However, firmness of fillets was not significantly affected by SPC inclusion. A panel evaluation was conducted using fillets from the control and highest SPC inclusion treatments. Significant differences were noted in both color and flavor of fillets between the two groups, with the control fillets being more pinkish in color and also having a more rancid flavor. Unlike Rumsey et al. (1994), Kaushik et al. (1995) showed that 100% of the fish meal could be

replaced with SPC as long as supplemental methionine was added to meet the requirement for rainbow trout.

Stickney et al. (1996) conducted a similar study in which fish meal concentrations were either partially or totally replaced with SPC and supplemental methionine in diets fed to 12 g rainbow trout. Fish fed experimental diets formulated with 15.9% SPC (25% of the crude protein) and 31.8% SPC (50% of the crude protein) exhibited similar growth compared to fish fed a fish meal control diet. Weight gain of rainbow trout fed a diet containing 63.7% SPC (100% of the protein) was significantly lower than fish fed the fish meal control diet and all other SPC supplemented diets. Feed conversion ratio did not differ significantly between treatments other than in trout fed the 63.7% SPC diet, which was significantly higher. Apparent crude protein digestibility values increased with increasing SPC concentration in the diet (82.6-90.6%). Results of this study indicated that SPC could replace up to 75% of the fish meal in fingerling rainbow trout diets with no negative effects on production. Médale et al. (1998) also reported no reduction in growth of 100 g rainbow trout fed diets in which 75% of the protein was supplied from SPC. Fish fed diets in which 100% of the protein was supplied by SPC exhibited reduced growth, which was at least partially attributed to a methionine deficiency.

Mambrini et al. (1999) also conducted a fish meal replacement study with 105 g rainbow trout in which SPC was progressively added to high energy diets (>20% lipid) to replace as much as 100% of the fish meal. Three diets were formulated with SPC supplying

100% of the protein (63% of the diet); one diet was not supplemented with methionine and two had methionine supplementation (0.22 and 0.42% of the diet, respectively). Fish fed SPC replacement levels of 75 and 100% exhibited reduced weight gain compared to fish fed the fish meal control diet. Trout fed diets at the 100% SPC replacement level supplemented with 0.22 and 0.42% methionine grew slightly better than those fed the unsupplemented diet. The authors concluded that the reduction in weight gain was a result of reduced feed intake at the highest SPC inclusion levels as feed efficiency was not significantly affected by dietary treatment. The authors also reported a significant reduction in lipid and energy apparent digestibility values at the highest SPC inclusion rates. Mambrini et al. (1999) theorized that interaction between the soy protein and dietary lipids and higher than expected isoflavone content in the SPC led to the reduced feed intake. Lipid digestibility of rainbow trout has been shown to be reduced when SBM was included in diet (Pongmaneerat and Watanabe 1993). Mambrini et al. (1999) suggested that undigested soy protein may be binding a portion of the dietary lipid, thus leading to lower lipid digestibility values and eventually reduced weight gain. This speculation does not appear to explain the reported reduction in feed intake. The isoflavone content in the SPC used by Mambrini et al. (1999) was more than 100 times the amount reported in previous research conducted at the same lab (Kaushik et al. 1995). The authors speculated that the high isoflavone content of the 100% SPC replacement diets may have directly impacted feed intake or negatively impacted metabolism after absorption. However; genistein (the most common soy isoflavone) supplementation in the diet at levels similar to those reported by Mambrini et al. (1999) have been shown not to cause reduction in growth of rainbow trout (Hart et al. 2007). Considering the higher

than normal levels of isoflavones reported by Mambrini et al. (1999), the possibility of other ANF also being increased in their SPC seems likely; although they did report low trypsin inhibitor activity (0.323 mg/g). Concentrations of other ANF, such as lectins, were not quantified.

Bureau et al. (1998) evaluated the effects of feeding purified alcohol extracts from SBM to rainbow trout (7 g) and two commercial SPC products from different suppliers. Both SPC diets were formulated to contain 32% fish meal and SPC (each ingredient supplied 50% of the protein). Weight gain of both treatments fed SPC were not significantly different from each other upon completion of the trial; however, weight gain of fish in which the purified alcohol abstract was supplemented into the diet was significantly reduced. The authors reported that neither SPC diet caused significant intestinal damage; however, supplementation with the purified alcohol extract resulted in a slight increase in abnormal appearing enterocytes. The authors concluded that some component of the purified alcohol extract of SBM is the primary growth deterrent present in SBM.

