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Use of Non-Native Columbia River American Shad (*Alosa sapidissima*) as an Alternative Fishmeal Source for Juvenile Sablefish (*Anoplopoma fimbria*)

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U.S. DEPARTMENT OF COMMERCE

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Northwest Fisheries Science Center

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Use of Non-Native Columbia River American Shad (*Alosa sapidissima*) as an Alternative Fishmeal Source for Juvenile Sablefish (*Anoplopoma imbria*)

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Plain Language Summary

Background

American shad are a non-native species that resides in marine and inland waters of the Pacific Northwest. They are one of the most abundant anadromous (hatching in freshwater, but maturing in saltwater) fish species in the northwestern United States. The population of shad is predicted to increase, but the effects of such an increase are not fully understood. Shad are believed to negatively affect native fish populations. There is currently a limited commercial harvest and a sport fishery for shad, but a large percentage of the population remains underutilized. Their large numbers and nutritional composition (57% protein, 28% fat) make them a good candidate species for fishmeal and fish oil production that would support a growing aquaculture industry.

At NWFSC, we have been raising sablefish, also known as black cod, as a model marine species for aquaculture and to meet the increasing demand for seafood. Fishmeal and fish oil are important ingredients for aquaculture feeds, but high demand and variable supply have resulted in price increases. Feed is a major concern in finfish aquaculture, making up 50–70% of the operating costs for most domestic fish producers. The Fish Feeds and Nutrition Team at NWFSC examined shad as an alternative protein and oil source for farmed sablefish by replacing fishmeal and partially replacing fish oil with shad meal in the diets of young sablefish.

Key Takeaways

Use of shad as an alternative fish protein/oil source for sablefish aquaculture looks promising. Young sablefish receiving a 50% shad-based feed showed similar growth as fish receiving industry-standard sardine-based feed (0% shad). The growth of sablefish receiving a feed with 100% shad meal was lower than that containing 50% shad meal replacement and the sardine-based control feed, but similar to a commercial salmon feed.

Controlling populations of non-native fish by utilizing them for fishmeal may help reduce pressures on industrial fisheries and increase the environmental sustainability of aquaculture.

Links used in this section:

- American shad: https://wdfw.wa.gov/species-habitats/species/alosa-sapidissima
- Sablefish: https://www.fisheries.noaa.gov/species/sablefish
- Aquaculture: https://www.fisheries.noaa.gov/species/sablefish/aquaculture
- Alternative fish protein/oil source: https://www.fisheries.noaa.gov/resource/outreach-materials/fact-sheet-alternative-feeds-and-nutrition

Abstract

In this study, we investigated the use of American shad (*Alosa sapidissima*) as an alternative fish protein/fish oil ingredient for aquaculture feeds. American shad is a non-native species that resides in marine and inland waters of the Pacific Northwest. The population of shad has increased since their introduction to the West Coast in the late 19th century, and is currently considered the largest anadromous fish population in the Columbia River. Shad are highly adaptable to various environmental conditions, and populations of shad are predicted to increase. Although the impacts of an increase in the shad population are not fully understood, shad are believed to negatively impact native fish populations. There is a limited commercial harvest and a sport fishery for shad, but a large percentage of the population remains underutilized. The nutritional composition of shad (57% protein, 28% lipid, dry weight basis) makes them a good species for fishmeal and fish oil production. Here we prepared experimental sablefish (*Anoplopoma fimbria*) feeds using shad meal to replace sardine meal at 0%, 50%, and 100%. The ten-week growth study showed that all juvenile sablefish grew well, with 100% survival. Fish receiving 50% shad meal in their feed had comparable growth to fish fed the sardine-based feed (0% shad), while growth of fish receiving feed with 100% shad meal replacement was slightly lower but similar to the growth of fish fed a commercial salmon feed. Feed efficiency of fish fed the 50% shad feed was similar to that of the 0% shad control feed, but higher than that of the 100% shad-based feed. These results highlight the potential for shad as a viable alternative for commercially harvested fishmeal for use in sablefish production. The potential for widespread application to other species is high, and therefore the inclusion of shad into aquaculture feeds may represent a means of reducing non-native fish populations and enhancing the environmental sustainability of aquaculture by reducing commercial pressure associated with fish meal harvest from wild fisheries.

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1 Introduction

Aquaculture is the fastest growing food-producing sector in the world, and has dramatically increased the demand for marine feed ingredients. Fishmeal and fish oil typically come from wild-caught forage fish that are not sold for direct human consumption, often referred to as industrial fisheries. High demand for industrial fish products has resulted in increasing prices, and fish feed is estimated to be 50–70% of the operating costs for fish producers (Rana et al. 2009). For sustained growth, the adoption of more ecologically and environmentally sound management practices in aquaculture is needed (Naylor et al. 2000, 2009). While alternative protein and oil sources have been investigated (e.g., terrestrial plant proteins, insects, algae), these sources have yet to completely replace fishmeal and fish oil in marine fish feeds due to nutrient deficiencies, species-specific sensitivities, palatability issues, cost, and other unknown factors (Hua et al. 2019).

Anadromous American shad (*Alosa sapidissima*) are native to the U.S. East Coast, but were introduced to the U.S. West Coast in 1871 (Haskell 2018). Since then, shad have become fully established in the Pacific Northwest, with an increasing abundance in recent years (Weitkamp 1994, Petersen et al. 2003, Hasselman et al. 2012a,b, Weitkamp et al. 2012). In 2019, a record 7.6 million shad were observed at the Bonneville Dam on the Columbia River, outnumbering all other migratory adult species of fish (Quinn et al. 2024). Due to limited research of shad in the Pacific ecosystems, the effects on native salmon populations are unclear, and no clear harmful effect on salmon from empirical studies nor from ecological principles have been observed (Quinn et al. 2024). However, shad may impact native fish populations negatively by reducing zooplankton abundance, shifting the source of marine-derived nutrients in the Columbia River basin (Haskell et al. 2006, Haskell 2018), and increasing predatory fish which feed on juvenile salmonids (Petersen et al. 2003, Haskell et al. 2006, Haskell 2018). Conversely, shad may provide some benefit by acting as an alternative food source for predatory fish (ISAB 2021) or birds that may otherwise feed on salmonids (Wargo Rub et al. 2019, Good et al. 2022).

