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Effects of feeding a fishmeal-free versus a fishmeal-based diet on post-smolt Atlantic salmon *Salmo salar* performance, water quality, and waste production in recirculation aquaculture systems

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ABSTRACT

The Atlantic salmon farming industry has progressively decreased the proportion of fishmeal used in commercial diets due to rising costs and sustainability concerns. A variety of alternate proteins have been identified to partially replace fishmeal; however, very little research has described the effect of feeding alternate protein, fishmeal-free diets to Atlantic salmon, particularly post-smolts cultured in recirculation aquaculture systems (RAS). Therefore, a 6-month study was conducted to compare the effects of feeding a fishmeal-free diet (FMF) versus a fishmeal-based diet (FM) on post-smolt Atlantic salmon performance, water quality, and waste production rates in six replicated RAS. Experimental diets were fed to Atlantic salmon (281 ± 5 g to begin) in triplicate RAS. Protein ingredients used in the FMF diet included mixed nut meal, poultry meal, wheat flour, and corn protein concentrate; while the FM diet contained menhaden meal, poultry meal, soy protein concentrate, and blood meal proteins. Fish oil derived from whiting fish trimmings was used in the FMF diet to establish a wild fisheries input to farmed fish output ratio of 0:1; while menhaden oil was the primary lipid source for the FM diet. Both diets were formulated with approximately 42% crude protein and 27% crude fat. Each RAS was operated with flushing rates that created an average system hydraulic retention time of 20 days (5% system volume flushed daily) and a mean feed loading rate of 3.2 kg feed/m^3 of daily make-up water volume. Atlantic salmon growth, survival, and feed conversion ratios (FCR) were unaffected ($P > 0.05$) by diet. At the conclusion of the study, Atlantic salmon fed the FMF and FM diets were 1.716 ± 0.076 and 1.720 ± 0.065 kg; cumulative survival was >99% for both; and average FCR was 0.89 ± 0.03 and 0.90 ± 0.02, respectively. The FMF diet resulted in greater total phosphorous (TP), carbonaceous biochemical oxygen (cBOD), and total suspended solids (TSS) mass per kg feed in the effluent ($P < 0.05$). The FMF and FM diets produced 0.009 ± 0.001 v. 0.006 ± 0.001 kg TP/kg feed; 0.079 ± 0.005 v. 0.056 ± 0.005 kg cBOD/kg feed; and 0.297 ± 0.028 v. 0.221 ± 0.032 kg TSS/kg feed, respectively. A significantly higher percentage of TSS was captured by radial flow settlers of RAS receiving the FMF diet compared to capture by settlers associated with the FM diet. Mass balance data, radial settler removal efficiency, and observations of flushed solids suggested that the FMF diet produced fecal matter with better settling characteristics. Lower TSS and true color values ($P < 0.05$), indicative of clearer water, were measured in RAS receiving the FMF diet. Total phosphorous (most of which was dissolved) was 4 times greater in the culture water of RAS that received the FMF diet, e.g., 4.3 ± 0.1 mg/L v. 0.9 ± 0.0 mg/L for the FM Diet. This was the first research attempt to formulate a fishmeal-free diet for Atlantic salmon with this ingredient profile and one of few studies to demonstrate uncompromised Atlantic salmon performance when feeding a diet without fishmeal.

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1. Introduction

Over the past several decades, the market price for fishmeal and fish oil has risen steadily due to static supply and increasing

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demand, which has driven the aquaculture industry to consider more economical and sustainable ingredients for use in aquafeeds (Naylor et al., 2000; Gatlin et al., 2007; Tacon and Metian, 2008; Naylor et al., 2009; FAO, 2014). A variety of potential alternate proteins have been identified, including: algal (Kiron et al., 2012) and bacterial (Aas et al., 2006) proteins, poultry by-product (Fowler, 1991); invertebrate and nut meals (Barrows and Frost, 2014), and a variety of plant-based proteins (Gatlin et al., 2007). Significant progress has been made to reduce or replace fishmeal in the diets of many aquaculture species without compromise to health or performance (Adelizi et al., 1998; Furuya et al., 2004; Kaushik et al., 2004; Gatlin et al., 2007; Salze et al., 2010; Rossi, 2011). For example, recent research indicates that fishmeal-free diets with alternate protein blends are capable of producing comparable rainbow trout *Oncorhynchus mykiss* growth compared to traditional fishmeal-based diets (Kaushik et al., 1995; Barrows et al., 2007; Gaylord et al., 2007; Davidson et al., 2013; Barrows and Frost, 2014).

Atlantic salmon *Salmo salar*, however, generally have a low tolerance for fishmeal substitution; particularly, for diets containing high levels of plant-derived proteins, such as soybean meal (Baeverfjord and Krogdahl, 1996; Francis et al., 2001). Several studies have shown that Atlantic salmon fed diets with partial fishmeal replacement by plant proteins exhibited reduced feed intake, decreased growth rates, and/or reduced nutrient digestibility and gut health compared to standard fishmeal-based diets (Mundheim et al., 2004; Kraugerud et al., 2007; Reftsie et al., 2010; Pratoomyot et al., 2011; Burr et al., 2013). Moreover, Espe et al. (2006) reported slower growth for Atlantic salmon fed fishmeal-free diets with various plant protein blends compared to a fishmeal-based diet. In contrast, a few studies have reported comparable Atlantic salmon growth and health, and/or nutrient digestibility when evaluating diets with partial fishmeal replacement versus diets with full fishmeal inclusion (Reftsie et al., 2001; Reftsie and Tiekstra, 2003; Aas et al., 2006; Torstensen et al., 2008; Øverland et al., 2009; Bendikson et al., 2011; Burr et al., 2012). To the authors' knowledge, however, only one study has demonstrated uncompromised Atlantic salmon growth performance when feeding a diet devoid of fishmeal. Burr et al. (2012) found that juvenile (31.5 g) Atlantic salmon fed diets containing blends of soy, corn, wheat, algae, and poultry by-product proteins grew at equal rates, to a mean size of approximately 250 g, compared to salmon fed a fishmeal-based diet.