Adelizi et al. (1998) also compared two SPC products manufactured by the same commercial supplier in a feed study with 35 g rainbow trout. Two of their test diets included 30% SPC (one standard SPC and one low allergen SPC). Weight gain and total consumption of feed by fish fed the SPC diets were not significantly different; however, feed conversion ratio of fish fed the low allergen SPC was significantly lower than those fed the standard SPC. Sensory analysis of the rainbow trout fillets was also conducted. Flavor intensity scores from trout fed the SPC diets did not differ significantly from those

fed a commercial control. The authors did note a more yellowish color in the fillets of the trout fed the fish meal free diets, which they attributed to xanthophyll content of other dietary ingredients.

Gaylord et al. (2006) tested the effectiveness of taurine as a nutritional supplement in plant-based diets fed to rainbow trout (27 g). They conducted a factorial study in which four fish meal-based diets (23.6% fish meal) and four plant-based diets (23% SPC) were supplemented with graded levels of taurine (0.0, 0.5, 1.0 and 1.5% of the diet). Weight gain, feed conversion ratio, protein retention and energy retention of fish fed the plant-based diet with no taurine supplementation were significantly lower compared to fish fed the fish meal-based diet with no supplementation. Taurine supplementation at 0.5% of the diet significantly improved all of the evaluated production parameters of trout fed the plant-based diets so that they were not significantly different when compared to fish fed the fish meal-based diets. There was no further benefit of supplementing higher levels of taurine in the plant-based diets. Taurine supplementation in the fish meal-based diets provided no additional benefits. The authors suggested that taurine should be considered when adding methionine and cystine supplementation to diets containing high levels of plant ingredients low in those amino acids. Taurine can be synthesized from cystine, but the authors theorized that rainbow trout may not be able to synthesize the quantities necessary for maximum growth.

Along with production efficiency and fillet quality, another concern when feeding SPC to rainbow trout is phosphorus waste, or the amount of phosphorus not available to the fish

that is excreted into the rearing water. The primary source of phosphorus in soy-based ingredients is phytate, which is not highly available to animals such as rainbow trout (NRC 1993). Diets can be supplemented with inorganic phosphorus sources. However, if this increases the total phosphorus output of rainbow trout, there could be problems with environmental degradation, especially in freshwater environments. Kim et al. (1998) conducted two studies in which they supplemented a fish meal free diet (32% SPC) with dicalcium phosphate. Decreased feed intake and weight gain of rainbow trout fed the SPC-based diet occurred in both studies, but they attributed this to a possible marginal sulfur amino acid deficiency in the diet (no supplemental methionine was added). There may have been a marginal lysine deficiency as well. Both the lysine and methionine contents of the SPC-based diet were formulated to exactly match the known requirements of rainbow trout. Unless these EAA were 100% available from all of the protein ingredients of the diet, a scenario that is unlikely given reported amino acid digestibility values of SPC-based diets (Table 2), a deficiency would have been present. Kim et al. (1998) reported phosphorus retention was significantly decreased in trout fed the SPC-based diet (25 and 15% for studies 1 and 2, respectively) when compared to those fed the fish meal-based diet in both studies (30 and 17%, respectively). Phosphorus loss was significantly higher in trout fed the SPC-based diet (14 and 17 g/kg weight gain, respectively) when compared to fish fed the fish meal-based diet in both studies (10 and 13 g/kg weight gain, respectively). This study clearly shows that supplementing an inorganic phosphorus source in high-SPC diets results in an increase in phosphorus output of rainbow trout.

Satoh et al. (2002) measured phosphorus absorption from a variety of ingredients (including SPC) in seven different sizes of rainbow trout (2, 5, 10, 20, 50, 100 and 200 g). The test diets were formulated so that the primary protein ingredients were the only sources of phosphorus present. The SPC-based diet was formulated with 30% SPC and contained a total of 2.5 g phosphorus/kg diet. The authors reported phosphorus absorption of rainbow trout fed the SPC-based diet to be lowest in the smallest fish and highest in the largest fish (3.4% in 2 g fish and 34.0% in 200 g fish). Higher phosphorus digestibility values in larger rainbow trout have also been reported elsewhere (Glencross et al. 2004; 2005). Satoh et al. (2002) reported phosphorus absorption from animal-based ingredients (no phytate) to generally be higher, especially for the smallest-sized fish (2 g). The authors reported improved phosphorus availability from SBM that had been extruded at 150°C prior to diet formulation. They inferred that the high cooking temperature caused the phosphoric acid to become disassociated from the phytate, thus improving the availability of phosphorus.