Given the relative abundance of shad in the Pacific Northwest, there is potential to expand this fishery beyond the current limited commercial and recreational harvests. However, a significant challenge to expansion may be their similar migration timing to spring Chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*O. nerka*), and steelhead (*O. mykiss*) in the Columbia River, where a commercial shad fishery may impact ESA-listed salmonid populations. Currently, there is a small commercial shad fishery in the lower Columbia River using purse seines that allow for the release of salmonids (Oregon Live 2011). Also, there are small tribal fisheries upriver in the Bonneville Dam pool and The Dalles Dam.[1] Populations of non-native fish in the Columbia River are projected to increase (Sol et al. 2021, Quinn et al. 2024). Recently, shad have even become established in rivers and lakes of Puget Sound, Washington, and have been increasing in numbers. The Washington Department of Fish and Wildlife (WDFW) is investigating ways to slow down the growth of the shad population in Puget Sound.[2] Shad have been shown to be nutritious (Gooch et al. 1987), and using shad

[1] https://en.wikipedia.org/wiki/Shad_fishing
[2] https://nwsportsmanmag.com/heres-lake-washingtons-next-damn-headache/

as an alternative source of protein and oil for aquaculture feeds would be beneficial in controlling population growth of shad while reducing pressures on industrial fisheries and increasing the environmental sustainability of domestic aquaculture.

Sablefish (*Anoplopoma fimbria*) are a deep-water species native to the Pacific Northwest that are high in fat and rich in omega-3 fatty acids. Sablefish populations are currently stable, but harvest is strictly regulated. Wild sablefish command a high price in local markets; as a result, there is strong interest in the aquaculture of this species. Over the past decade, sablefish aquaculture research at the National Oceanic and Atmospheric Administration (NOAA)/Northwest Fisheries Science Center (NWFSC) has resulted in significant advancements in the rearing of sablefish from eggs to market size (see review by Goetz et al. 2021). Recently, a partnership with the Jamestown S'Klallam Tribe for the aquaculture of sablefish was initiated at NWFSC's Manchester Research Station to rear sablefish and triploid steelhead trout in net pens in Puget Sound.[3] Development of low-cost, sustainable alternative feeds will be instrumental to the success of this grow-out business.

The Fish Feeds and Nutrition Team at NWFSC has used sablefish as a model for carnivorous cold-water marine species in a number of alternative feed trials. This legacy has allowed for the evaluation of the relative efficiencies of different novel ingredients in diets, fed to the same species, through successive studies (Johnson et al. 2015, 2020, Nicklason et al. 2016, 2020, Rhodes et al. 2016, Anulacion et al. 2023). In this two-part feeding and digestibility study, we evaluated shad as an alternative ingredient for juvenile sablefish by replacing fishmeal and fish oil with shad meal in the diet of juvenile sablefish. The study 1) measured changes in feed intake, growth, feed efficiency, and whole-body nutrient composition; and 2) determined the digestibility of shad meal protein in juvenile sablefish.

[3] https://www.intrafish.com/aquaculture/cooke-partnering-with-tribe-to-farm-black-cod-trout-in-washington-state/2-1-682969

2 Materials and Methods

2.1 Fish Capture and Preparation of Experimental Feeds

Adult shad of mixed sex (weight 1–1.5 kg/fish) were caught by hook and line below the Bonneville Dam on the lower Columbia River (lat 45°39.017′N, long 121°56.292′W) during their peak return migration in July 2020. Fish were sacrificed with a blow to the head, maintained on ice, transported to the laboratory (NWFSC, Seattle), and stored at –20°C until processed into experimental diets. Experimental sablefish feeds containing shad and plant proteins were prepared at NWFSC. Shad (whole body) were cooked, dried, and ground into meal form using a heated ball mill (Nicklason et al. 2016). The shad meal was blended with plant proteins and other ingredients and pelletized using a C. W. Brabender (Hackensack, New Jersey) Prep Center with a single screw feed extruder attachment (Table 1).

2.2 Fish Culture

Juvenile sablefish, ~0.5 g, obtained from the Manchester Research Station (Port Orchard, Washington), were transported to Seattle in April 2021. Fish were kept in a recirculating seawater system and fed a salmon fry feed (2.5–4 mm; BioVita Fry, Bio-Oregon, Longview, Washington) containing primarily marine ingredients until the start of the experiment.

2.3 Conditioning Period

In August 2021, when they reached an average weight of 34 g, fish were sorted for uniform size and transitioned from the salmon fry feed to the conditioning feed. The formulation of the conditioning feed was identical to that of 0% shad feed used in the subsequent growth trial (Table 1). The purpose of the conditioning period was to increase feed acceptance of the experimental feeds during the growth trial and exclude any fish from the study that would not accept the experimental feeds. The conditioning period lasted for four weeks.

2.4 Feeding Trial

Feeding trials were conducted following the protocols developed by Johnson et al. (2015). In September 2021, conditioned fish were again sorted for uniform size and randomly distributed among 16 replicate, 160 L, semi-square tanks. Four experimental feeds—a commercial salmon diet (reference feed: BioBrood, Bio-Oregon), a sardine feed (0% shad), a 50% sardine and 50% shad feed, and a 100% shad feed—were randomly assigned to four tanks each (each tank containing 16 fish, average weight 53.0 ± 0.5 g).

The feeding trial lasted ten weeks. For each tank, fish were fed to apparent satiation (5 min maximum feeding duration) every other day and the feed consumption was recorded. This feeding schedule was chosen based on previous research (Friesen 2008) demonstrating that juvenile sablefish have an extended gut evacuation period, and consistent feed intake and satisfactory growth can be achieved by feeding this species every other day.

Table 1. Formulations of experimental diets (in g ingredient/kg of dry feed) with varying amounts of shad meal. Bold font highlights the amounts of sardine meal, shad meal, and fish oil.

Ingredient	0% shad	50% shad	100% shad
Sardine meal[a]	**300.0**	**150.0**	**0.0**
Shad meal	**0.0**	**183.0**	**365.0**
Soy protein concentrate	160.0	160.0	160.0
Corn protein concentrate	133.0	133.0	133.0
Wheat flour	210.0	211.0	212.0
Fish oil	**123.0**	**89.0**	**56.0**
Trace minerals[b]	1.0	1.0	1.0
Vitamin premix[c]	15.0	15.0	15.0
Vitamin C	5.0	5.0	5.0
Choline	5.0	5.0	5.0
Betaine	2.5	2.5	2.5
L-methionine	2.0	2.0	2.0
L-lysine	12.0	12.0	12.0
L-threonine	2.0	2.0	2.0
Mono-cal phosphate	20.0	20.0	20.0
Taurine	10.0	10.0	10.0

[a] From Mexico.
[b] U.S. Fish and Wildlife Service Mineral Premix #3. Contributed, per kg diet: zinc, 75 mg; manganese, 20 mg; copper, 1.5 mg; iodine, 10 mg.
[c] U.S. Department of Agriculture Agricultural Research Service Vitamin Premix #702. Contributed, per kg diet: vitamin A, 14475 IU; vitamin D, 9600 IU; vitamin E, 198 IU; vitamin K3, 1.6 g; thiamin mononitrate, 13.7 mg; riboflavin, 14.4 mg; pyridoxine hydrochloride, 20.6 mg; pantothenate DL-calcium, 70 mg; cyancobalamin, 0.05 mg; nicotinic acid, 32.7 mg; biotin, 0.50 mg; folic acid, 3.75 mg; inositol, 900 mg.

