Affordable Nutrient Density of Aquatic Foods in the FAO uFISH Database Assessed Using Nutrient Rich Food (NRF) Indices

Emma Johnsson

A thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Public Health

University of Washington
2025

Committee:

Adam Drewnowski

Cristen Harris

Program Authorized to Offer Degree:

Nutritional Sciences

©Copyright 2025
Emma Johnsson

University of Washington

Abstract

Affordable Nutrient Density of Aquatic Foods in the FAO uFISH Database Assessed Using Nutrient Rich Food (NRF) Indices

Emma Johnsson

Chair of the Supervisory Committee:
Adam Drewnoski
Food Systems, Nutrition and Health Department

Background: Fish and shellfish have the potential to improve global public health by alleviating protein-energy malnutrition and closing micronutrient gaps. **Objectives**: To determine nutrient density of fish and shellfish in the FAO/INFOODS uFISH database using the Nutrient Rich Food (NRF) index and compare their affordability in relation to protein and priority micronutrient content. **Methods**: Two versions of NRF index were applied to the uFISH database. NRF6.2 was based on 6 priority micronutrients: iron, zinc, calcium, vitamin A, vitamin B12, and folate. NRF9.2, specifically tailored to fish and shellfish, used protein, calcium, iron, potassium, magnesium, selenium, vitamin A, vitamin D, and omega-3 fatty acids. Saturated fat and sodium were the 2 nutrients to limit. The NRF score was the sum of percent daily values (%DVs) for nutrients to encourage minus the sum of %DVs for nutrients to limit, capped at 100%. Food prices were obtained from GlobeFish. Affordability was calculated as protein and nutrients per penny. **Results**: The NRF6.2 score identified mollusks, and especially bivalves, as the best aquatic source of priority micronutrients. The NRF9.2b identified small pelagic fish as the most nutrient rich, followed by bivalves. Mollusks scored higher compared to finfish and crustaceans. Mackerel, tilapia, squid, and mussels provided the most protein per penny. Mackerel and tilapia provided the most NRF6.2 and NRF9.2b nutrients per penny. **Conclusion**: Fish and shellfish are an affordable source of protein, omega-3, and priority micronutrients. Disaggregating species within the broad seafood category reveals differences in cost and nutrient density, with mackerel, tilapia, squid, and mussels earning the highest scores.

Keywords Nutrient profiling, affordability, price index, Nutrient Rich Food (NRF) index, seafood, aquatic foods, fish, shellfish, aquaculture, micronutrients

1. Introduction

Micronutrient shortfalls and protein-energy malnutrition continue to challenge global public health (Passarelli et al., 2024). Populations of lower- and lower middle-income countries (LMIC) are affected the most (Beal & Ortenzi, 2022). Diets that are inadequate in iron, zinc, folate, iodine, selenium, vitamin A, and vitamin B12 are more common among women and young children (Passarelli et al., 2024). Dietary inadequacies have been linked to child stunting, anemia, blindness, and impaired cognitive development, and later-life osteoporosis and heart disease (Weffort & Lamounier, 2023). Protein-energy malnutrition is reported to affect nearly 150 million people worldwide (Jiang et al., 2023).

Nutrient-rich aquatic foods have the potential to alleviate nutrient deficiencies and protein-energy malnutrition. Global production of seafood reached a record high of 223.2 million tons in 2022 (FAO, 2024c). FAO food balance sheets indicate that the amount of aquatic foods available for human consumption reached a mean of 20.6 kg/capita/year (FAO, 2024a). However, about 12.6 kg/capita/year (or 73%) was consumed in upper middle-income and high-income countries. The amount of fish and seafood in lower- and lower middle-income countries (LMIC) was estimated at 5.3 kg/capita/year. In some lower-income countries, seafood was the main source of animal protein (FAO, 2024a), being less costly than meat or dairy.

The potential for aquatic foods to assure healthy diets across LMIC remains largely untapped (FAO, 2024b). Seafood is particularly rich in iron, calcium, zinc, selenium, iodine, and vitamin B12 (Viana et al., 2023) and is a sustainable source of high quality protein (Byrd et al., 2022). Omega-3 fatty acids from fish and seafood, are important for infant brain development (Banaszak et al., 2024; Swanson et al., 2012). One serving of powder made from dried small fish provides 20% or more of the daily recommendation for calcium and 37% or more of the daily DHA recommendation for children and pregnant or lactating women (Byrd et al., 2021).

This study assessed affordable nutrient density of fish and seafood in the FAO/INFOODS Global Food Composition Database for Fish and Shellfish (uFISH) (*INFOODS: FAO/INFOODS Databases*, 2016). Two versions of the Nutrient Rich Food (NRF) index, a validated nutrient profiling model (Drewnowski, 2009), were the measures of nutrient density. Analyses stratified fish and shellfish by phylum, subphylum, or biological distinction (finfish, crustaceans, and mollusks). We also created an NRF Affordability Index for Fish and Shellfish by linking NRF nutrient profiles with available retail prices from GlobeFish (FAO, 2024d). Integrating nutrient density metrics with cost opens the door to future assessments of affordable nutrient density, a key theme for the FAO (Anna Herforth et al., 2020). This study was the first to assess nutrient density of aquatic foods in the uFISH database and to explore relations between nutrient density and cost.

2. Methods

2.1 Nutrient composition database

The FAO/INFOODS Global Food Composition Database for Fish and Shellfish (uFISH) (*INFOODS: FAO/INFOODS Databases*, 2016) provides reliable, globally sourced data for the energy and nutrient content of fish, crustaceans, and mollusks. A total of 515 food items are included, covering 78 unique fish and shellfish species. The data are expressed per 100 grams edible portion of each aquatic food. Available are data on energy (kcal/100g), macronutrients, including protein and amino acids, fats and fatty acids, including omega-3 fatty acids, and vitamins and minerals. The FAO database was developed to enable countries and researchers to incorporate more comprehensive data on fish and shellfish into food composition tables. The FAO database includes underutilized but nutritionally important fish, and codes each item by species, habitat, and capture method. The FAO/INFOODS uFISH is the most comprehensive resource to date, along with databases from Denmark (The National Food Institute, & Technical University of Denmark, 2024), Japan (MEXT, 2015), and the US (USDA, ARS, 2024).

The uFISH database was missing some nutrient values for some aquatic foods. Comparable aquatic foods were identified in the USDA Food and Nutrient Database for Dietary Studies 2021-2023 and those nutrient values were used to fill in missing data wherever possible. Values were imputed from Frida (The National Food Institute, & Technical University of Denmark, 2024), a Danish food database, if no comparable USDA data were available.

2.2 Stratification by groups

Aquatic foods were organized into categories as shown in Supplementary Table 1. Aquatic foods were classified by phylum, subphylum, or biological distinction (finfish, crustaceans, and mollusks). Finfish and mollusks were further organized into 7 broad taxonomic groups. The finfish groups were small pelagic (n = 12), cichlid (n = 24), demersal (n = 96), and salmonid (n = 69). Mollusk taxonomic groups were bivalve (n = 66), gastropod (n = 12), and cephalopod (n = 36). Aquatic foods were also assigned to 21 categories by species, namely abalone, bass, catfish, clam, cod, conch, crab, crayfish, lobster, mackerel, mussel, octopus, oyster, pike, salmon, scallop, shrimp or prawn, sole, squid, tilapia and trout. The uFISH database also classifies aquatic foods by state (cooked, raw, and preserved), habitat (farmed versus wild), and habitat salinity (freshwater versus saltwater).

2.3 Nutrient profiling

The Nutrient Rich Food Index (NRF) is calculated using two subscores: NRn, based on nutrients to encourage, and LIM, based on nutrients to limit. Two versions of the NRF were applied to the FAO aquatic foods database: NRF6.2 and NRF9.2b. The two nutrients to limit (LIM) for this analysis were sodium and saturated fat. This food category does not contain added sugar and added sugar data were not available.

The NRF6.2 score was based on 6 priority micronutrients, identified as lacking in diets of LMIC (Beal et al., 2017), namely iron, zinc, calcium, vitamin A, vitamin B12, and folate. The classic NRF9.2 score was based on protein, fiber, calcium, iron, potassium, magnesium, vitamin A, vitamin C, and vitamin D. Aquatic foods contain negligible amounts of fiber and vitamin C. Hence, a new variant called NRF9.2b was developed to capture the unique nutritional qualities of aquatic foods, that included protein, selenium, calcium, iron, potassium, magnesium, vitamin A, vitamin D, and omega-3 fatty acids. No corrections for protein digestibility were completed as all seafood is a complete source of protein (Durazzo et al., 2022).

The NRF scores were calculated by obtaining the sum of percent daily values (%DVs) of nutrients to encourage minus the sum of %DVs for saturated fat and sodium (LIM). The percent daily value was calculated as the daily value provided per 100 g and capped at 100%. Reference daily values for micronutrients included in the NRF6.2 and NRF9.2b were those used by the US Food and Drug Administration (Program, 2024).

2.4 Protein Affordability and NRF Price Indices

Price data were obtained from the FAO Globefish price dashboard and European price report for October 2024 (FAO, 2024d). Aquatic food species groupings were matched with similar items in the price report. Prices were converted from Euro to USD using the exchange rate as of October 2024 (1.09) (Federal Reserve, n.d.). Abalone and crayfish were excluded as no price data was available. Approximate percent yields were obtained from the USDA Agriculture Handbook No. 102 and used to calculate the cost of each item per kg edible portion (EP) (USDA Agricultural Resarch Service, 1975). Cost per 100 g protein was calculated for each species grouping and broad taxonomic group by dividing the cost per 100 g EP by the mean grams of protein per 100 g. Affordability was calculated by dividing the mean NRF score by the cost per kg EP.

2.5 Statistical analyses

Statistical analysis compared nutrient content of aquatic foods by phylum, habitat, biological, ecological and taxonomic groups. Mean, median, and standard deviations of specific nutrients including protein, amino acids, fatty acids, vitamins, and minerals as well as of NRF6.2 and NRF9.2b were calculated for each aquatic food group. SPSS (Statistical Package for the Social Sciences v 16.0), JMP Pro (v 17 and v 18), and R version 4.4.1 were used for statistical analyses. Tests of significance were based on one-way ANOVA to reveal statistically significant differences between group means. Tukey's HSD post-hoc tests between paired groups to determine which specific groups differ significantly from one another for each nutrient or NRF score. The significance level for all statistical tests was $\rho < 0.05$.

3. Results

3.1 Nutrient density of Finfish, Mollusks, and Crustaceans

Table 3.1 shows the mean values (M) and standard deviations (SD) of select minerals, vitamins, and omega-3s per 100 grams EP by aquatic food category. There were significant differences between groups for all nutrients. Mollusks were higher than finfish and crustaceans in most minerals, including iron ($p < 0.0001$), zinc ($p < 0.0001$), magnesium ($p < 0.0001$), and selenium ($p < 0.0001$). Mollusks and crustaceans contained similar levels of calcium. Finfish were higher in potassium than mollusks ($p < 0.0001$) and crustaceans ($p < 0.0001$). Crustaceans were higher than finfish in iron ($p = 0.0006$), zinc ($p = 0.008$), magnesium ($p = 0.002$), and selenium ($p < 0.0001$).