Vielma et al. (1998; 2000) conducted two studies evaluating the effectiveness of dietary phytase inclusion in SPC-containing diets fed to rainbow trout. In the first study, supplemental vitamin D (cholecalciferol) was added (2,500 IU/kg, 250,000 IU/kg, or 2,500,000 IU/kg), with or without supplemental phytase (1,500 U/kg) to six experimental diets containing 50% SPC. Rainbow trout (51 g) fed diets supplemented with phytase gained significantly more weight than those fed diets without phytase. Phytase significantly increased phosphorus availability and increased lipid, ash and mineral concentrations (Mg, P, Ca, Mn and bone ash) in the body. The authors concluded that

dietary phytase supplementation had a significant effect on phosphorus utilization when feeding a high level of SPC, but vitamin D did not. Vielma et al. (1998) also concluded that phytase supplementation can help reduce phosphorus load when feeding higher levels of SPC. SPC contains less total phosphorus than fish meal, so if that phosphorus is made more available to rainbow trout through phytase supplementation, the diets can be formulated to contain less total phosphorus when SPC is the primary source of crude protein and EAA.

In the second study, Vielma et al. (2000) fed rainbow trout (250 g) four high-energy diets (36% protein and 28% lipid) formulated with or without a combination of SPC and SBM as a partial fish meal replacement (31.5% SPC, 12.1% SBM and 13.3% fish meal) and with or without phytase supplementation (1,000 U/kg). Upon completion of the trial, trout fed the soy-based diets gained significantly more weight and exhibited significantly higher specific growth rates than those fed the fish meal control, regardless of phytase supplementation. There was a significant decrease in bone ash in fish fed the soy-based diets, which was slightly increased by phytase supplementation. The authors concluded that this was a result of a slight phosphorus deficiency in the soy-based diets, but that this deficiency was not severe because whole body ash and phosphorus content was not decreased in the soy-fed fish. Phosphorus excreted was significantly lower in fish fed the soy-based diets. Finally, Vielma et al. (2000) evaluated phosphorus availability for algal growth from the feed and fish waste. They reported that phosphorus availabilities for algal growth from the soy-based feed and fecal matter from trout fed the soy-based feeds were lower compared to fish fed the fish meal diets. Vielma et al. (2000) concluded that

rainbow trout can be fed high-energy, soy-based diets that are less polluting than fish meal-based diets with no decrease in production.

Cheng et al. (2004) evaluated the effects of supplementing soy-based diets with phytase on macro- and micronutrient apparent digestibility coefficients. Five experimental diets (50% SPC) were formulated with graded levels of phytase (0, 500, 1,000, 2,000 and 4,000 FTU/kg diet) and fed to rainbow trout (100 g). There were significant decreases in protein and amino acid digestibility values at all levels of phytase supplementation; however, these differences were slight and ranged between 95 and 99.5%. They attributed this slight decrease in digestibility to sample handling. The more significant findings were the effects of phytase treatment on mineral digestibility coefficients. There were significant increases in Ca, Mg, Mn, Zn, phytate-phosphorus and total-phosphorus availability values (Table 2). Apparent digestibility coefficients were increased from 6.28 to 69.7% for phytate-phosphorus and 39.7 to 95.0% for total-phosphorus by supplementing with 500 FTU phytase/kg diet. Copper and iron availabilities were not improved by phytase supplementation and the authors theorized that these minerals were more tightly bound to phytate than other minerals.

### Summary

Small rainbow trout appear to be more sensitive to SPC inclusion in practical diets than larger fish, but diets for juvenile fish have successfully incorporated up to 50% of the crude protein and EAA. In larger fish, SPC have successfully incorporated up to 100%

of the dietary crude protein and EAA. At this time, fingerling formulations appear to need at least 25% fish meal. Supplementation of SPC-based diets with methionine appears necessary and supplemental taurine appears beneficial. Phosphorus availability in trout diets formulated with SPC is a concern and needs to be addressed either through further processing of ingredients or phytase treatment. Rainbow trout diets in which the phosphorus has been made more available should prove less polluting in freshwater environments.