Fish were cared for humanely following the guidelines of the National Research Council (NRC 2011). Throughout the trial, weekly water quality measurements taken included temperature, salinity, alkalinity, ammonia, nitrite, nitrate, dissolved oxygen, and pH (Table 2).

At the end of the trial, after a four-day fast, fish were weighed and percent weight gain and thermal growth coefficients (TGC) were calculated using the following formulas:

$$\text{Weight gain (\%)} = [(\text{Final weight} - \text{Initial weight})/\text{Initial weight}] \times 100 \quad (1)$$

$$\text{TGC} = 1{,}000 \times [(\text{Final weight}^{1/3} - \text{Initial weight}^{1/3})/(T \times t)] \quad (2)$$

where:

Final weight and *Initial weight* are measured in grams,
T = temperature in °C, and
t = number of days.

Table 2. Water quality parameters for the duration of the feeding study.

Feed study (Week)	Temp (°C)	Salinity (g/L)	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	DO (mg/L)	pH
1	12.6	26.7	0.01	0.147	3.7	9.35	7.90
2	12.3	27.2	0.00	0.160	3.2	9.46	7.88
3	12.0	26.4	0.00	0.123	4.5	8.71	8.05
4	12.0	26.2	0.00	0.127	3.6	8.89	7.91
5	12.4	26.3	0.00	0.126	4.3	8.56	7.93
6	12.5	26.7	0.01	0.165	3.5	8.80	7.94
7	12.5	26.2	0.00	0.180	4.2	8.64	7.94
8	11.5	26.6	0.00	0.196	3.8	10.00	7.81
9	11.5	26.0	0.00	0.162	4.2	8.81	8.03
10	11.6	26.7	0.04	0.204	3.5	8.98	7.85
Average	**12.09 ± 0.43**	**26.50 ± 0.35**	**0.01 ± 0.01**	**0.16 ± 0.03**	**3.85 ± 0.42**	**9.02 ± 0.45**	**7.92 ± 0.07**
Digestibility study	12.1	28.1	0.00	0.330	4.6	8.94	8.03

2.5 Sampling

At the end of the ten-week trial, fish were euthanized in accordance with procedures developed by the American Veterinary Medical Association (AVMA 2007); fish were anesthetized using MS-222 (Argent Laboratories, Redmond, Washington), followed by a blow to the head.

2.5.1 Body indices

Individual fish lengths (fork length) were recorded (mm), along with whole-body weights (g) and liver weights (g). Condition factor (CF) and hepatosomatic index (HSI) were determined using the following equations:

$$\text{CF} = [\text{weight (g)}/\text{length (cm)}^3] \times 100 \tag{3}$$

$$\text{HSI} = (\text{liver weight}/\text{fish weight}) \times 100 \tag{4}$$

Tank averages were calculated from individual body indices and used for statistical analysis.

2.5.2 Experimental feeds

Feeds were assessed for feed intake (FI), feed efficiency (FE), and protein retention efficiency (PRE), calculated from the following equations:

$$\text{FI} = \text{total weight feed consumed (g) per tank/number of fish in tank } (n) \tag{5}$$

$$\text{FE} = [(\text{final weight} - \text{initial weight})/\text{feed consumed}] \times 100 \tag{6}$$

$$\text{PRE} = \frac{[\text{final fish protein (g)} - \text{initial fish protein (g)}]}{\text{protein consumed from feed (g)}} \times 100 \tag{7}$$

2.6 Digestibility Trial

Sablefish used in the digestibility trial were reared on a salmon broodstock feed (BioBrood) until they reached approximately 550 g. Larger fish were needed for this portion of the study to ensure an adequate amount of fecal material could be collected from each fish.

In March 2022, 75 fish were equally distributed into three large tanks (6,400 L) and assigned an experimental feed: a basal diet (BioVita Starter, Bio-Oregon), or a basal diet containing either 30% sardine meal or 30% shad meal. Diets were prepared with an inert digestibility marker (0.1% yttrium oxide) to measure the apparent digestibility of fishmeal and shad meal by sablefish (Table 3). Fish were fed to apparent satiation for seven days. Fish were then sacrificed as described above and feces collected from the last 3 cm of the hind gut by dissection (Hajen et al. 1993, Friesen et al. 2013). Unfortunately, fecal material collected from the hind gut of the sablefish were too small for individual analyses. Therefore, samples were pooled for digestibility marker analyses.

The digestibility marker in the feed and feces was analyzed via inductively coupled plasma optical emission spectrometry (ICP-OES) by the Experimental Station Chemical Laboratories (ESCL), University of Missouri, Columbia, Missouri. Nitrogen content of feed and fecal samples was determined at NWFSC via methods listed below for feeds and whole-body fish samples. The protein apparent digestibility coefficients (ADC) were calculated from the following equations (Burr et al. 2011):

$$ADC_{diet} = 100 - 100\ \frac{\%\text{ yttrium in diet} \times \%\text{ protein in feces}}{\%\text{ yttrium in feces} \times \%\text{ protein in diet}} \tag{8}$$

$$ADC_{ingredient} = [(a + b)ADC_t - (a)ADC_r]b^{-1} \tag{9}$$

where:

$ADC_{ingredient}$ = apparent digestibility coefficient of protein in the test ingredient,
ADC_t = apparent digestibility coefficient of protein in the test diet,
ADC_r = apparent digestibility coefficient of protein in the basal diet,
p = proportion of the test ingredient (for the current study, $p = 0.30$),
$a = (1 - p)$ × protein content of the basal diet, and
$b = p$ × protein content of the test ingredient.

Table 3. Feed formulations (in g ingredient/kg feed) for shad digestibility trial. Yttrium oxide is included in formulations as an inert marker for digestibility calculations.

Ingredient	Basal diet	Basal diet + shad	Basal diet + fishmeal
BioVita Starter[a]	1,000	700	700
Shad meal	0	300	0
Sardine meal[b]	0	0	300
Yttrium oxide	1	1	1

[a] Ingredients: Fishmeal, fish oil, wheat gluten, wheat flour, hydrolyzed hake, dried whey powder, porcine gelatin, mono ammonium phosphate, vitamin/mineral premix, astaxanthin, ethoxyquin.
[b] From Mexico.

2.7 Chemical Analyses

Proximate composition on feed and whole-body samples was performed at NWFSC. Moisture content was determined gravimetrically by drying samples to a constant weight overnight in a 105°C oven. Protein, lipid, and ash content were determined in accordance with Association of Official Analytical Collaboration International Official Methods 968.06, 920.39, and 942.05, respectively (AOAC 2000). Initial whole-body composite samples ($n = 3$) were prepared from five fish each from the conditioning tank at the beginning of the study, and final whole-body composite samples were prepared from eight fish per treatment tank at the end of the study. Composites were analyzed in triplicate to determine tank means and results presented on a wet weight basis.