Mollusks were also the highest in Folate and Vitamin B12 compared to finfish and crustaceans (all $p < 0.0001$). Finfish and crustaceans were similar in vitamin B12 content, but crustaceans were higher in folate than finfish ($p = < 0.0001$), although no seafood category was a good source of folate (<10% DV). Mollusks were higher in vitamin A than crustaceans ($p < 0.0001$) with finfish containing the least vitamin A. Finfish were highest in vitamin D ($p < 0.0001$) and were also higher than crustaceans ($p < 0.0001$) and mollusks ($p = 0.051$) in omega-3 fatty acids. Mollusks and crustaceans contained similar amounts of vitamin D, but mollusks were significantly higher in omega-3s compared to crustaceans ($p < 0.0001$).

Table 3.1 also shows mean NRF6.2 and NRF9.2b scores by aquatic food category. Mollusks scored higher than crustaceans on both NRF6.2 ($p < 0.0001$) and NRF9.2b ($p < 0.0001$). Crustaceans scored higher than finfish on NRF6.2 ($p < 0.0001$) and NRF9.2b ($p = 0.005$).

	Crustacean (N=152)		Finfish (N=249)		Mollusk (N=114)		
	Mean	SD	Mean	SD	Mean	SD	P-value
Protein (g)	20.1[b]	3.09	21.5[a]	2.74	19.5[b]	10.0	.0014
Iron (mg)	1.16[b]	0.89	0.59[c]	0.58	4.38[a]	2.84	<.0001
Zinc (mg)	2.63[b]	1.45	0.88[c]	1.48	8.06[a]	11.78	<.0001
Calcium (mg)	98.91[a]	119.43	24.25[b]	18.31	117.82[a]	121.72	<.0001
Potasssium (mg)	281[b]	84.0	369[a]	71.1	303[b]	132	<.0001
Magnesium (mg)	44.0[b]	13.6	28.6[c]	4.60	96.0[a]	91.4	<.0001
Selenium (mcg)	45.93[b]	15.52	29.26[c]	13.11	65.96[a]	33.59	<.0001
Folate (mg)	20.3[b]	14.1	9.41[c]	3.22	29.6[a]	30.5	<.0001
Vitamin B12 (mcg)	4.10[b]	2.92	3.60[b]	2.93	16.42[a]	11.89	<.0001
Vitamin A (mcg)	18.87[b]	18.27	9.44[c]	7.58	41.99[a]	32.41	<.0001
Vitamin D (mcg)	0.00[b]	0.00	6.89[a]	8.27	0.18[b]	0.38	<.0001
Omega-3 (g)	0.20[b]	0.10	0.81[a]	0.94	0.63[a]	0.46	<.0001
NRF6.2	123.76[b]	33.83	85.20[c]	31.19	161.95[a]	55.78	<.0001
NRF9.2b	167.19[b]	27.27	153.01[c]	51.36	214.09[a]	43.92	<.0001

Table 3.1 Nutrient content per 100g and NRF scores of Crustaceans, Finfish, and Mollusks *Note.* Means within rows that do not share a superscript letter are significantly different at the $p<.05$ level based on Tukey's HSD post hoc tests.

Figure 3.1 displays nutrients provided per 100g of Crustaceans, Finfish, and Mollusks in mean percent daily value (%DV). The sum of the %DV is used to calculate NRF scores, so the stacked bar chart format used in Figure 3.1 helps visualize which nutrients contribute most to differences in NRF scores between categories. Both mollusks and crustaceans were excellent sources (>20% DV) of zinc, while finfish was a poor source (<10%) of zinc. Only mollusks were an excellent source of iron, and only finfish were an excellent source of vitamin D. Crustaceans and mollusks were good sources of calcium (>10%). All seafood categories were excellent sources of selenium, vitamin B12, and protein. Finfish and mollusks were both excellent sources of omega-3 fatty acids.

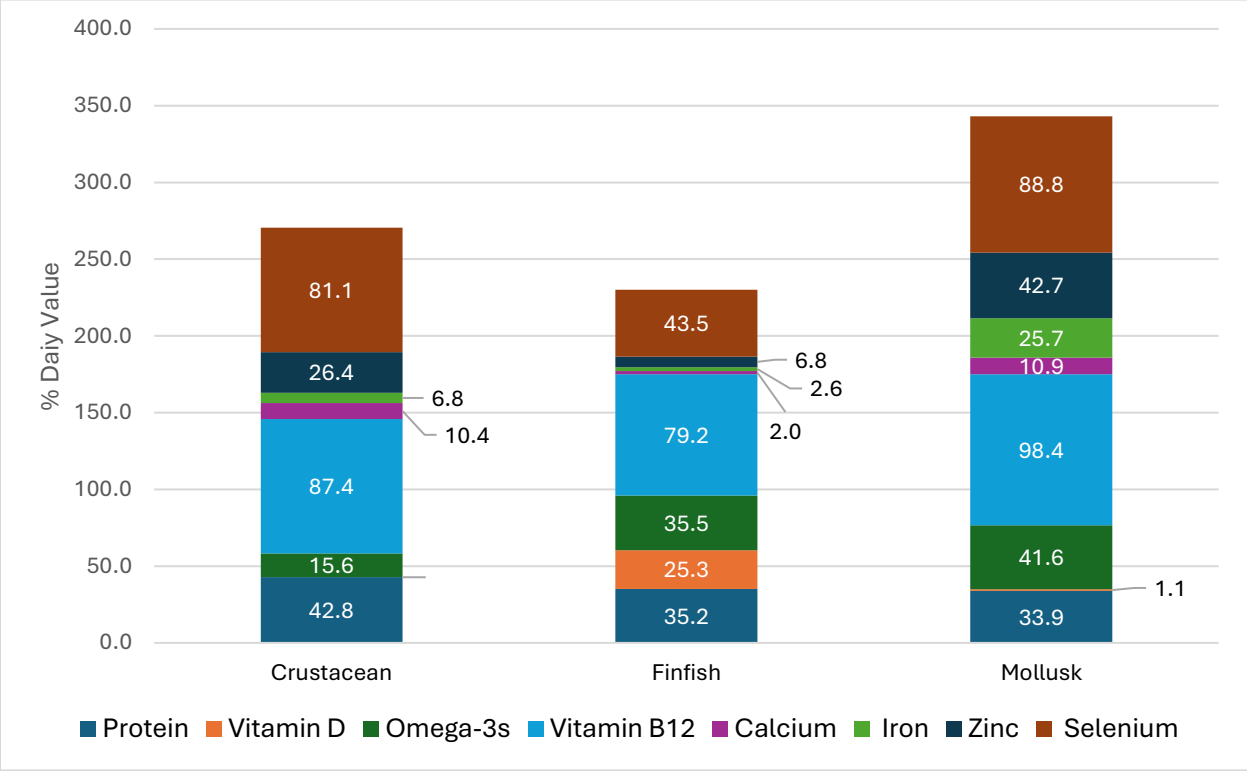


Figure 3.1 Mean % DV Nutrients Provided per 100 g by Aquatic Food Category

3.2 Assessing Finfish, Mollusks, and Crustaceans by broad taxonomic group and capture method

Separating crustaceans, finfish, and mollusks into broad taxonomic groups showed differences in nutrient density amongst Finfish (Table 3.2.1) and Mollusks and Crustaceans (Table 3.2.2).

Bivalves were highest in iron, significantly higher than all other broad taxonomic groups (all $p<0.0001$) besides gastropods ($p=0.4211$) which were the second highest in iron, followed by cephalopods. Gastropods were significantly higher in iron compared to crustaceans, cichlids, demersal fish, and small pelagic fish (all $p<0.0001$), but not significantly higher in iron than cephalopods ($p = 0.0673$). Bivalves and gastropods were highest in zinc. Bivalves were significantly higher in zinc compared to all other groups of finfish, crustaceans, and mollusks (all

p<0.0001) except for gastropods (p=0.1130). Gastropods were significantly higher than any other group in calcium (all p<0.0001). Bivalves and crustaceans were higher in calcium than cephalopods and all finfish (all p<0.05) besides small pelagic fish which contained similar amounts of calcium as crustaceans (p = 0.2022). Cephalopods, small pelagic fish, salmonids, and cods were significantly higher in potassium than cichlids, demersal fish, bivalves, and crustaceans (all p<0.05). Gastropods were significantly higher than all other groups in magnesium (all p <0.0001). Bivalves and cephalopods were the second highest and contained significantly more magnesium than any crustacean or finfish group (all p<0.05). There were no significant differences in magnesium between finfish groups (all p >0.05). Small pelagic fish, bivalves, and cephalopods were highest in selenium, significantly higher than all other groups (all p<0.05). Excluding small pelagic fish, crustaceans were higher in selenium compared to all other finfish groups (all p<0.0001).

Aquatic foods are not typically good sources of folate. However, bivalves were significantly higher in folate (all p<0.0001), vitamin B12 (all <0.05), and vitamin A compared to all other groups. Cephalopods were the second highest in vitamin B12, significantly higher in B12 than crustaceans (p <0.0001) and all finfish (all p<0.0001) besides small pelagic fish (p = 0.6496). Cephalopods were the second highest in vitamin A and were significantly higher in vitamin A than any group of finfish (all p<0.05), but not significantly higher in vitamin A than crustaceans (0.2263) or gastropods (0.4473). Amongst finfish, all groups were similar in vitamin A content besides cod which was significantly lower in vitamin A compared to salmonids (p=0.0072) and demersal fish (p=0.0169).

Small pelagic fish were significantly higher in vitamin D than any other group (all p<0.0001). Cichlids and salmonids were significantly higher in vitamin D than any other group (all p<0.0001) besides small pelagic fish. Cichlids were a better source of vitamin D than salmonids (p <0.0001). Small pelagic fish and salmonids contained similar amounts of omega-3 fatty acids (p = 0.3978), more than any other group (all p <0.0001). Bivalves and cephalopods contained more omega-3s than crustaceans, gastropods, demersal fish, cods, and cichlids (all p<0.05).

Table 3.2.1 and Table 3.2.2 also display the mean NRF6.2 and NRF9.2b scores by broad taxonomic group. Bivalves scored higher than any other group on NRF6.2 (all p <0.0001). Cephalopods and crustaceans scored higher on the NRF6.2 compared to gastropods (both p <0.05) and any finfish group (all p <0.05) besides small pelagic fish. Small pelagic fish scored similarly to crustaceans (p =0.4791) and cephalopods (p =0.1927) on the NRF6.2. Small pelagic fish score the highest on the seafood specific score, NRF 9.2b, significantly higher than any other group (all p<0.0001), followed by bivalves which scored significantly higher than all other groups (all p<0.05) besides cichlids (p=0.9069) which scored the third highest, followed by cephalopods.