### **Soy Protein Concentrate in Diets fed to Atlantic Salmon**

SPC has also been evaluated as an alternative source of crude protein and EAA in diets fed to Atlantic salmon. Results from those feeding studies have been summarized in Table 3. Apparent digestibility values of macro- and micronutrients in Atlantic salmon fed diets containing SPC have been summarized in Table 4.

In one of the earliest published salmonid SPC feed studies, Olli et al. (1994) fed graded levels of several soy-based protein sources (0, 14, 28, 42 and 56% of the protein) to Atlantic salmon. In the four SPC diets, fish meal was replaced with SPC at the rates of 9.4, 18.8, 28.2 and 37.6% of the diet. Methionine supplementation was included to meet the requirements of Atlantic salmon. Fish fed all levels of SPC gained weight as well as those fed a fish meal control. The authors reported that protein and lipid excretion of Atlantic salmon was not affected by feeding SPC and that they were similar to values from fish fed the control diet.

Refstie et al. (1998) conducted an Atlantic salmon feeding trial in which soy proteins provided 40% of the dietary crude protein. They used a proprietary SPC (62.5% protein with reduced content of oligosaccharides, lectins and trypsin inhibitors) with a high fiber content (17%). Two test diets, one containing SBM and the other with SPC, and a fish meal control were fed to 107 g Atlantic salmon. Weight gain, specific growth rate, feed intake, feed conversion ratio and survival were not significantly different between fish fed the SPC and control diets. Fish fed the SPC diet had a significantly higher condition factor than fish fed the control and SBM diets. The authors also reported similar nitrogen, fat and energy apparent digestibility values for Atlantic salmon fed the control and SPC diets (Table 4). The fish were fed a commercial fish meal diet prior to the experimental period and they readily switched to the SPC-based diet. The authors noted that fish fed the SBM-based diet did not readily switch when presented with the experimental diet. The authors concluded that Atlantic salmon need time to adapt to a high-SBM diet, but that this does not appear to be the case when fed a SPC-based diet. The authors further concluded that one of the antinutrients removed during the processing of the SBM must be at least partially contributing to the reduced response of salmon fed diets containing higher levels of SBM.

Brown et al. (1997) evaluated the effects of feeding two different SPC to juvenile Atlantic salmon (3.9 g). Three diets were formulated to contain one SPC at 10, 20 or 30% of the diet and a fourth diet was formulated to contain 30% of the second SPC. Methionine supplementation was added. Atlantic salmon were fed their respective

dietary treatments for eight weeks. Weight gain of fish fed the first SPC was not significantly different compared to fish fed a control diet, but weight gain of fish fed the second product was significantly lower than fish fed the control diet. As previously discussed in the rainbow trout section, differences in the chemical composition of SPC tested may have resulted in the differences in weight gains. However, the initial studies with small Atlantic salmon clearly demonstrated that SPC can replace as much as 50% of the fish meal with no detrimental effects on weight gain.

Storebakken et al. (1998) formulated experimental diets for Atlantic salmon (100 g) containing either traditional SPC or phytase-treated SPC (5,000 FTU). The SPC contributed 75% of the protein (48% of the diet). Fish fed both SPC diets gained significantly less weight than fish fed the control diet, but all treatments grew faster than published growth rates. Similar results were noted for specific growth rate and feed intake; however, the authors reported that specific growth rate and feed intake of fish fed the SPC diets equaled those of fish fed the control after day 64. These results are similar to those of Refstie et al. (1998) in which Atlantic salmon fed soy-based diets needed time to adapt to the feed. Phytase pretreatment of SPC resulted in feed conversion ratios similar to those of fish fed the control diet. Feed conversion ratio for fish fed the untreated SPC diet was significantly higher. Fish fed phytase-treated SPC exhibited improved nitrogen retention and decreased metabolic nitrogen excretion compared to fish fed the control diet. These findings are significant because unlike phosphorus in freshwater, nitrogen is the first limiting nutrient for algae production in saltwater systems. Storebakken et al. (1998) also noted similar results for phosphorus metabolism. Fish fed

the treated SPC had higher phosphorus apparent digestibility values and retained more phosphorus. The lower availability of phosphorus from the untreated diet is supported by Glencross et al. (2004) who showed that phosphorus present in SPC (largely phytate-bound) was not digestible by smaller Atlantic salmon (66 g). Storebakken et al. (1998) showed that phytase treatment also increased Ca, Mg and Zn apparent digestibility values.