2.8 Statistical Analysis

One-way analysis of variance (ANOVA) was performed to detect significant differences in growth, body indices, feed efficiency, and tissue chemical composition attributable to feed. When a difference was detected, Tukey's honestly significant difference (HSD) post-hoc test was employed to determine significance of differences between treatments. Statistical analyses were conducted with the JMP statistical package (JMP Statistical Discovery LLC, Cary, North Carolina) with values considered significantly different at $\alpha < 0.05$.

3 Results

3.1 Water Quality

All water quality parameters remained within acceptable ranges for sablefish (Table 2). Water temperature and salinity averaged 12.09 ± 0.43°C and 26.50 ± 0.35 g/L, respectively. Ammonia, nitrite, and nitrate levels averaged 0.01 ± 0.01, 0.16 ± 0.03, and 3.85 ± 0.42 mg/L, respectively. Dissolved oxygen averaged 9.02 ± 0.45 mg/L, and pH averaged 7.92 ± 0.07.

3.2 Growth

Fish grew well throughout the study and 100% survival was observed for all feed treatments (Figure 1). The length and weight of the sablefish at the beginning of the study were 186 ± 8 mm and 54.29 ± 0.59 g, respectively. At the end of the ten-week trial, the length of the fish across all treatment groups was 265.7 ± 11.9 mm (ranging from 234–293 mm). The fish from the 0% shad diet were found to be longer than those from the 100% shad diet and the reference diet fish (Figure 2a, Tukey's HSD: $p = 0.0202$). The average weight of the fish across all treatment groups at the end of the study was 188.14 ± 21.96 g (ranging from 112–240 g). The weight of the fish from the 100% shad diet was lower than fish from the 0% and 50% shad diets (Figure 2b, Tukey's HSD: $p = 0.0066$). The percent weight gain of the fish from the 100% shad diet was lower than fish from the 0% and 50% shad diets, but similar to fish from the reference diet (Figure 2c, Tukey's HSD: $p = 0.0024$).

3.3 Body Indices

The body indices measured, CF (1.00 ± 0.09) and HSI (1.88 ± 0.23), were found to be within the normal range observed for sablefish in our laboratory. No differences in CF were observed between the treatment groups (Figure 3a, Tukey's HSD: $p = 0.4554$), but the HSI of the fish receiving the 100% shad diet was higher than fish receiving the reference diet (Figure 3b, ANOVA, Tukey's HSD: $p = 0.0370$).

3.4 Feed Performance

The average FI for all tanks was 147 ± 12 g per fish. Although no differences in FI were observed between treatment groups of 0–100% shad diet, the reference diet group had lower FI than the 0% and 50% shad groups. FI of reference diet and 100% shad diet was similar (Figure 4a).

The FE of the fish from the reference, 0%, and 50% shad diets was found to be similar, while fish from the 100% shad diet were similar to 0%. The FE of the fish from the 100% shad diet was found to be lower than fish from the reference and 50% shad diets (Figure 4b). The PRE of fish from the 100% shad diet was lower compared to fish from the reference and 50% shad diets, but similar to fish from the 0% shad diet (Figure 4c). The TGC of the reference and 0% shad diet was found to be similar, while fish from the reference and 100% shad diets were also found to be similar. TGC of the fish from the 0% and 50% shad diets was higher than fish from the 100% shad diet (Figure 4d).

Chemical analyses of the feed showed that the reference diet had the highest levels of % protein and % lipid compared to the other diets, while the % protein and % lipid of the 100% shad diet were higher than the 0% shad diet (Figures 5a, 5b). The % ash and % moisture were found to be different among all diets (Figures 5c, 5d).

Chemical analyses of the whole body showed that % protein, % lipid, and % ash of the fish sampled at the beginning of the study were lower than fish sampled at the end of the study, while the % moisture in the whole body was higher at the beginning of the study. The % protein in the whole body collected at the at the end of the study was similar across all the treatments groups (Figure 6a), but fish from the 100% shad diet had lower % lipid compared to fish from other diets (Figure 6b). The % ash was found to be similar in fish collected at the end of the study (Figure 6c), but the % moisture was higher in fish from the 100% shad diet compared to fish from other diets (Figure 6d).

3.5 Digestibility

A digestibility trial was performed to investigate how well sablefish can break down and absorb protein from the shad meal ingredient. Due to limited sample size, no statistical analyses were performed; however, while the protein composition of the three feeds was similar, the ADC_{diet} of the shad feed was found to be the lowest of the three feeds. Similarly, the $ADC_{ingredient}$ of the shad meal was lower than the sardine meal (Table 4).

Table 4. Protein and yttrium composition of feeds and feces from the digestibility trial of sablefish, and apparent digestibility coefficients (ADC) for protein of feeds and test ingredients. Feed values are means ± SD of composite samples.

	Basal	**Sardine**	**Shad**
Feed			
Protein (%)	57.82 ± 0.05 (*n* = 2)	60.39 ± 0.01 (*n* = 2)	59.07 ± 0.26 (*n* = 2)
Yttrium (mg/kg)	761.3 ± 5.7 (*n* = 3)	804.7 ± 12.6 (*n* = 3)	792.7 ± 9.3 (*n* = 3)
Ingredient			
Protein (%)	n/a	69.29 (*n* = 2)	61.97 (*n* = 2)
Fecal			
Protein (%)	35.06 (*n* = 1)	33.92 (*n* = 1)	36.81 (*n* = 1)
Yttrium (mg/kg)	2,139 (*n* = 1)	1,675 (*n* = 1)	1,627 (*n* = 1)
ADC_{diet}	78.43	73.04	69.63
$ADC_{ingredient}$	n/a	62.50	50.53

3.6 Figures

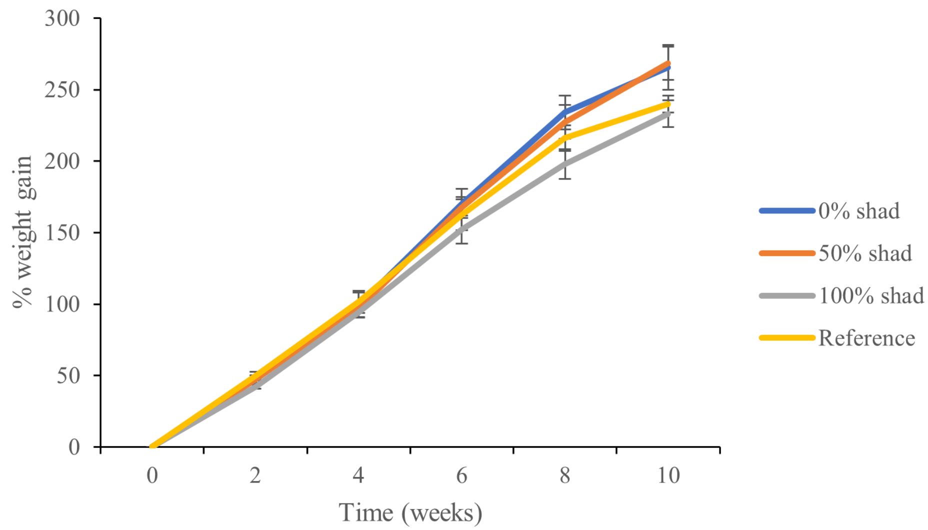

Figure 1. Percent weight gain of the juvenile sablefish (mean ± SD, *n* = 4 tanks per diet) fed different experimental feeds during the course of the ten-week growth study.