	Cichlid (N=24)		Cod (N= 48)		Demersal (N = 96)		Small Pelagic (N=12)		Salmonid (N = 69)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	P- value
Protein (g)	20.9^{cd}	2.25	21.6^{cd}	2.58	20.7^{cd}	2.91	23.8^{bcd}	3.51	22.5^{c}	2.03	<.0001
Iron (mg)	1.02^{cd}	1.01	0.20^{d}	0.07	0.71^{cd}	0.62	1.24^{cd}	0.19	0.45^{d}	0.19	<.0001
Zinc (mg)	1.85^{b}	2.83	0.45^{b}	0.07	1.12^{b}	1.80	0.52^{b}	0.09	0.57^{b}	0.23	<.0001
Calcium (mg)	40.8^{d}	45.5	16.2^{d}	7.41	27.7^{d}	13.4	38.4^{cd}	12.0	17.7^{d}	7.53	<.0001
Potasssium (mg)	321^{bc}	43.6	394^{a}	67.5	337^{b}	65.2	433^{a}	67.1	402^{a}	58.3	<.0001
Magnesium (mg)	30.1^{cd}	4.52	29.0^{d}	4.09	27.6^{d}	4.95	35.2^{cd}	5.23	28.3^{d}	3.13	<.0001
Selenium (mcg)	29.3^{c}	7.07	30.8^{c}	5.53	27.9^{c}	14.0	66.2^{a}	8.60	23.6^{c}	4.99	<.0001
Folate (mg)	12.5^{bc}	1.13	9.65^{c}	2.13	10.2^{c}	2.21	2.13^{c}	0.19	8.34^{c}	3.55	<.0001
Vit. B12 (mcg)	1.31^{d}	0.21	1.47^{d}	0.48	4.10^{cd}	3.88	7.81^{bc}	0.74	4.44^{cd}	0.87	<.0001
Vit. A (mcg)	2.63^{de}	3.61	1.89^{e}	0.57	12.4^{cd}	8.20	4.80^{cde}	0.59	13.8^{cd}	4.34	<.0001
Vitamin D (mcg)	21.0^{b}	1.07	1.44^{d}	0.77	1.50^{d}	1.31	30.1^{a}	3.75	9.23^{c}	3.21	<.0001
Omega-3 (g)	0.16^{c}	0.10	0.26^{c}	0.10	0.37^{b}	0.30	1.56^{a}	0.88	1.89^{a}	1.02	<.0001
NRF6.2	75.5^{cd}	37.0	69.3^{d}	21.1	89.6^{c}	39.9	103^{bcd}	2.85	90.5^{c}	15.3	<.0001
NRF9.2b	219^{bc}	17.2	153de	14.6	120^{f}	39.9	289^{a}	9.39	152^{e}	28.6	<.0001

Table 3.2.1 Nutrient content per 100g of Finfish by Broad taxonomic group *Note.* Means within rows that do not share a superscript letter are significantly different at the p<.05 level based on Tukey's HSD post hoc tests.

	Crustacean (N=152)		Bivalve (N= 66)		Cephalopod (N = 36)		Gastropod (N=12)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	P-Value
Protein (g)	20.1^{d}	3.09	13.6^{e}	5.74	25.2^{b}	6.48	34.8^{a}	11.6	<.0001
Iron (mg)	1.16^{c}	0.89	5.21^{a}	3.12	2.88^{b}	1.95	4.27^{ab}	1.26	<.0001
Zinc (mg)	2.63^{b}	1.45	10.6^{a}	14.9	4.10^{b}	2.27	5.76^{ab}	3.19	<.0001
Calcium (mg)	98.9^{bc}	119	117^{b}	73.5	44.5^{d}	20.1	344^{a}	213	<.0001
Potasssium (mg)	281^{c}	84.0	240^{d}	98.5	408^{a}	129	334^{abc}	92.3	<.0001
Magnesium (mg)	44.0^{c}	13.6	67.7^{b}	31.1	79.5^{b}	24.3	301^{a}	163	<.0001
Selenium (mcg)	45.9^{b}	15.5	63.5^{a}	37.7	74.1^{a}	21.8	27.9^{bc}	6.34	<.0001
Folate (mcg)	20.3^{b}	14.1	40.9^{a}	35.8	16.2^{bc}	5.72	7.44^{bc}	1.08	<.0001
Vitamin B12 (mcg)	4.10^{cd}	2.92	19.8^{a}	11.0	11.2^{b}	11.6	5.38^{bcd}	0.95	<.0001
Vitamin A (mcg)	18.9^{bc}	18.3	55.2^{a}	35.7	26.9^{b}	14.1	14.6^{bcde}	1.29	<.0001
Vitamin D (mcg)	0.00^{e}	0.00	0.25^{e}	0.44	0.09^{e}	0.26	0.00^{de}	0.00	<.0001
Omega-3 (g)	0.20^{c}	0.10	0.66^{b}	0.39	0.74^{b}	0.56	0.12^{c}	0.01	<.0001
NRF6.2	124^{b}	33.8	192^{a}	50.0	132^{b}	24.2	84.8^{cd}	16.2	<.0001
NRF9.2b	167^{d}	27.3	229^{b}	45.6	207^{c}	15.2	150de	27.8	<.0001

Table 3.2.1 Nutrient content per 100g of Crustaceans and Mollusks by Broad taxonomic group *Note.* Means within rows that do not share a superscript letter are significantly different at the p<.05 level based on Tukey's HSD post hoc tests.

Table 3.2.3 shows differences in nutrient content of finfish by capture method. Wild fish were significantly more rich in iron, zinc, vitamin B12, potassium, magnesium, and selenium than farmed finfish (all $p < 0.05$). Farmed fish were significantly higher than wild finfish in vitamin A ($p = 0.022$) and total fat (<0.0001). Farmed and wild finfish contained similar levels of calcium, folate, vitamin D, and omega 3. However, wild fish had a significantly higher ratio of omega-3 to total fat (p<.0001). Overall, wild fish scored higher than farmed fish on both the NRF6.2 (p <0.0001) and NRF 9.2b (p <0.0001) (Table 3.2.3).

	Farmed (N=132)		Wild (N=117)		
	Mean	SD	Mean	SD	P-value
Protein (g)	21.30	2.79	21.80	2.67	0.146
Iron (mg)	0.52[b]	0.31	0.68[a]	0.77	0.036*
Zinc (mg)	0.60[b]	0.30	1.19[a]	209	0.002*
Calcium (mg)	22.31	19.10	26.55	17.12	0.072
Potassium (mg)	350.48[b]	66.59	389.60[a]	70.49	<.0001*
Magnesium (mg)	26.97[b]	3.73	30.52[a]	4.77	<.0001*
Selenium (mcg)	24.51[b]	9.83	34.62[a]	14.27	<.0001*
Folate (mcg)	9.28	3.15	9.55	3.31	0.510
Vitamin B12 (mcg)	2.94[b]	1.48	4.34[a]	3.85	0.0001*
Vitamin A (mcg)	10.47[a]	5.36	8.38[b]	9.37	0.022*
Vitamin D (mcg)	6.50	6.61	7.33	9.82	0.434
Omega-3 (g)	0.88	0.99	0.72	0.87	0.1842
Total fat (g)	6.90[a]	4.96	3.24[b]	3.57	<.0001*
Omega-3: Total fat	0.12[b]	0.10	0.25[a]	0.09	<.0001*
NRF6.2	75.90[b]	30.64	95.69[a]	28.47	<.0001*
NRF9.2b	64.91[b]	36.94	85.77[a]	33.94	<.0001*

Table 3.2.3 Nutrient content of Finfish by Capture method *Note.* Superscripts and * indicate significant differences between mean nutrient values at the p<.05 level in farmed versus wild finfish based on one-way ANOVA tests.

Figure 3.2 displays nutrients provided per 100g by broad taxonomic group in mean percent daily value (%DV), the metric that is used to calculate NRF scores. All groups were excellent sources (>20% DV) of selenium, vitamin B12, and protein. Bivalves, gastropods, cephalopods, and crustaceans were excellent sources of zinc. Only gastropods were an excellent source of calcium. Small pelagic fish, cichlids, and salmonids were excellent sources of vitamin D. Bivalves, cephalopods, demersal fish, small pelagic fish, and salmonids were all excellent sources of omega-3 fatty acids. Only bivalves were an excellent source of iron, while cephalopods and gastropods were good sources of iron (>10% DV).