Storebakken et al. (2000) conducted a similar study with larger Atlantic salmon, excluding only the phytase-treated SPC diet. They compared the results of feeding a fish meal control and a 50% SPC diet (SPC supplied 75% of the dietary protein) to 200 g Atlantic salmon. Unlike the results from their previous study (Storebakken et al. 1998), fish fed the SPC diet grew as well as those fed the control diet. Feed conversion ratio was slightly higher in fish fed the SPC diet. Nitrogen digestibility was slightly decreased in fish fed the SPC diet; however, nitrogen retention was similar. The authors attributed the slight increase in feed conversion ratio in fish fed the SPC diet to the lower apparent digestibility value of nitrogen. Fecal nitrogen excretion was higher in fish fed the SPC diet, but metabolic excretion was higher in fish fed the control diet, so total nitrogen excretion was virtually identical for both treatments. Phosphorus absorption was significantly reduced in fish fed the SPC diet, but retention was not. Phosphorus excretion and whole-body phosphorus concentration were significantly reduced in fish fed the SPC diet. Storebakken et al. (2000) also reported significant reductions in Ca, Mg and Zn absorption in fish fed the SPC diet. The authors concluded that feeding SPC

untreated with phytase did not have a negative impact on growth, but that it resulted in a subclinical phosphorus deficiency.

Refstie et al. (2001) partially replaced fish meal with SPC (30% of the dietary protein) in medium and high lipid diets (32 and 39% fat, respectively) for grow-out Atlantic salmon (560 g). Weight gain and protein accretion in fish fed the SPC diets were significantly higher than fish fed the fish meal control. The authors reported that the inclusion of SPC did not cause distal enteritis (an inflammation of the distal portion of the intestines).

These results are similar to other published studies (Ingh et al. 1991, 1996; Baeverfjord and Krogdahl 1996; Krogdahl et al. 2000), in which Atlantic salmon fed SBM exhibited enteritis, but fish fed SPC did not. While the SPC content of 19.7% of the diet used by Refstie et al. (2001) was lower than the SPC concentration of 28% of the diet used by Ingh et al. (1991), these results showed that Atlantic salmon could remain healthy for the entire grow-out period while being fed a diet containing a high percentage of SPC.

Refstie et al. (2001) conducted one of the few long-term grow-out studies that showed SPC-fed Atlantic salmon can perform as well as or better than fish fed a fish meal control.

### Summary

Atlantic salmon have successfully been fed diets in which SPC replaced 50-75% of the fish meal with no decrease in production. Greater than 50% of the fish meal can be replaced with SPC (and supplemental methionine) in fingerling Atlantic salmon diets

with no decrease in production. Grow-out diets can incorporate as much as 50% SPC (replacing 75% of the fish meal) as long as supplemental methionine is added to the diet. Phytase treatment can improve phosphorus availability and may improve growth rate when feeding diets containing higher inclusion rates of SPC. Phytase treatment can also improve nitrogen retention, resulting in less pollution to saltwater environments, and availability of other minerals.

### **Recommended SPC Inclusion Levels in Salmonid Diets**

Based upon the results of these studies, SPC can readily be formulated into diets for rainbow trout and Atlantic salmon. Table 5 highlights several diet formulations utilized in the studies reviewed. Fish fed those diets grew as well as or better than those fed a fish meal control diet. SPC inclusion rate in the selected diets ranged from 20-60% of the diet. Even if SPC were included in salmonid diets at the lowest rate, this would constitute a major new market for SPC. Total salmonid aquaculture production was approximately two million metric tonnes (mt) in 2004 (FAO 2006). Assuming a feed conversion of one to one and using 2004 production values, 20% inclusion of SPC in salmonid diets would result in a demand for two hundred thousand mt of SPC. Despite its potential as an alternative protein source, very little, if any SPC is used in commercial feed formulations today. Total annual global production of SPC is less than five hundred thousand mt and the cost of SPC is typically greater than US \$1000 per mt (Chajuss 2001; Hardy 2006). Currently, fish meal costs about the same per mt as SPC; however, annual production is approximately seven million mt (Hardy 2006). The key distinction

between the two is that fish meal supply is not likely to increase, but SPC supply has the potential to increase. SBM production in the US alone is nearly 40 million mt per year (USDA 2007). With SBM production being so high, the potential to increase SPC production to meet the demands of aquaculture feed manufacturers does exist.