The efficient use of sustainable feed ingredients has become increasingly important to the salmon farming industry over the past several decades due to steady growth in production and the coinciding demand for feed (Bostock et al., 2010; FAO, 2014). Historically, the salmon farming industry has used large proportions of fishmeal in commercial diets and has therefore been a net consumer of marine resources, producing wild fisheries input to farmed fish output ratios as high as 5:1 (Naylor et al., 2009); however, the industry has recognized that continued use of large quantities of fishmeal is not economically or environmentally sustainable and has progressively reduced the amount of fishmeal used in commercial diets. Bostock et al. (2010) reported that use of fishmeal and fish oil by the salmon industry began to decline from 1995 to 2005, experienced an even sharper drop from 2005 to present, and is expected to follow a similar trend until at least 2020. Alternate proteins including soya concentrates, sunflower meal, and poultry by-products are now commonly used to partially replace fishmeal in commercial salmon diets (Marine Harvest, 2015). Nevertheless, additional research is needed to further reduce or completely eliminate fishmeal in Atlantic salmon diets.

Accompanying the trends for increased Atlantic salmon production and reduced use of fishmeal in diets is the need to evaluate new and possibly more environmentally benign culture methods for Atlantic salmon. A growing number of commercial salmon companies are now producing smolts using recirculation aquaculture systems (RAS) (Bergheim et al., 2009), with a few farms raising post-smolts up to 0.5–1 kg prior to transfer to sea cages (Dalsgaard et al., 2013) and more currently operating or under construction in Norway. In addition, there is recent interest in culturing Atlantic salmon to market-size in land-based, closed containment systems that utilize RAS technology (Thorarensen and Farrell, 2011; Summerfelt and Christianson, 2014; Davidson et al., In Press). At present, there are approximately one dozen facilities worldwide that are raising Atlantic salmon to market-size in RAS (Summerfelt et al., 2015a). Thus, research on a range of culture aspects, including evaluation of sustainable diets fed to Atlantic salmon in RAS, would provide beneficial information for this developing industry sector.

Diets that are fed in RAS, particularly systems operated with long hydraulic retention times and/or high feed loading rates, can have a profound effect on culture tank water quality compared to flow-through and open systems that continuously exchange water, because metabolic wastes tend to accumulate in RAS (Davidson et al., 2009; Martins et al., 2009). In addition to providing optimal fish performance, alternate protein diets should be compatible with the production system, should minimize nutrient excretion and dissolution, and should result in water quality that is conducive to fish health. Ideally, newly developed diets should also generate fecal waste that has favorable mechanical properties for RAS applications, such as fecal stability (Brinker and Friedrich, 2012). Research evaluating waste production characteristics of alternate protein diets fed in RAS applications is limited. Davidson et al. (2013) evaluated the effect of feeding a grain-based diet without fishmeal versus a fishmeal-based diet fed to rainbow trout in low exchange RAS and found that the fishmeal-free diet resulted in greater accumulation of total ammonia nitrogen, total suspended solids, and carbonaceous biochemical oxygen demand in the culture water. Total phosphorus levels in the culture water and the effluent were lower for RAS associated with the grain-based diet, and culture water was clearer (based on true color and ultraviolet transmittance levels). Differences in solids removal efficiency across filtration devices were also measured as a consequence of diet. Despite these water quality differences, rainbow trout growth and survival were equal between dietary treatments (Davidson et al., 2013).

The research study described herein mirrored Davidson et al. (2013), but evaluated a fishmeal-free diet for Atlantic salmon that contained mixed nut (pistachio or almond byproduct) and poultry meal proteins. In addition, fish oil used in the fishmeal-free diet was derived from whiting fish trimming waste, which resulted in a wild fisheries input to farmed fish output of 0:1 (Monterey Bay Aquarium, 2011). The primary objective of this study was to compare the effects of feeding a fish meal-free diet versus a fishmeal-based diet on Atlantic salmon performance, water quality, and waste production in replicated recirculation aquaculture systems.

2. Methods

2.1. Experimental design & diet descriptions

Six replicated RAS (9.5 m^3) were randomly assigned to one of two dietary treatments (Fig. 1) to begin the 6-month study. Atlantic salmon cultured in three systems were fed a fishmeal-free (FMF) diet; while salmon cultured in the remaining three systems were fed a fishmeal-based (FM) diet. The experimental diets were manufactured at the USDA-ARS Fish Technology Center (Bozeman, MT, USA). The primary protein ingredients used in the FMF diet were mixed nut meal, wheat flour, corn protein concentrate, and poultry meal (Table 1). The FM diet was formulated to represent a commercial-type Atlantic salmon diet containing menhaden meal,

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