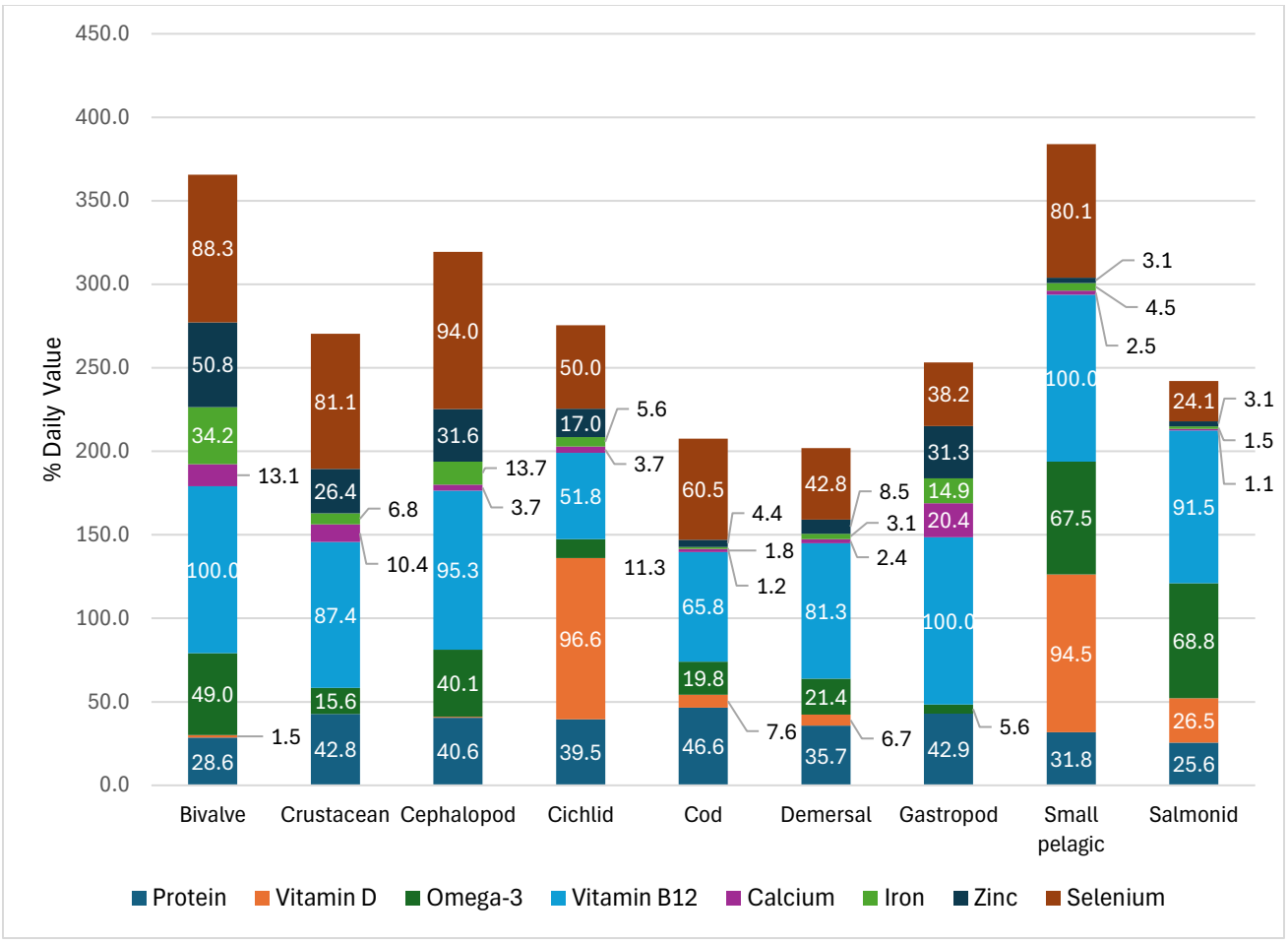


Figure 3.2 Mean %DV Protein and Micronutrients Provided by Broad Taxonomic Group

3.3 Comparing nutrient content by Species Groups

Further separating crustaceans, finfish, and mollusks into species groups showed differences in nutrient density within each species group (Table 3.3.1 and Table 3.3.2).

Table 3.3.1 shows the nutrient content of aquatic foods per 100 grams EP by species grouping. The table is color coded based on percent daily value (%DV): Green indicates that the species group is an excellent source of a nutrient, providing >20% DV per 100 gram serving, yellow indicates that the species group is a good source of a nutrient, providing >10% DV, and red indicates that the species group is a poor source of a nutrient, providing <10% DV.

Conch, mussels, octopus and oysters were excellent sources of both iron and zinc (Table 3.3.1). Oysters were significantly higher in zinc than any other species (all $p < 0.0001$). Clams and abalone were excellent sources of iron and good sources of zinc. Clams were significantly higher in iron than any other species (all $p < 0.0001$). Apart from clams, mussels, conch, oysters, and octopus contained more iron than all other species (all $p < 0.05$) besides abalone. All crustacean

species were good or excellent sources of zinc, but poor sources of iron. Clams and conch were excellent sources of calcium, while crab, oysters and shrimp were good sources of calcium. All species were good or excellent sources of potassium and magnesium. Mackerel, squid, and trout provided significantly more potassium than catfish, tilapia, clams, mussels, oysters, and any crustacean species (all $p < 0.05$). Conch provided more magnesium than any other species (all $p < 0.0001$). All species were excellent sources of selenium and vitamin B12 (Table 3.3.1), with clams being significantly higher than any other species in both selenium (all $p < 0.0001$) and vitamin B12 (all $p < 0.0001$). Octopus, squid, mussels and mackerel contained significantly more selenium than all species (all $p < 0.05$) besides clams. Apart from clams, octopus and oysters were significantly higher in vitamin B12 than all species (all $p < 0.0001$) other than lobster.

Most aquatic species were poor sources of vitamin A except for clams and mussels which were good sources of vitamin A (Table 3.3.1). Clams provided significantly more vitamin A than mussels ($p = 0.0265$), and mussels provided significantly more vitamin A than any other species (all $p < 0.0001$) apart from clams. All crustacean and mollusk species were poor sources of vitamin D. Mackerel, salmon, tilapia, and trout were excellent sources of vitamin D. Mackerel was higher in vitamin D than any other species (all $p < 0.0001$), and tilapia was higher in vitamin D than any other species (all $p < 0.0001$) apart from mackerel. All bivalve and cephalopod species were excellent sources of omega-3s. Gastropods, abalone and conch, were poor sources of omega-3s. Crustaceans were good sources of omega-3s, and finfish were good or excellent sources of omega-3s. Salmon was significantly higher in omega-3 fatty acids than any other species ($p < 0.05$). Mackerel was significantly higher in omega-3s than any other species (all $p < 0.0001$) apart from salmon.

Legend
>20% DV / 100 g
10-20% DV / 100 g
<10% DV /100 g

Species group	N	Iron (mg) Mean	SD	Zinc (mg) Mean	SD	Calcium (mg) Mean	SD	Potassium (mg) Mean	SD	Magnesium (mg) Mean		Selenium (mcg) Mean	SD	Vit. B12 (mcg) Mean	SD	Vit. A (mcg) Mean	SD	Vit. D (mg) Mean	SD	Omega 3 (g) Mean	SD
Crab	40	0.93^{efg}	0.69	4.49^{b}	1.35	112^{cde}	48.8	274^{f}	83.6	48.9^{eg}	16.2	48.8^{de}	10.6	7.65^{e}	2.13	35.3_{c}	23.3	0.00^{f}	0.00	0.23^{g}	0.06
Crayfish	12	1.29^{defg}	0.92	1.51^{bcd}	0.42	39.8^{cdef}	17.6	283^{def}	38.2	28.8^{fgh}	2.24	35.6^{efg}	6.68	1.94^{ghi}	0.19	15.4^{defgi}	0.67	0.00^{ef}	0.00	0.16^{g}	0.02
Lobster	24	0.88^{efg}	0.75	2.66^{bcd}	0.6	57.0^{cdef}	15.5	328^{bcdef}	73.3	37.3^{efgh}	10.3	59.3^{cd}	19.2	1.34^{hi}	0.41	5.72^{ghi}	2.04	0.00^{f}	0.00	0.24^{g}	0.18
Shrimp /Prawn	76	1.35^{def}	0.98	1.82^{bcd}	0.65	114^{cd}	161	270^{f}	88.6	45.9^{efg}	11.6	41.8^{ef}	14.5	3.44^{fg}	2.11	14.9^{efg}	13.1	0.00^{f}	0.00	0.18^{g}	0.09
Bass	12	1.04^{defg}	0.10	0.79^{bcd}	0.11	25.2^{f}	8.08	393^{abcd}	55.1	32.7^{efgh}	3.21	25.4^{g}	3.77	3.93^{fghi}	0.5	13.6^{defghi}	5.92	3.72^{d}	0.38	0.83^{cde}	0.20
Catfish	64	0.76^{fg}	0.71	1.27^{cd}	2.19	25.1^{f}	13	310^{def}	51.4	25.8^{h}	4.67	27.3^{g}	14.8	2.63^{ghi}	1.42	12.9^{efg}	9.42	0.80^{ef}	0.57	0.33^{g}	0.29
Cod	48	0.20^{g}	0.07	0.45^{d}	0.07	16.2^{f}	7.41	394^{ab}	67.5	29.0^{h}	4.09	30.8^{g}	5.53	1.47^{h}	0.48	1.89^{i}	0.56	1.44^{e}	0.77	0.26^{g}	0.10
Mackerel	12	1.24^{defg}	0.19	0.52^{bcd}	0.09	38.4^{def}	12	433^{a}	67.1	35.2^{efgh}	5.23	66.2^{bc}	8.6	7.81^{e}	0.74	4.8^{fghi}	0.59	30.1^{a}	3.75	1.56^{b}	0.88
Pike	12	0.21^{fg}	0.06	0.97^{bcd}	0.1	32^{ef}	3.51	405^{abc}	63.3	29.2^{fgh}	2.96	33.7^{efg}	19.3	13.7^{d}	1.22	12.7^{efghi}	0.87	3.47^{d}	0.31	0.21^{g}	0.05
Salmon	41	0.45^{g}	0.21	0.50^{d}	0.11	14.4^{f}	4.83	396^{ab}	58	28^{h}	2.96	25.9^{g}	4.61	4.7^{f}	0.98	11.1^{efghi}	3.35	9.38^{c}	3.6	2.61^{a}	0.67
Sole	8	0.51^{defg}	0.15	0.56^{bcd}	0.09	44.3^{cdef}	19.4	363^{abcdef}	46.9	31.3^{efgh}	3.52	27.6^{fg}	3.77	1.75^{fghi}	0.37	5.52^{efghi}	0.49	0.83^{ef}	0.07	0.26^{fg}	0.06
Tilapia	24	1.02^{defg}	1.01	1.85^{bcd}	2.83	40.8^{f}	45.5	321^{cdef}	43.6	30.1^{fh}	4.52	29.3^{g}	7.07	1.31^{hi}	0.21	2.63^{hi}	3.61	21.0^{b}	1.07	0.16^{g}	0.10
Trout	28	0.46^{fg}	0.17	0.67^{d}	0.32	22.6^{f}	8.21	410^{a}	58.7	28.6^{h}	3.39	20.3^{g}	3.4	4.05^{fg}	0.49	17.8^{def}	1.9	9.00^{c}	2.88	0.82^{ce}	0.00
Abalone	3	3.34^{bcde}	0.76	1.4^{bcd}	0.34	42.8^{cdef}	10.4	$291^{abcdefg}$	69.3	74.5^{bcde}	16.8	27.9^{efg}	6.34	5.38^{efghi}	0.95	$13.6^{cdefghi}$	2.61	0.00^{ef}	0.00	0.10^{dfg}	0.00
Conch	9	4.58^{bc}	1.27	7.22^{b}	2.11	445^{a}	130	348^{abcdef}	98	377^{a}	104	NA	NA	NA	NA	15.0^{defghi}	0	0.00^{ef}	0.00	0.12^{g}	0.00
Clams	6	9.17^{a}	2.03	1.69^{bcd}	0.37	282^{b}	68.9	256^{efg}	54.6	104^{b}	21.0	160^{a}	34.1	46.7^{a}	7.34	102^{a}	17.6	0.00^{f}	0.00	0.44^{cdefg}	0.30
Mussels	27	5.84^{b}	3.49	3.01^{bcd}	1.58	75.8^{cdef}	30.5	256^{f}	85.8	73.9^{bc}	23.1	67.6^{bc}	13.2	15.1^{d}	4.96	83.2^{b}	16.2	0.00^{f}	0.00	0.70^{cdef}	0.29
Oysters	27	4.54^{c}	1.88	22^{a}	17.9	126^{c}	56.1	182^{g}	52.6	55.0^{de}	34.8	45.6_{ef}	18.6	21.8^{c}	4.51	26.9cd	15	0.61^{ef}	0.49	0.74^{cde}	0.47
Scallops	6	1.48^{defg}	0.67	2.89^{bcd}	0.9	91.4^{cdef}	33.2	408^{abcde}	129	60.6^{cdefg}	17.8	28.7^{efg}	12.5	4.49^{efghi}	1.44	9.9^{defghi}	8.8	0.00^{ef}	0.00	0.33^{defg}	0.22
Octopus	12	4.12^{c}	1.44	6.03^{bc}	2.33	57.4^{cdef}	14.7	382^{abcde}	96.1	96.2^{b}	25.1	79.5^{b}	21.2	26.6^{c}	6.42	39^{c}	8.49	0.25^{ef}	0.38	0.36^{dfg}	0.12
Squid																					

Table 3.3.1 Nutrient content per 100g by phylum and species group

Note. Means within rows that do not share a superscript letter are significantly different at the p<.05 level based on Tukey's HSD post hoc tests.