### **Conclusions**

The primary SPC markets currently are human consumption and specialty products for the pet feed industry. SPC is a promising protein alternative for aquaculture diets and research has shown that SPC can readily replace as much as 100% of the fish meal in salmonid diets (with methionine supplementation) without a decrease in production. The phytate content of SPC is problematic. Continued processing or enzymatic treatment of SPC is necessary to make the phosphorus available to salmonids. If SPC is going to become an economically viable protein alternative to fish meal in the salmonid industry, SPC production needs to increase and costs need to be reduced.

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Table 1: Summary of results from studies in which SPC was formulated into diets fed to rainbow trout.

Dietary inclusion rate of SPC	Results	Reference
33.0%	Reduced growth in comparison to fish meal control; feed conversion identical to control; protein digestibility was significantly lower than control	Rumsey et al. 1993
9.4-37.6%	Similar growth in comparison to fish meal control; no significant effects on body composition, condition factor, hepatosomatic index or fecal protein and lipid content	Olli and Krogdahl 1994
57%	Reduced growth in comparison to fish meal control; no intestinal damage; immune response to SPC indicating an inflammatory or hypersensitivity response	Rumsey et al. 1994
22-62%	Growth, feed efficiency and protein efficiency similar to fish meal control; whole body composition and protein retention similar to fish meal control	Kaushik et al. 1995
15.9-63.7%	SPC inclusion up to 50% of the protein resulted in similar growth and feed conversion to fish meal control	Stickney et al. 1996
30-31%	Reduced growth and feed intake and increased FCR in comparison to fish meal control	Adelizi et al. 1998
32%	Compared diets in which half of the protein was supplied by soy products, including two varieties of SPC; fish fed one variety exhibited better growth; both SPC treatments grew significantly less than those fed a methanol extracted SBM	Bureau et al. 1998
32%	Reduced feed intake and weight gain and increased phosphorus output in comparison to fish meal control	Kim et al. 1998
30-65%*	Feed intake and growth similar to fish meal control at SPC inclusion of 50 and 75% of protein; 100% SPC replacement resulted in reduced feed intake and growth; phosphorus availability increased with SPC inclusion	Médale et al. 1998
50%	Phytase supplementation increased weight gain and phosphorus absorption; cholecalciferol supplementation resulted in reduced weight gain and had no effect on phosphorus utilization	Vielma et al. 1998
31.9-63.5%	Reduced growth and feed intake at greater than 50% SPC inclusion; methionine supplementation increased feed intake and growth, but still less than fish meal control; protein digestibility and amino acid availability were similar, but lipid and energy digestibility were reduced at highest levels of SPC inclusion	Mambrini et al. 1999
31.5%	Increased growth and specific growth rate in comparison to fish meal control; Phosphorus load and availability of phosphorus to algae was reduced in SPC treatment	Vielma et al. 2000
30%	Percent phosphorus absorption increased as body weight increased	Satoh et al. 2002
50%	Phytase supplementation increased apparent digestibility coefficients of minerals (except copper and iron)	Cheng et al. 2004
23%	Decreased growth and increased feed conversion in comparison to fish meal control; taurine supplementation improved growth and feed conversion to equal fish meal	Gaylord et al. 2006

\*Authors did not present dietary formulations, so SPC content in the diet was estimated via back-calculation.

Table 2: Summary of apparent digestibility values for SPC in diets fed to rainbow trout.