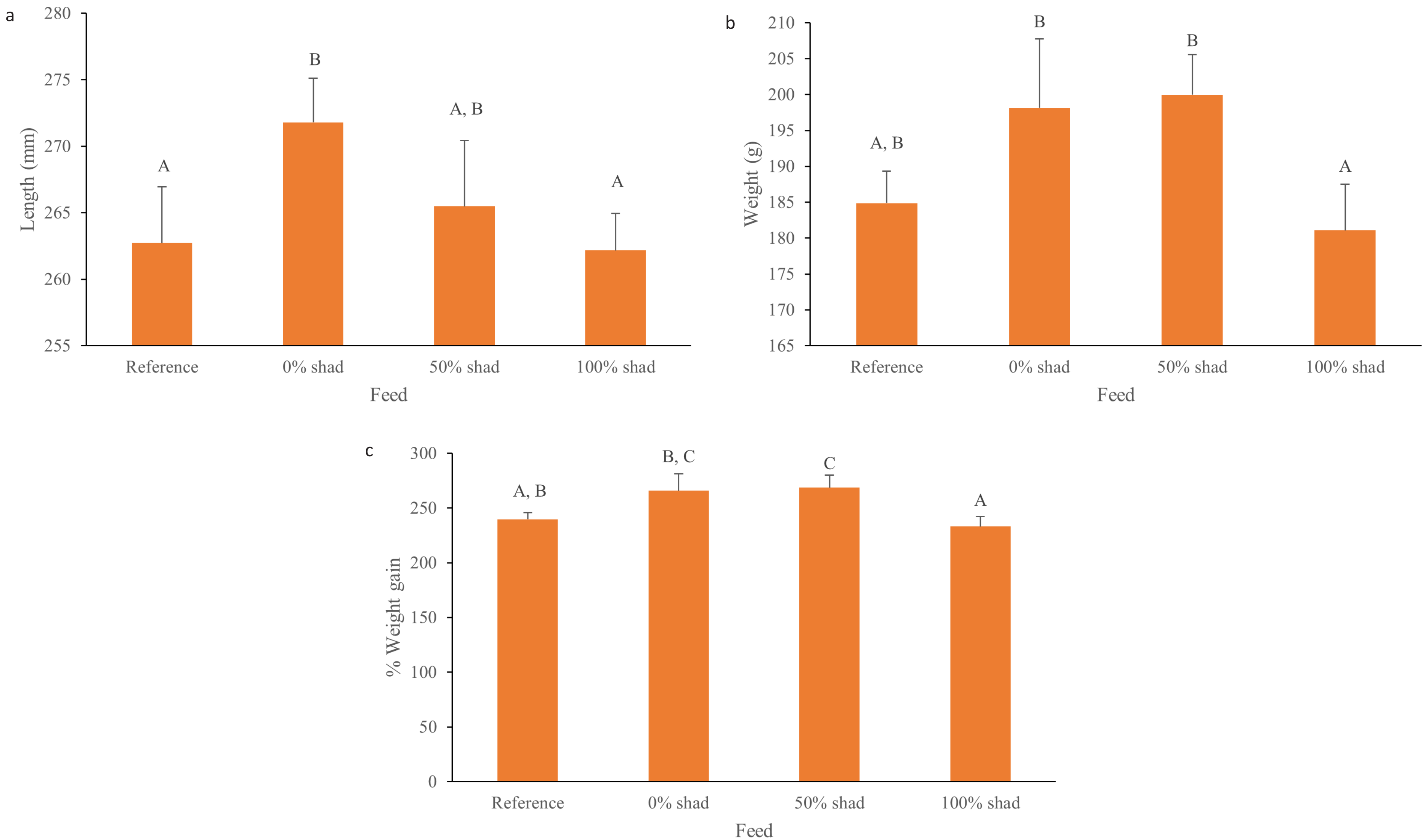

Figure 2. Mean + SD ($n = 4$ tanks per diet) of a) length, b) weight, and c) % weight gain of the juvenile sablefish fed different experimental feeds, at the end of the ten-week growth study. Treatments with different letters above the error bars are significantly different (ANOVA, Tukey's HSD: $p < 0.05$).

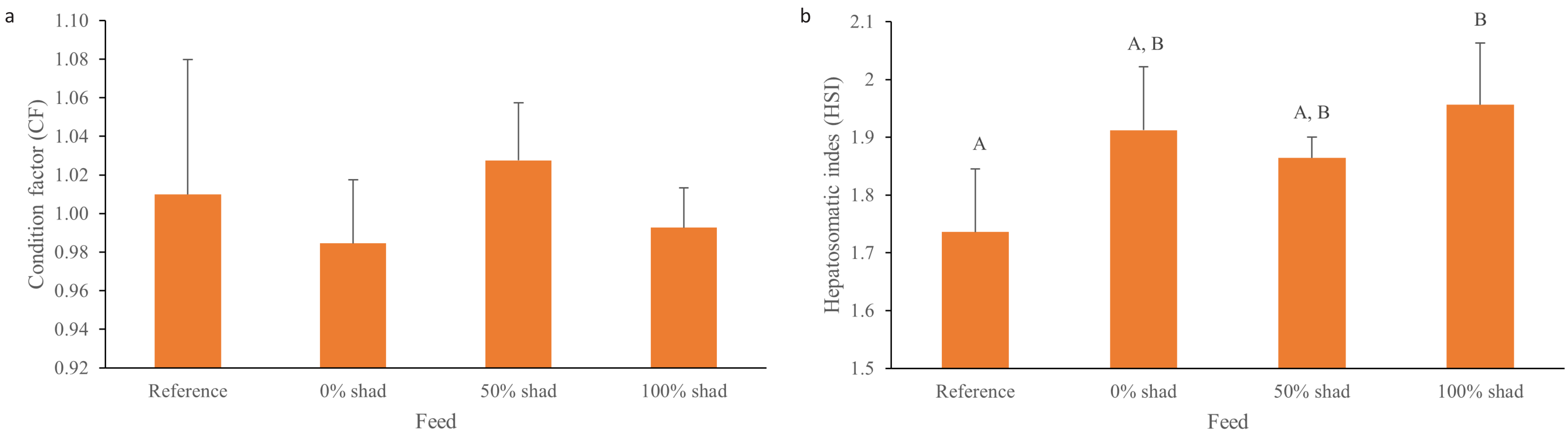

Figure 3. Mean + SD ($n = 4$ tanks per diet) of a) condition factor (CF) and B) hepatosomatic index (HSI) of the juvenile sablefish receiving different experimental feeds, at the end of the ten-week growth study. Treatments with different letters above the error bars are significantly different (ANOVA, Tukey's HSD: $p < 0.05$).