Table 3.3.2 displays NRF6.2 and NRF9.2b scores by species groups. Oysters scored the highest on the NRF6.2, significantly higher than any other species ($p < 0.0001$) besides clams ($p = 0.877$) which scored the second highest. On the NRF9.2b, the seafood specific score, oysters, clams and mussels still score highly, but mackerel stand out as the highest scoring aquatic food. Mackerel scored significantly higher than any other species (all $p < 0.0001$) besides clams ($p = 1.000$). Tilapia scored much higher on the NRF9.2b than the NRF6.2 with a significantly higher score than all species ($p < 0.05$) besides mackerel, clams, oysters, and mussels which score higher, and squid ($p = 0.9937$) and octopus ($p = 0.9992$) which score similarly.

		NRF6.2		NRF9.2b	
Species group	N	Mean	SD	Mean	SD
Crab	40	160^{bc}	9.07	183^{fg}	19.6
Crayfish	12	137^{cd}	11.3	176^{efghi}	15.7
Lobster	24	86.3^{fgh}	21.6	173^{gh}	14.8
Shrimp/Prawn	76	114^{de}	28.7	156^{hijk}	30.1
Bass	12	106^{defg}	3.87	140^{ijk}	6.86
Catfish	64	82.7^{gh}	46.4	106^{l}	39.0
Cod	48	69.3^{h}	21.1	153^{hijk}	14.6
Mackerel	12	103^{defg}	2.85	289^{a}	9.39
Pike	12	115^{def}	1.74	164^{ghijk}	31.9
Salmon	41	84.0^{fgh}	14.0	162^{hik}	27.2
Sole	8	82.3^{efgh}	14.0	139^{hijkl}	5.85
Tilapia	24	75.5^{gh}	37.0	219^{cd}	17.2
Trout	28	100^{efg}	11.9	136^{j}	23.6
Abalone	3	112^{cdefgh}	0.59	106^{jl}	6.27
Conch	9	75.9^{fgh}	1.50	165^{ghijk}	8.95
Clams	6	203^{ab}	7.93	278^{ab}	22.8
Mussels	27	170^{bc}	39.0	228^{cd}	39.2
Oysters	27	228^{a}	43.3	244^{bc}	22.4
Scallops	6	127^{cdef}	1.92	129^{jkl}	7.04
Octopus	12	157^{bc}	15.2	207^{def}	4.46
Squid	24	119^{de}	16.7	208^{de}	18.5
P-value		<.0001		<.0001	

Table 3.3.2 NRF6.2 and NRF9.2b by Species groups *Note.* Darker shading indicates a higher mean NRF score. P-values included in the table are results of a one-way ANOVA between species. Means within columns that do not share a superscript letter are significantly different at the $p < .05$ level based on Tukey's HSD post hoc tests.

Figure 3.3 displays nutrients provided per 100g of each species group in mean percent daily value (%DV). The stacked bar chart format used in Figure 3.3 helps visualize which nutrients contribute most to differences in NRF scores between species groups as the NRF is proportional to the sum of the %DV of nutrients to encourage included in the algorithm.

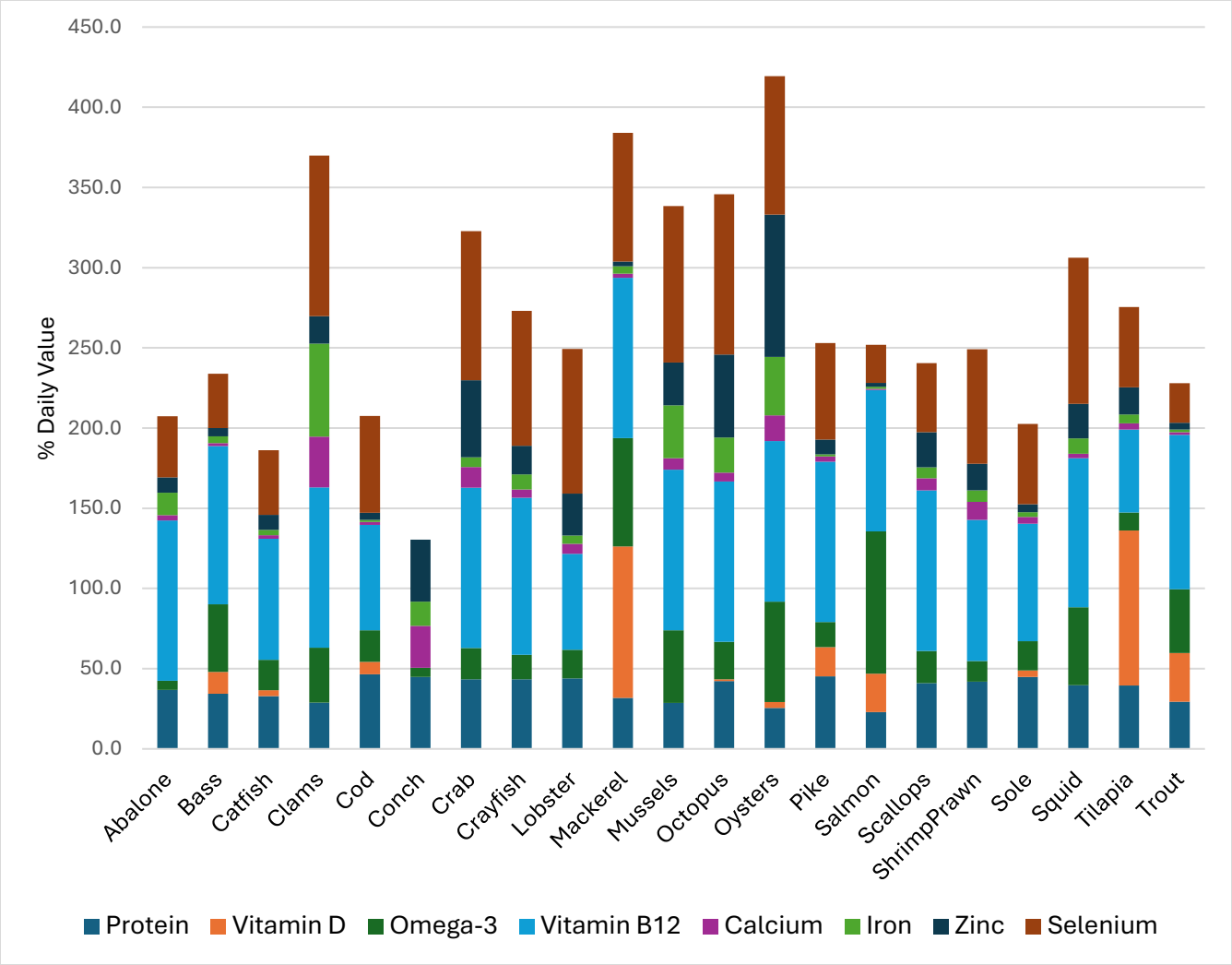


Figure 3.3 Mean %DV Protein and Micronutrients Provided by Species Group

3.4 Ranking of Aquatic foods by NRF scores

Table 3.4.1 provides final rankings on NRF6.2 and NRF9.2b by broad taxonomic group and by species group. Notably, bivalves, including oysters, clams and mussels, score highly on the NRF6.2, followed by crustaceans, of which crab scores highest, and cephalopods, of which octopus scores highest. On the NRF9.2b, small pelagic fish surpass bivalves. Bivalves, including clams, oysters, and mussels, fall shortly behind mackerel. Tilapia scores the next highest.

Broad Taxonomic Group Ranking	Highest NRF6.2		Highest NRF9.2b	
1	Bivalve	192	Small pelagic	289
2	Cephalopod	132	Bivalve	229
3	Crustacean	124	Cichlid	219
4	Small pelagic	103	Cephalopod	207
5	Salmonid	90.5	Crustacean	167
6	Demersal	89.6	Cod	153
7	Gastropod	84.8	Salmonid	152
8	Cichlid	75.5	Gastropod	150
9	Cod	69.3	Demersal	120
Species Ranking	Highest NRF6.2		Highest NRF9.2b	
1	Oysters	228	Mackerel	289
2	Clams	202	Clams	278
3	Mussels	170	Oysters	243
4	Crab	160	Mussels	228
5	Octopus	157	Tilapia	219
6	Crayfish	137	Squid	208
7	Scallops	127	Octopus	207
8	Squid	119	Crab	183
9	Pike	115	Crayfish	176
10	Shrimp/Prawn	114	Lobster	173
11	Abalone	111	Conch	183
12	Bass	106	Pike	164
13	Mackerel	103	Salmon	162
14	Trout	100	Shrimp/Prawn	156
15	Lobster	86.3	Cod	153
16	Salmon	84	Bass	140
17	Catfish	82.7	Sole	139
18	Sole	82.3	Trout	136
19	Conch	75.9	Scallops	129
20	Tilapia	75.5	Abalone	106
21	Cod	69.3	Catfish	106

Table 3.4.1 Ranking by NRF6.2 and NRF9.2b

3.5 Protein Affordability

Table 3.5.1 compares protein affordability between broad taxonomic groups. Gastropods and demersal fish provided the most protein per penny at less than $5 for 100 grams of protein, on average (Table 3.5.1). Salmonids, cephalopods, cichlids, and cod provided the second most protein per penny at less than $10 for 100 grams of protein. Demersal fish provided 100 grams of

protein for less than 15$. Finally, crustaceans and bivalves were the least affordable sources of protein.

Broad taxonomic group	Avg. Cost / 100 g Protein
Crustacean	$39.32
Cichlid	$7.40
Cod	$9.18
Demersal	$13.58
Small pelagic	$3.45
Salmonid	$5.34
Bivalve	$52.28
Cephalopod	$5.17
Gastropod	$3.01

Table 3.5.1 Average cost (USD) per 100 g protein by broad taxonomic group

After breaking the broad taxonomic groups further into species groups, conch, tilapia, mackerel, squid, and mussels provided the most protein per penny at less than $5 for 100 g protein (Table 3.5.2). The next most affordable source of protein was bass, octopus, and cod at less than $10 per 100 g protein. Pike, sole, scallops, and catfish provided 100 g protein for less than $20. Crab and shrimp/ prawn were less than 30$ per 100 g of protein, on average. The least affordable sources of protein were lobster, which cost nearly 60$ per 100 g protein, and oyster, at over $150 per 100 g protein (Table 3.5.2).