Fish size (g)	Temperature °C	Fecal collection <sup>a</sup>	Formulation	Digestibility	Reference
200-300	15.0	Post-excretion <sup>b</sup>	SPC 33.0% of the diet	Nitrogen: 81.6 Energy: 79.5	Rumsey et al. 1993
100	17.1	Post-excretion	Reference (70:30) <sup>c</sup>	Dry matter: 74.3 Protein: 96.1 Energy: 83.3	Kaushik et al. 1995
83	15.0	Stripping	SPC 15.9-63.7% of the diet	Protein: 86.3-90.6	Stickney et al. 1996
100	16.0	Post-excretion	SPC 30-65% of the diet <sup>d</sup>	Protein: 86.2-94.7 Phosphorus: 28.7-61.1 (increased as SPC inclusion increased)	Médale et al. 1998
52	14.0	Stripping	SPC 50% of the diet	Magnesium: 47.7-63.2 Phosphorus: 41.2-74.2 Calcium: -117.0- -31.6 Manganese: -2.9-22.8 Zinc: 52.5-31.1 (Ca and P values were significantly increased by phytase supplementation)	Vielma et al. 1998
102	18.0	Post-excretion	SPC 31.9-63.5% of the diet	Dry matter: 66.8-78.5 Protein: 91.0-94.2 Lipid: 72.1-94.1 Energy: 70.5-87.0 Methionine: 91.3-95.9 Cystine: 88.0-91.9 Lysine: 93.5-97.0 Threonine: 88.8-93.5 Arginine: 94.5-97.9 Isoleucine: 92.1-96.3 Leucine: 92.2-96.2 Valine: 91.6-95.7 Histidine: 93.5-96.8 Phenylalanine: 72.1-85.5 (dry matter, lipid, energy and phenylalanine digestibility values were all significantly reduced at the highest SPC inclusion rate)	Mambrini et al. 1999
2-200	15.0-18.0	Post-excretion	SPC 30% of the diet	Phosphorus: 3.7-34.0% (phosphorus availability increased with fish size)	Satoh et al. 2002

Table 2, continued

100	14.5	Stripping	SPC 50% of the diet	Dry Matter: 77.4-79.6 Protein: 97.6-98.8 Arginine: 99.0-99.5 Histidine: 97.0-98.8 Isoleucine: 96.6-98.2 Leucine: 96.3-98.3 Lysine: 98.7-99.3 Methionine: 96.6-98.0 Phenylalanine: 96.9-98.6 Threonine: 95.0-96.7 Tryptophan: 97.3-98.3 Valine: 96.5-98.4 Alanine: 97.4-98.7 Aspartic acid: 98.2-99.0 Cystine: 95.3-97.3 Glutamic acid: 98.7-99.4 Glycine: 98.1-99.1 Proline: 97.4-98.5 Serine: 97.1-98.5 Tyrosine: 96.3-97.2 Calcium: -51.6-21.3 Magnesium: 58.8-83.9 Phytate-P: 6.3-75.4 Total-P: 39.7-96.6 Copper: 80.2-84.4 Iron: 54.1-67.2 Manganese: 25.2-90.0 Zinc: 18.7-73.9 (phytase supplementation led to significant decreases in protein and amino acid and significant increases in Ca, Mg, phytate-P, Total-P, Mn and Zn digestibility values)	Cheng et al. 2004
266	22.1	Post-excretion and Stripping	Reference (70:30) <sup>c</sup>	<u>Post-excretion</u> Organic Matter: 82.0 Phosphorus: 58.9 Energy: 85.6 Nitrogen: 106.9 <u>Stripping</u> Organic Matter: 67.2 Phosphorus: 76.3 Energy: 87.3 Nitrogen: 97.9	Glencross et al. 2004; Glencross et al. 2005

<sup>a</sup> Stripping (massaging the gastrointestinal tract to expel samples); post-excretion (allowing defecation and collecting samples from within tank).

<sup>b</sup> Metabolism chambers were used in which urine, fecal and gill N excretions were measured.

<sup>c</sup> Reference diet 70% and test ingredient 30% of the experimental diet.

<sup>d</sup> Authors did not present dietary formulations, so SPC content was estimated.

Table 3: Summary of results from studies in which SPC was formulated into diets fed to Atlantic salmon.

Dietary inclusion rate of SPC	Results	Reference
28%	No intestinal abnormalities as a result of feeding SPC	Ingh et al. 1991
37.6%	Growth, carcass lipids, fecal excretion of nutrients and fecal dry matter content similar to fish meal control	Olli et al. 1994
10-30%	Tested two varieties of SPC, similar growth at all levels of SPC inclusion for the first variety (10-30%); reduction in growth when fed the second SPC variety (only tested 30%)	Brown et al. 1997
28.1%	Growth, condition factor, specific growth rate and feed conversion similar between fish fed fish meal and SPC diets	Refstie et al. 1998
48%	Reduced growth and feed intake through 63 days, after 63 days growth rate equal to fish meal control; improved FCR, protein digestibility, protein retention and reduced nitrogen excretion in fish fed SPC treated with phytase	Storebakken et al. 1998
17.8-22.2%	No intestinal abnormalities in SPC fed fish; when disease challenged, significant decrease in cumulative mortality rate as a result of feeding SPC	Krogdahl et al. 2000
50%	Similar growth rate to fish meal control; feed conversion significantly increased; total phosphorus excretion higher in fish meal fed fish; whole body concentration of specific minerals lower in SPC fed fish	Storebakken et al. 2000
15.6-19.7%	Increased growth in comparison to fish meal control; no distal enteritis as a result of feeding SPC	Refstie et al. 2001

Table 4: Summary of apparent digestibility values for SPC in diets fed to Atlantic salmon.