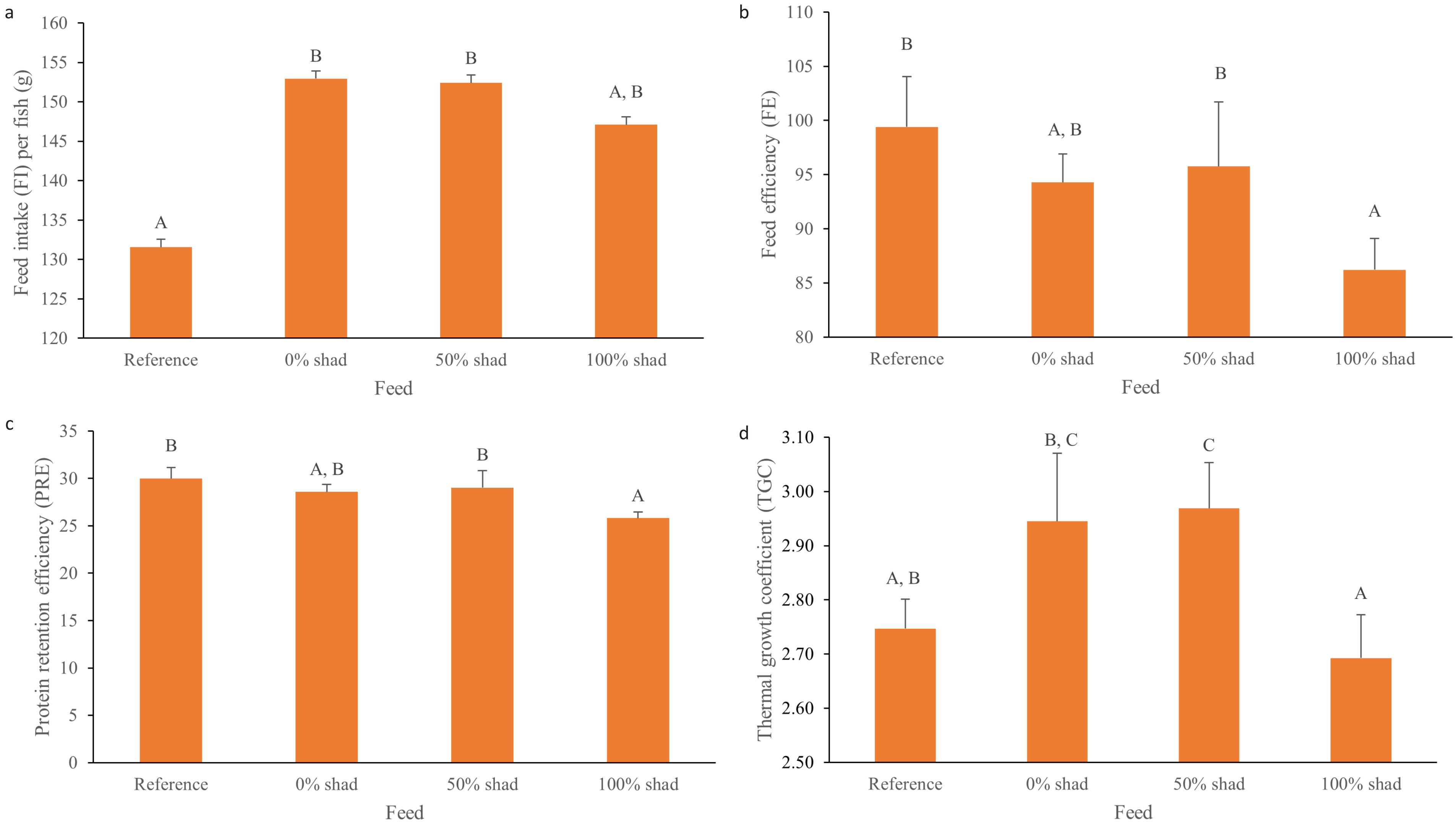

Figure 4. Mean + SD ($n = 4$ tanks per diet) of a) feed intake (FI), b) feed efficiency (FE), c) protein retention efficiency (PRE), and d) thermal growth coefficient (TGC) of the juvenile sablefish fed different experimental feeds during the ten-week growth study. Treatments with different letters above the error bars are significantly different (ANOVA, Tukey's HSD: $p < 0.05$).