Species group	Avg. Cost / 100 g Protein
Crab	$28.36
Crayfish	N/A
Lobster	$59.72
Shrimp/Prawn	$28.53
Bass	$7.32
Catfish	$17.36
Cod	$9.18
Mackerel	$3.45
Pike	$11.84
Salmon	$5.75
Sole	$14.60
Tilapia	$2.45
Trout	$4.98
Abalone	N/A
Conch	$2.74
Clams	$57.48
Mussels	$4.53
Oysters	$168.20
Scallops	$16.49
Octopus	$7.41
Squid	$3.56

Table 3.5.2 Average cost (USD) per 100 g protein by species group

3.6 NRF6.2- and NRF9.2-Affordability Indices

Table 3.6.1 displays the cost and calculated mean NRF6.2 and NRF 9.2b affordability indices by broad taxonomic group. Small pelagic fish provided the highest NRF9.2b affordability index.

Broad taxonomic group	Cost/Kg (USD)	NRF6.2 affordability index	NRF9.2b affordability index
Bivalve	10.37	2.70	3.22
Crustacean	25.24	1.57	2.11
Cephalopod	10.25	10.13	15.89
Cod	7.53	3.50	7.72
Demersal	10.98	3.19	4.27
Gastropod	7.09	8.09	14.31
Small pelagic	4.44	12.54	35.18
Salmonid	7.88	7.52	12.63
Cichlid	7.46	6.16	12.39

Gastropods, cephalopods, salmonids, and cichlids score similarly on the NRF9.2b affordability index (Table 3.6.1). Small pelagic fish have the highest NRF6.2 affordability index with cephalopods, gastropods, and salmonids closely behind (Table 3.6.1).

Table 3.6.1 NRF6.2 and NRF9.2b affordability indices by broad taxonomic group

Figure 3.6.1 demonstrates tradeoffs between affordability and nutrient richness of aquatic foods by plotting the inverse mean cost per kilogram edible portion (EP) versus NRF score. Additionally, the bubble size is proportional with the grams of protein per 100 g edible portion.

Figure 3.6.1 A plots affordability against the mean NRF6.2 score by broad taxonomic group. Although bivalves scored highest on the NRF6.2, they were among the least affordable aquatic foods. When taking affordability into account, small pelagic fish, cephalopods, and gastropods provide the most NRF6.2 nutrients per penny (Table 3.6.1 and Figure 3.6.1 A).

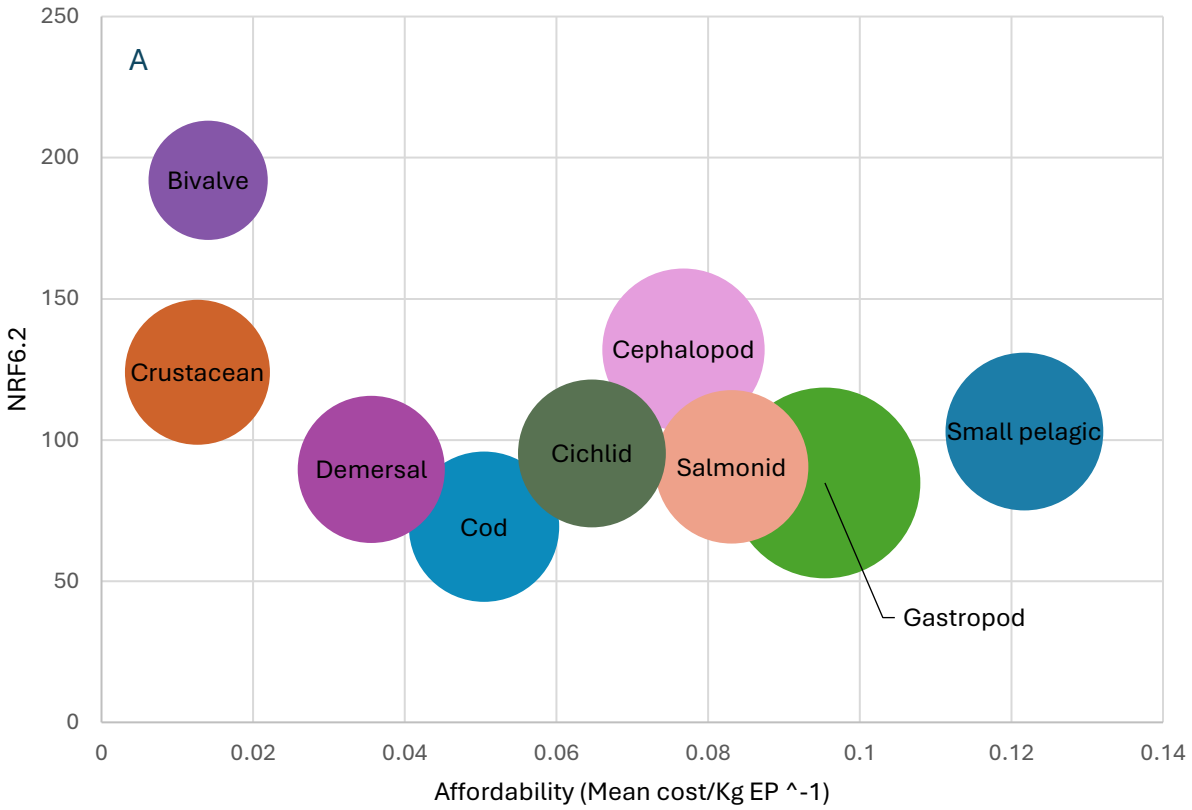


Figure 3.6.1 A Bubble plot of NRF6.2 versus Affordability. Bubble sizes are proportional to protein content.

Figure 3.6.1 B plots mean NRF9.2b against affordability by broad taxonomic group. Small pelagic fish were both the most affordable and the highest scoring on the NRF9.2b allowing them to score the highest on the NRF9.2b affordability index by far. Bivalves also scored highly on NRF9.2b, but their high cost resulted in a lower score on the NRF9.2b compared to cephalopods, gastropods, salmonids, and cichlids (Table 3.6.1 and Figure 3.6.1 B).

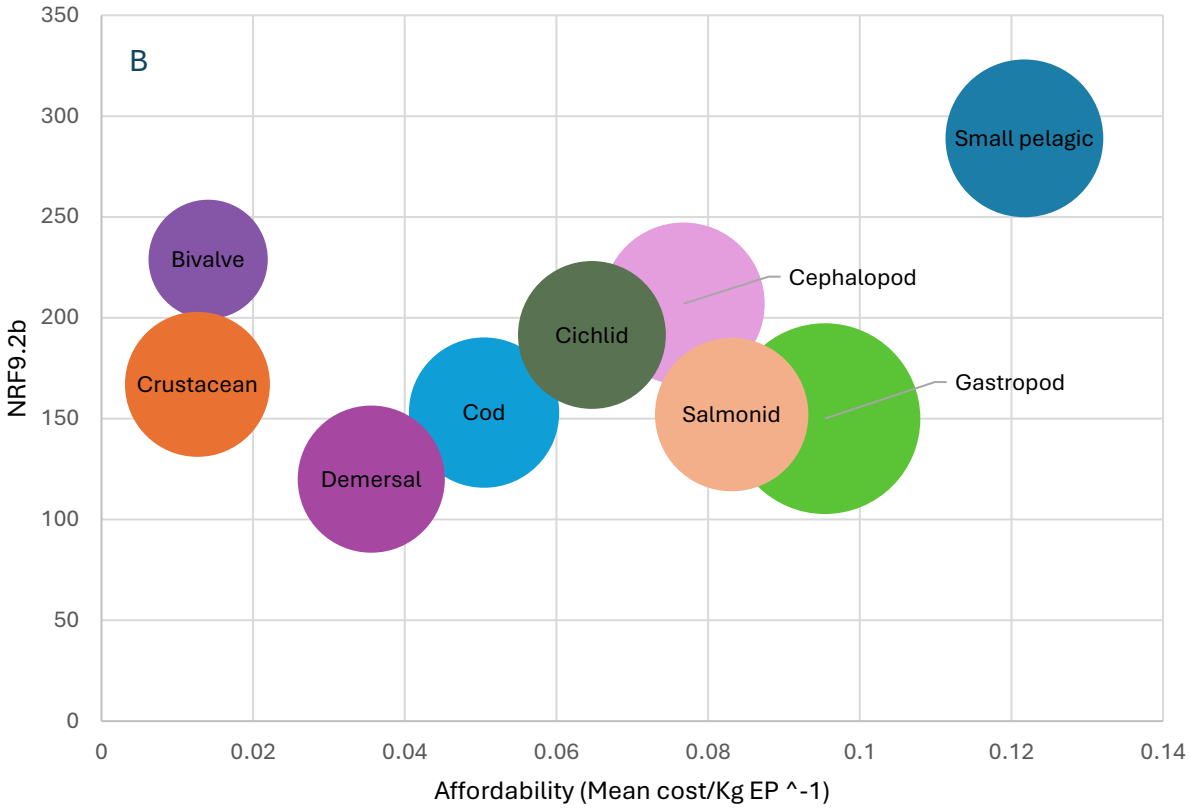


Figure 3.6.1 B Bubble plot of NRF9.2b versus Affordability. Bubble sizes are proportional to protein content.

Figure 3.6.3 is a bar plot displaying the NRF affordability indices by broad taxonomic group, which helps to visualize the trends described above.