Fish size (g)	Temperature °C	Fecal collection <sup>a</sup>	Formulation	Digestibility	Reference
107	7-8	Stripping	SPC 28.1% of the diet	Nitrogen: 84.2 Fat: 81.7 Energy: 71.8	Refstie et al. 1998
100	7-9	Stripping	SPC 48.0% of the diet	Nitrogen: 85.0-88.2 Phosphorus: 29.7-48.8 Calcium: 3.0-10.4 Potassium: 96.6 Magnesium: 40.7-53.4 Manganese: 3.8-8.5 Sodium: -246- -244 Strontium: -3.4-0.9 Zinc: 16.0-52.2	Storebakken et al. 1998
200	8-9	Stripping	SPC 50% of the diet	Nitrogen: 85.8	Storebakken et al. 2000
>560	~4-15	Stripping	SPC 15.6-19.7% of the diet	Nitrogen: 84.1-86.9 Lipid: 82.2-89.9 Energy: 77.3-81.8	Refstie et al. 2001
66	15	Post-excretion	Reference (70:30) <sup>b</sup>	Organic Matter: 78.3 Phosphorus: -20.4 Energy: 101.2 Nitrogen: 90.1	Glencross et al. 2004

<sup>a</sup> Stripping (massaging the gastrointestinal tract to expel samples); post-excretion (allowing defecation and collecting samples from within tank).

<sup>b</sup> Reference diet 70% and test ingredient 30% of the experimental diet.

Table 5: Selected rainbow trout and Atlantic salmon SPC-containing diet formulations that resulted in similar or superior weight gain in comparison to fish meal control.

Ingredient	Species					
	Rainbow trout			Atlantic salmon		
Fish meal	-	32.5	13.3	18.4	15.3	42.3
SPC	62.0	31.8	31.5	37.6	50.0	19.7
SBM	-	-	12.1	-	-	-
Blood meal	-	-	-	3.0	-	-
Wheat	-	18.9	10.3	16.2	9.62	8.79
Gelatinized wheat starch	23.0	-	-	-	-	-
Binder	1.0	-	-	2.0	4.07 <sup>a</sup>	4.11 <sup>b</sup>
Vitamin Premix	1.0	1.0	3.9 <sup>b</sup>	1.0	x <sup>a</sup>	x <sup>a</sup>
Mineral Premix	1.0	0.5	x <sup>b</sup>	1.0	x <sup>a</sup>	x <sup>a</sup>
Fish oil	12.0	3.6	28.0	15.8	20.7	24.9
Canola oil	-	6.1	-	-	-	-
Skimmed milk (dry)	-	-	-	3.0	-	-
NaCl	-	-	-	0.5	-	-
Dicalcium phosphate	-	2.7	-	-	-	-
Limestone	-	0.4	-	-	-	-
Lecithin	-	-	-	1.0	-	-
50% Choline	-	1.0	-	-	-	-
Vitamin C	-	0.2	-	0.1	-	-
Lysine	-	0.5	0.7	-	-	-
Threonine	-	0.2	-	-	-	-
Methionine	0.04	0.6	0.2	0.33	0.3	0.2
Phytase	-	-	1200 U/kg	-	-	-
Astaxanthine	-	-	-	0.0005	-	-
Study duration (weeks)	12	10	24	16	12	34
Fish size (g)	83	12	250	Not given	200	560
Production method	Dry pelleted	Extruded	Extruded	Dry pelleted	Extruded	Extruded
Source	Kaushik et al. 1995	Stickney et al. 1996	Vielma et al. 2000	Olli et al. 1994	Storebakken et al. 2000	Refstie et al. 2001

<sup>a</sup> Vitamin, mineral and binder combined.

<sup>b</sup> Vitamin and mineral premixes combined.