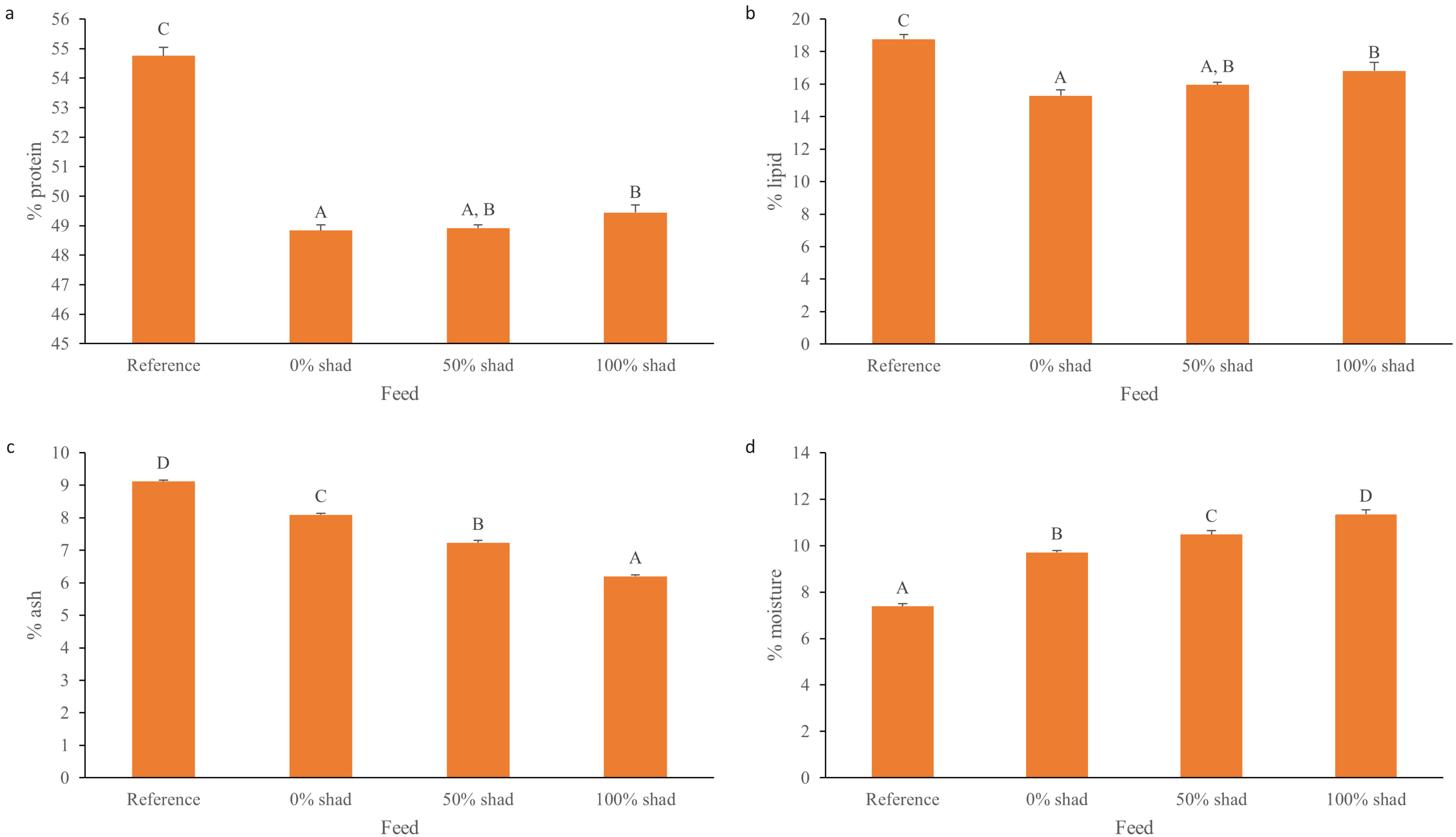

Figure 5. Mean + SD ($n = 3$) of a) % protein, b) % fat, c) % ash, and d) % moisture of experimental feeds used in the ten-week juvenile sablefish growth study. Percent protein, % lipid, and % ash are based on dry weight. Treatments with different letters above the error bars are significantly different (ANOVA, Tukey's HSD: $p < 0.05$).

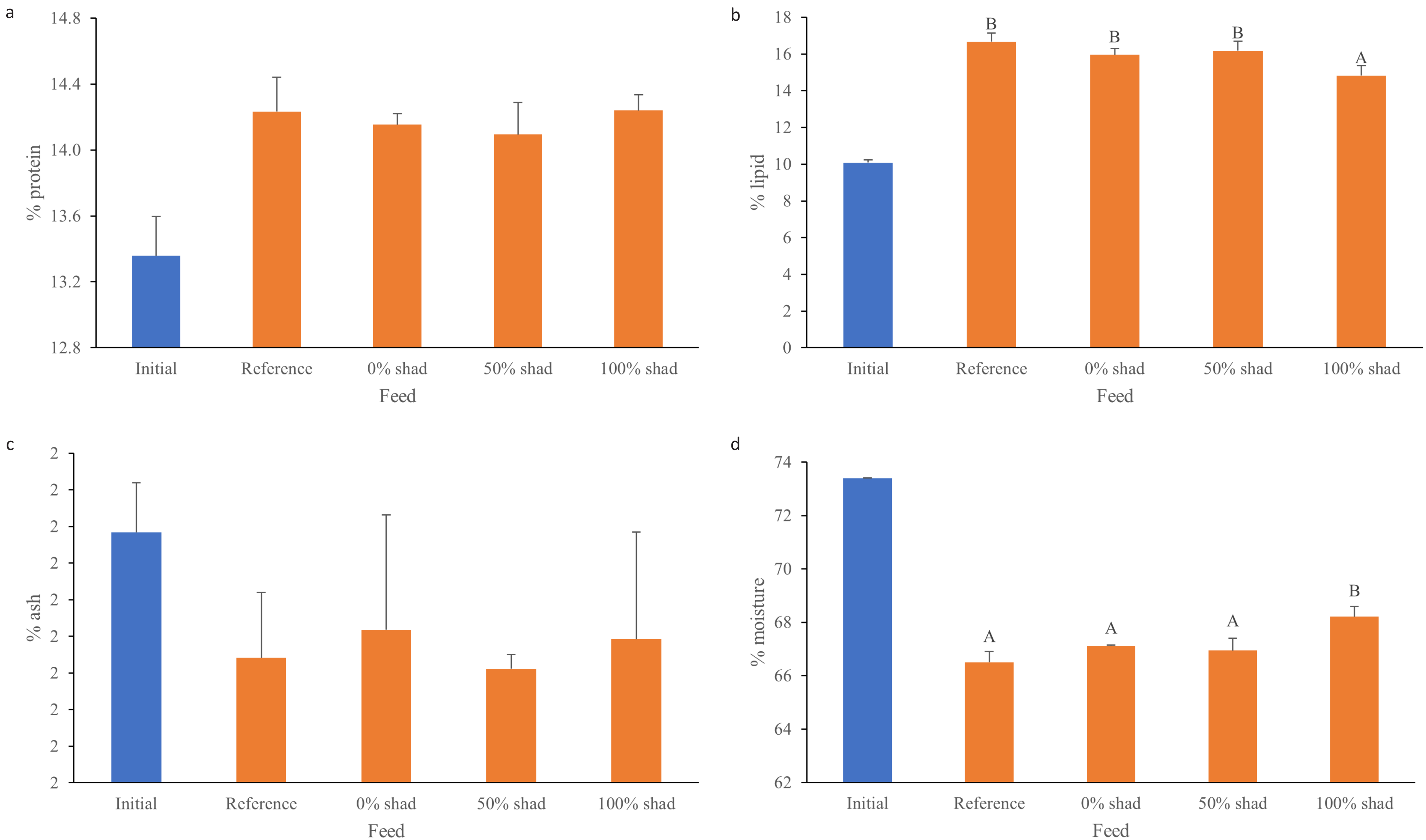

Figure 6. Chemical analyses of fish whole body samples collected at the beginning and at the end of the ten-week juvenile sablefish growth study. Percent protein, % lipid, and % ash are based on wet weight. Different letters signify statistical differences between treatment groups (ANOVA, Tukey's HSD: $p < 0.05$). Values are mean + SD of three composites for initial fish, three tank composites for reference fish, and four tank composites for other fish. Values for initial fish are shown for comparison, but were not included in statistical evaluations.

4 Discussion

4.1 Benefits of Shad as an Alternative Source of Fishmeal and Fish Oil

The growing demand for alternative feed in aquaculture, driven by its rapid expansion to become the world's fastest-growing food-producing sector, has highlighted the urgent need for sustainable solutions. The increase in demand for forage fish, commonly used to produce fishmeal, is unsustainable; as a result of high demand and higher prices, feeds are estimated to be 50–70% of the operating costs of farmed fish production (Rana et al. 2009). In order for sustained growth, adaptation of more ecologically and environmentally sound management practices in aquaculture is needed (Naylor et al. 2000, 2009). Insects and plant-based feeds are being investigated as alternative fish feeds in aquaculture by a variety of researchers (Riddick 2014, Hua et al. 2019, Redman et al. 2019, Saloum et al. 2022, Saputra and Lee 2023). We have also been investigating alternative feeds at our laboratory by supplementing juvenile sablefish diet with the use of mealworm and algae ingredients (Johnson et al. 2020, Anulacion et al. 2023, Johnson et al. 2025). Results have been mixed, but most of these ingredients have shown promise for use in sablefish feeds at some level.