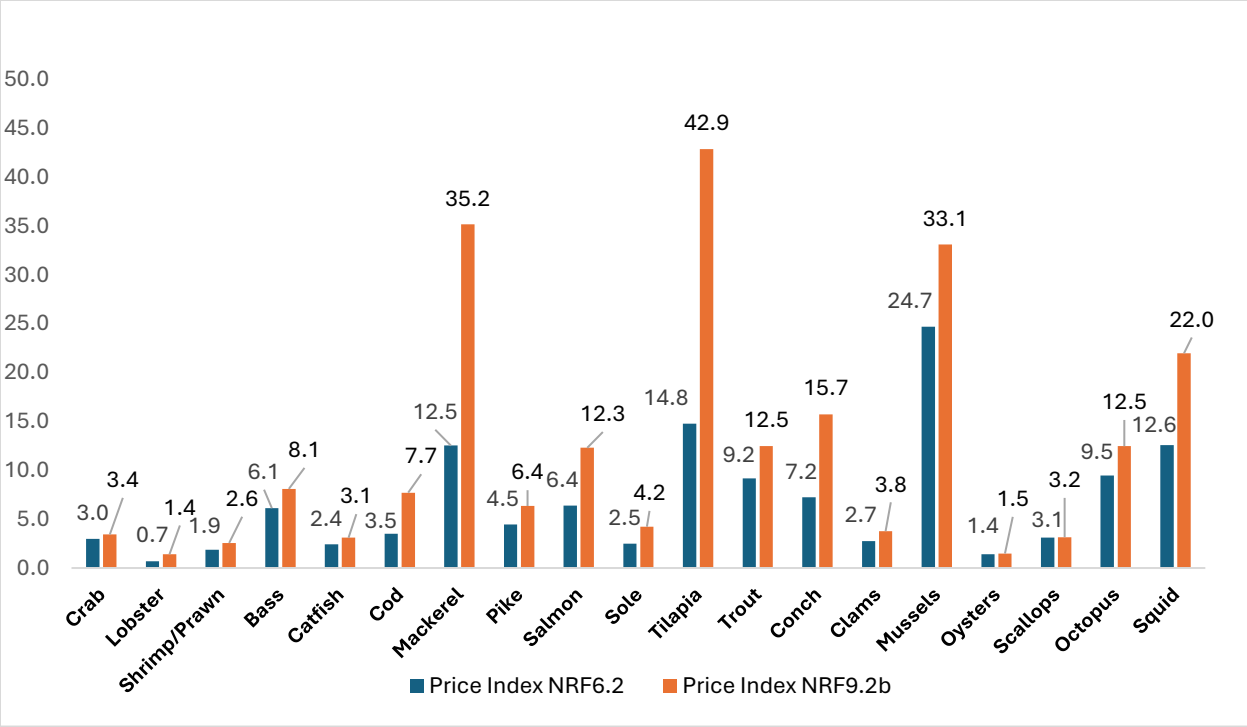


Figure 3.6.3 NRF affordability indices by broad taxonomic group

Table 3.6.2 displays the cost and calculated mean NRF6.2 and NRF 9.2b affordability indices by species group. Mussels have the highest NRF6.2 affordability index. Tilapia, squid and mackerel all score similarly high on the NRF6.2 affordability index following mussels. Tilapia, mackerel and mussels have the highest NRF9.2b affordability indices (Table 3.6.2).

Species Group	Cost/kg (USD)	Yield	Price Index NRF6.2	Price Index NRF9.2b
Crab	13.33	0.25	3.00	3.43
Lobster	34.44	0.28	0.70	1.41
Shrimp/Prawn	27.96	0.46	1.88	2.57
Bass	6.74	0.39	6.13	8.10
Catfish	6.50	0.19	2.42	3.10
Cod	7.53	0.38	3.50	7.72
Mackerel	4.44	0.54	12.54	35.18
Pike	9.81	0.38	4.46	6.35
Salmon	8.56	0.65	6.38	12.31
Sole	19.71	0.60	2.51	4.23
Tilapia	5.10	1.00	14.79	42.90
Trout	7.19	0.66	9.17	12.48
Conch	7.09	0.68	7.24	15.74
Clams	14.72	0.20	2.75	3.78
Mussels	3.51	0.51	24.70	33.13
Oysters	17.95	0.11	1.40	1.49

Scallops	5.30	0.13	3.11	3.16
Octopus	13.11	0.79	9.46	12.47
Squid	7.38	0.78	12.58	21.99

Table 3.6.2 NRF6.2 and NRF9.2b Affordability Indices by Species Group

Figure 3.6.2 A plots affordability against the mean NRF6.2 by species group. The bubble size is proportional with the grams of protein per 100 g EP. Tilapia score low on the NRF6.2, but are very affordable. Mussels score fairly well on the NRF6.2, and are also very affordable. Squid and mackerel score moderately well on the NRF6.2 and are also moderately affordable.

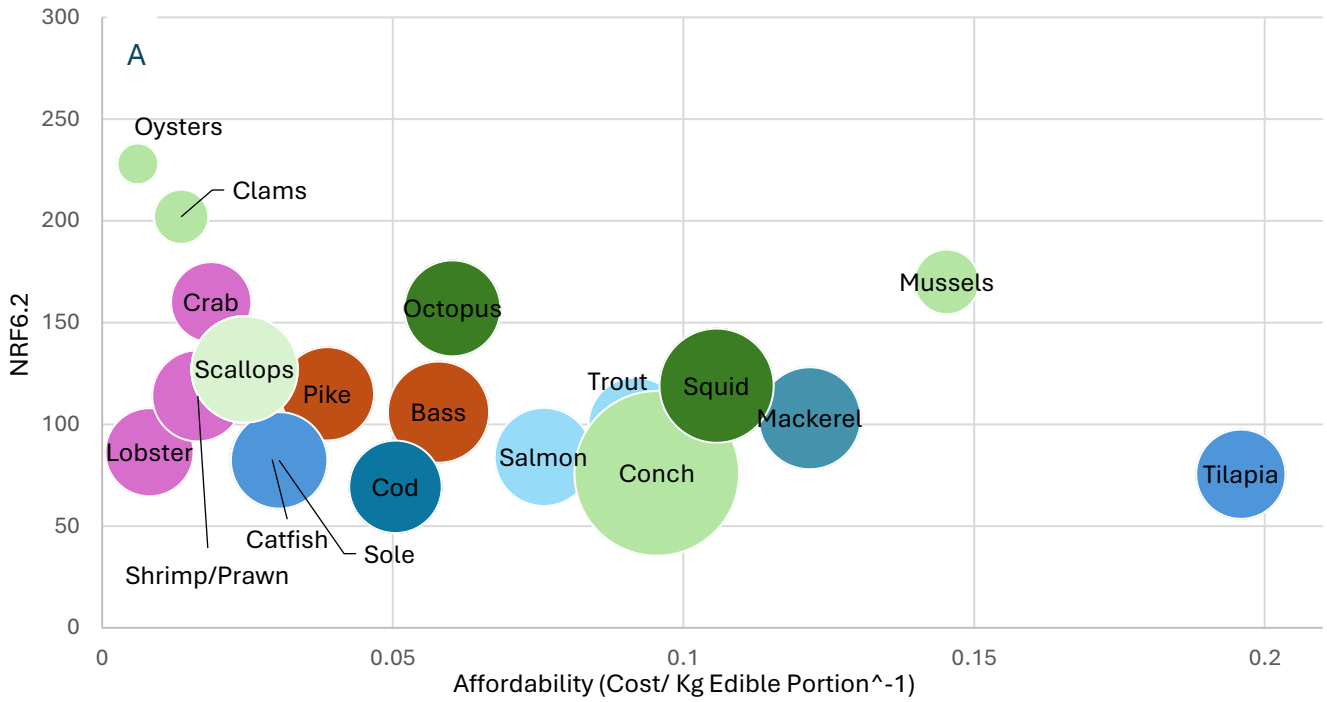


Figure 3.6.2 A Bubble plot of NRF6.2 versus Affordability by species group. Bubble sizes are proportional to protein content.

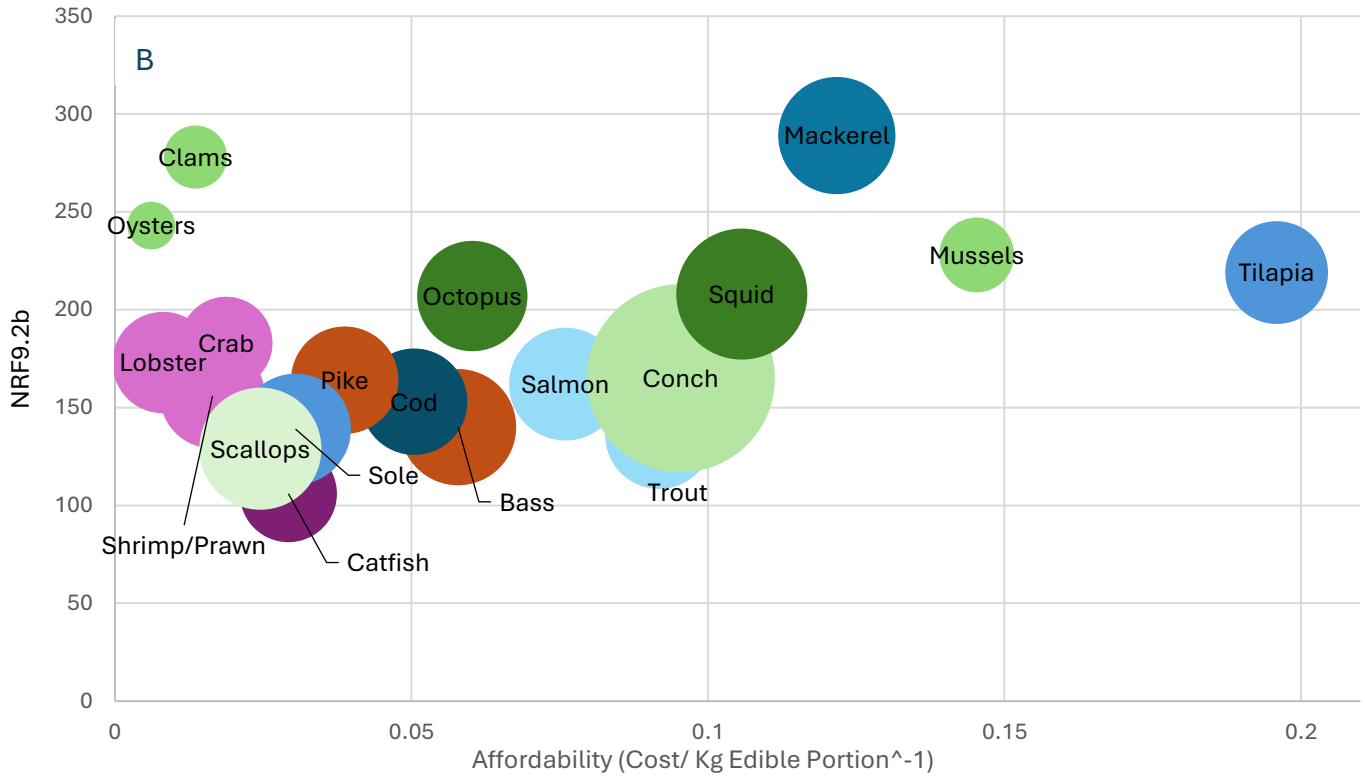


Figure 3.6.2 A Bubble plot of NRF9.2b versus Affordability by species group. Bubble sizes are proportional to protein content.

4. Discussion

This report represents the first detailed analysis of the FAO/INFOODS uFISH database and the first attempt to assess the affordable nutrient density of aquatic foods. The uFISH database, although not comprehensive, provides data for a broader range of seafood species than previously available, allowing comparison between several categories of finfish, shellfish, cephalopods and crustaceans.