The economic viability of using non-native shad as an alternative feed source further enhances its potential. Shad can be easily obtained from the Columbia River via tribal fishermen or caught by angling. Their vast availability, low commercial value, and absence of specific size or daily catch limits, further contributes to their economic feasibility as an alternative source of fishmeal and fish oil. Shad are highly adaptable to various environmental conditions, and the population of shad is expected to increase (Sol et al. 2021, Quinn et al. 2024). Changes to the environment (i.e., increase in water temperature) can lead to various adverse effects including alterations in water chemistry, habitat loss, changes in community structure, and ultimately a decline in the populations of native fish species that are unable to adapt to the evolving environmental conditions. The geographic range of shad is increasing; for example, they are now found in Puget Sound. To address the problem of the expanding shad population and its potential effect on native populations of fish in Puget Sound, WDFW is working with tribal groups to find ways to remove invasive shad, and is encouraging anglers to assist in removal of shad from Lake Washington. The shad are believed to be feeding on sockeye salmon fry in the lake (L. Harding, WDFW, personal communication). However, the ecological effects of shad in the Columbia River and Lake Washington are not clearly understood and warrant further research (Quinn et al. 2024). In conclusion, shad presents a promising alternative to traditional fishmeal and fish oil in aquaculture. By addressing the challenges associated with unsustainable fishing practices and high feed costs, underutilized shad can contribute to the sustainability and economic viability of sablefish aquaculture operations.

4.2 Benefits of Heated Ball Mill Processing

The heated ball mill process (Nicklason et al. 2016, 2020) offers a significant advantage over commercially produced fishmeal made using the wet reduction process (Pigott and Stansby 1967). This alternative process is advantageous for small-scale fish farms as it requires minimal setup time and does not necessitate continuous operation. The process has demonstrated efficiency and effectiveness in retaining low molecular weight soluble proteins in juvenile sablefish growth (Nicklason et al. 2016). Using this process, we were able to efficiently manufacture the shad meal with comparable protein and higher lipid contents compared to the commercially available industry-standard sardine meal. The commercial salmon feed purchased from Bio-Oregon (now Skretting), used as a reference feed, had higher % protein and % lipid than the experimental feeds while having lower % moisture content, but this feed was especially formulated for salmon growth.

The growth of the sablefish receiving different diets were similar in the first four weeks of the growth study, but after the fourth week, the growth of the fish receiving 100% shad diet saw lower growth rate compared to other diets. The cause of the reduced growth in fish receiving the 100% shad diet is unknown, but could have been caused by a nutrient deficiency that did not become apparent until fish doubled in size around Week 4 and depleted endogenous stores. Also, we observed a notable difference between the sardine meal and the in-house produced shad meal. The heated ball mill homogenizes, cooks, and grinds the shad in one easy step. Yet, despite the removal of unground bone particulate through a U.S. #8 mesh screen, some smaller bones remained. We did not attempt to grind the shad meal further and made the 50% and 100% shad diets using the meal produced.

The coarser texture of the shad meal may have contributed to the reduced growth observed in the 100% shad diet. This could also explain the lower digestibility of the shad meal compared to the sardine meal. All other indices measured also show fish receiving 100% shad diet had lower growth, lower feed efficiency, and lower TGC than the 0% and 50% shad diets. Furthermore, fish receiving 100% shad diet exhibited lower lipid and higher moisture content in their whole body.

Another factor that could affect the reduced growth rate observed in the 100% shad diet is a thiamine deficiency. Shad from the Columbia River are known to have high thiaminase activity (Wetzel et al. 2011), which can potentially induce low thiamine (vitamin B1) levels in predatory fish. Thiamine deficiency can result in sublethal effects and direct mortality, and has emerged as a possible contributor to decreased survival and reduced reproductive success in a variety of fish taxa (Harder et al. 2018), as well as decreased growth (Fitzsimons et al. 2009). The thiamin deficiency could have occurred around Week 4 of the study, which could have affected the growth of the juvenile sablefish receiving the 100% shad diet. We did not test for thiaminase levels in the shad meals; however, thiaminase in raw carp (*Hypophthalmichthys molitrix*), shad, and alewife (*Alosa pseudoharengus*) was found to be inactivated after 5 min at 180°F (82°C; Gnaedinger and Krzeczkowski 1966). The heated ball mill process (Nicklason et al. 2016) cooks, grinds, dries, pasteurizes, and mixes all the ingredients at low temperatures (70–100°C) in a single operation. Any thiaminase in the shad meal should have been inactive after this process. Currently, we lack the resources to replicate the experiment. However, if we were to repeat it, we would separate the oil from the shad meal, grind it to match commercially available sardine meal, pelletize the feed, and then reintroduce the oil. We believe this modified process would make the shad meal a more comparable alternative replacement for sardine meal.

4.3 Reference Diet

The reference diet, especially formulated for salmon growth, contains high levels of protein and lipids. We have used this diet for many years at the laboratory as a reference feed to ensure fish received from Manchester Research Station are exhibiting growth typical for juvenile sablefish. In this study, the fish receiving the reference diet had the lowest FI, while FE was the highest compared to other diets. The TGC, fish growth normalized for both size and temperature over time, was similar to the fish receiving the 100% shad diet. The fish receiving the reference feed saw similar growth compared to the 0% and 50% shad diets until the eighth week of the study, but the growth declined in the final two weeks of the study. While it is not known why the growth of the sablefish declined after the eighth week, the lower feed consumption likely affected the growth rate. The diet formulated for salmon growth, high in protein and lipid, may not be optimal for sablefish growth, and feed preference may have contributed to the lower feed consumption observed after the eighth week. Additional research is needed to verify this.

4.4 Summary

The demand for fishmeal and fish oil in aquaculture feeds has surged in recent years, and utilizing American shad as an alternative fish protein/oil for aquaculture appears promising. Non-native shad caught from the Columbia River were processed into fishmeal and fed to juvenile sablefish in a ten-week growth study. Nutritional values of shad meal were found to be comparable to the industry standard sardine meal, and fish grew well in both length and weight with no mortalities throughout the study. Juvenile sablefish receiving 50% shad meal saw comparable growth to the fish receiving sardine meal, while fish receiving 100% shad meal showed slightly lower growth compared to the sardine meal. The growth of fish receiving 100% shad meal was comparable to that of fish receiving a commercial salmon feed. Overall, our findings suggest that non-native American shad can serve as a viable and cost-effective alternative ingredient for juvenile sablefish. This and the potential for application to other widely cultured carnivorous fish species could alleviate pressures on industrial fisheries and enhance the environmental sustainability of aquaculture. Reducing or controlling shad populations could also benefit native fish species, including ESA-listed salmonids in the Pacific Northwest.

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