Mollusks had the highest content of priority micronutrients. Bivalves, including oysters, clams, and mussels had the highest NRF6.2 scores. This is consistent with the observations of Beal et al which identified bivalves, in addition to crustaceans, canned fish with bones, and dried small fish as top sources of priority micronutrients (Beal & Ortenzi, 2022). Beal et al. found that bivalves were the only food with at least moderate density of all six priority micronutrients (Beal & Ortenzi, 2022). Of note, the uFISH database includes raw, cooked, and smoked fresh aquatic foods, but not dried or canned small fish with bones. Mollusks also had higher average NRF9.2b scores compared to finfish and crustaceans.

However, dividing finfish, mollusks, and crustaceans into smaller groups revealed that small pelagic fish scored highest, surpassing bivalves. These findings are consistent with Hallstrom et al., which also identified small pelagic fish and bivalves as the most nutrient-rich, using similar methods on the Swedish food database, except that they did not cap nutrients that exceeded daily recommended intake (Hallström et al., 2019). Bianchi et al. similarly used the NRF algorithm to assess fish and shellfish, using multiple databases, including uFISH, finding that oysters and small pelagic fish ranked highest based on nutrient density. Small pelagic fish species and wild caught pink salmon ranked the highest based on combined climate and nutritional impact (Bianchi et al., 2022). Golden et al. compared aquatic and terrestrial source foods and found that aquatic foods were higher in priority micronutrients with small pelagic fish, bivalves, and salmonids being the most nutrient rich (Golden et al., 2021).

Although mollusks and crustaceans were highly nutrient-dense, they provided the least nutrients per penny due to their high cost per edible portion. Two exceptions were mussels and squid which were affordable sources of micronutrients. The present analyses clearly demonstrate that seafood can be an affordable source of protein, omega-3, and important micronutrients. Mackerel, tilapia, mussels, and squid provided the highest NRF6.2 and NRF9.2b nutrients per penny as they were both nutrient dense and affordable. Mackerel, tilapia, squid, and mussels also provided the most protein per penny.

Wild finfish had higher mean NRF6.2 and NRF9.2b scores compared to farmed fish. This may be because the wild finfish category included nutrient-rich small pelagic fish. Small pelagic fish are forage fish that are a major component of fishmeal and fish oil used to feed predatory finfish grown in aquaculture. Willer et al. compared the nutrient composition of Atlantic salmon to the small pelagic fish that are used to feed them and found that vitamin D, zinc, and selenium were retained while vitamin B12, vitamin A, Omega-3, iron, iodine and calcium were higher in the small pelagic fish used for fish feed than in farmed salmon (Willer et al., 2024). This represents a net loss of micronutrients available for human consumption. Farmed species are consumed at higher rates in higher income countries while lower income countries have historically relied more on smaller, more nutrient-dense and affordable fish species.

The FAO roadmap for the “Blue Transformation” is intended to guide the expansion of global sustainable aquaculture production by at least 35 percent by 2030, in alignment with the Sustainable Development Goal (SDG) to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture (*SDG Goal 2*, n.d.). The growth of aquaculture requires effective management and oversight to ensure that resources are distributed equitably and that guidelines are followed to ensure social, environmental, and economic sustainability. The FAO’s stated mission is to expand aquaculture while reducing fish loss and waste, increasing seafood consumption across the global south, supporting local economies, and improving gender equity across the aquatic food value-chain (*Blue Transformation - Roadmap 2022–2030*, 2022). Priority actions include supporting small and medium scale fish farmers

through information, technology, and policy. The most recent update on the state of world fisheries and aquaculture came in October 2024. Progress has been made in many areas while other areas have drifted from the target, including the biologically sustainable management of fish stocks.

Aquaculture remains dominated by a small number of countries (*FISH4ACP*, 2025). In many low- and middle-income countries (LMIC), small pelagic fish caught by small-scale fisheries that support local economies while providing an affordable source of micronutrients and protein that can be made accessible year round through canning, drying, salting, and smoking (FAO, 2024b). Aquatic foods are rich in micronutrients that are difficult to obtain from plant-based sources. Small fish have the potential to fill the micronutrient gap for calcium, selenium, and zinc for millions of women in LMIC in Africa and Asia (Duke University & WorldFish, 2023).

There are several limitations to the ability to capture affordable nutrient density of fish and shellfish using the uFISH and Globefish databases. Firstly, some gaps in the uFISH database were present requiring some values be imputed with values from the USDA Food and Nutrient Database (USDA, ARS, 2024) and Frida Database (The National Food Institute, & Technical University of Denmark, 2024). Secondly, the database contains a wider range of species from a broader array of regions than available in any other seafood composition tables, but it is not comprehensive for all species and regions within each broad category, so findings may not be representative of other seafood items in each category. Importantly, the small pelagic fish category was limited to only mackerel species in the uFISH database. The inclusion of a broader array of small pelagic species would strengthen the findings of this study. The expansion of the FAO database would allow for more comprehensive analysis and comparison of aquatic species. Aquatic plant species would be a valuable addition to the uFISH database. Currently, algae and other phytoplankton, in addition to corn, soy, and insects, are being utilized in fish feed as alternatives to wild fish, influencing the nutritional properties of the final product. Aquatic plants are often overlooked as valuable sources of micronutrients, EPA, and DHA. Expanding their use for direct human consumption could offer a sustainable way to address micronutrient gaps. The Globefish price data is updated monthly to reflect the current prices, given ongoing fluctuations in the market. For this analysis, average prices from October 2024 were utilized to compare the affordability of different categories of seafood, but affordability may vary by season and status of fish stocks. Lastly, the Globefish price dashboard provides prices of seafood items derived from multiple origins to the European market. Prices may not be representative of the cost to consumers outside of Europe.

Additionally, affordable foods are not always accessible. An analysis of trade patterns by Nash et al. found that international trade diverts nutrients caught in marine fisheries from nutrient-insecure LMIC toward wealthy, nutrient-secure countries (*Trade and Foreign Fishing Mediate Global Marine Nutrient Supply | PNAS*, n.d.). Ideally, distribution processes should match food quality with dietary deficiencies and food security and micronutrient deficiencies should be

considered when developing trade agreements. Future directions for this research include tailoring nutrient affordability indices to reflect the accessibility and affordability of aquatic foods to vulnerable populations in LMIC. Nutrient profiling models may also be further tailored to reflect the specific needs of vulnerable groups in different countries or regions to direct food system solutions that aim to increase the production and accessibility of fish and shellfish.

4. Conclusion

Aquatic foods have the potential to close gaps in dietary micronutrients globally. Efforts should focus on targeted food systems solutions that improve and preserve the accessibility and affordability of nutrient rich aquatic foods to vulnerable populations. The nutrient affordability index is a valuable tool to weigh the trade-offs between nutrient richness and cost. The present analysis identified mackerel, tilapia, squid, and mussels as affordable sources of protein and priority micronutrients that can play a role in addressing micronutrient inadequacies and protein-calorie malnutrition globally.

REFERENCES

Anna Herforth, Yan Bai, Kristi Mahrt, & Alissa Ebel. (2020). *Cost and affordability of healthy diets across and within countries*. FAO. https://doi.org/10.4060/cb2431en

Banaszak, M., Dobrzyńska, M., Kawka, A., Górna, I., Woźniak, D., Przysławski, J., & Drzymała-Czyż, S. (2024). Role of Omega-3 fatty acids eicosapentaenoic (EPA) and docosahexaenoic (DHA) as modulatory and anti-inflammatory agents in noncommunicable diet-related diseases – Reports from the last 10 years. *Clinical Nutrition ESPEN*, *63*, 240–258. https://doi.org/10.1016/j.clnesp.2024.06.053

Beal, T., Massiot, E., Arsenault, J. E., Smith, M. R., & Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PloS One*, *12*(4), e0175554. https://doi.org/10.1371/journal.pone.0175554

Beal, T., & Ortenzi, F. (2022). Priority Micronutrient Density in Foods. *Frontiers in Nutrition*, *9*, 806566. https://doi.org/10.3389/fnut.2022.806566

Bianchi, M., Hallström, E., Parker, R. W. R., Mifflin, K., Tyedmers, P., & Ziegler, F. (2022). Assessing seafood nutritional diversity together with climate impacts informs more comprehensive dietary advice. *Communications Earth & Environment*, *3*(1), 1–12. https://doi.org/10.1038/s43247-022-00516-4

Blue Transformation—Roadmap 2022–2030. (2022). FAO. https://doi.org/10.4060/cc0459en

Byrd, K. A., Pincus, L., Pasqualino, M. M., Muzofa, F., & Cole, S. M. (2021). Dried small fish provide nutrient densities important for the first 1000 days. *Maternal & Child Nutrition*, *17*(4), e13192. https://doi.org/10.1111/mcn.13192

Byrd, K. A., Shieh, J., Mork, S., Pincus, L., O'Meara, L., Atkins, M., & Thilsted, S. H. (2022). Fish and Fish-Based Products for Nutrition and Health in the First 1000 Days: A Systematic Review of the Evidence from Low and Middle-Income Countries. *Advances in Nutrition*, *13*(6), 2458–2487. https://doi.org/10.1093/advances/nmac102

Drewnowski, A. (2009). Defining nutrient density: Development and validation of the nutrient rich foods index. *Journal of the American College of Nutrition*, *28*(4), 421S-426S. https://doi.org/10.1080/07315724.2009.10718106

Durazzo, A., Di Lena, G., Gabrielli, P., Santini, A., Lombardi-Boccia, G., & Lucarini, M. (2022). Nutrients and Bioactive Compounds in Seafood: Quantitative Literature Research Analysis. *Fishes*, *7*(3), Article 3. https://doi.org/10.3390/fishes7030132

FAO. (2024a). *Apparent consumption of aquatic foods*. https://doi.org/10.4060/cd0683en

FAO. (2024b). *Aquatic foods: An untapped potential for healthy diets*. FAO. https://doi.org/10.4060/cd0683en

FAO. (2024c, October). *The state of World fisheries and aquaculture 2024*. FAO-.Org. https://doi.org/10.4060/cd0683en

FAO. (2024d, November 10). *GLOBEFISH | European Price Report October 2024*. FAO.Org. https://openknowledge.fao.org/items/4630a189-e96b-402d-a5b0-77b979dd63b5

Federal Reserve. (n.d.). *Foreign Exchange Rates—H.10*. Federalreserve.Gov. Retrieved February 23, 2025, from https://www.federalreserve.gov/releases/h10/hist/dat00_eu.htm

FISH4ACP. (2025). FAO>org. https://www.fao.org/in-action/fish-4-acp/where-we-work/en/

Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matthey, H., Eurich, J. G., Gephart, J. A., Fluet-Chouinard, E., Nyboer, E. A., Lynch, A. J., Kjellevold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K. M., … Thilsted, S. H. (2021). Aquatic foods to nourish nations. *Nature*, *598*(7880), 315–320. https://doi.org/10.1038/s41586-021-03917-1

Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., & Ziegler, F. (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production*, *230*, 402–411. https://doi.org/10.1016/j.jclepro.2019.04.229

INFOODS: FAO/INFOODS Databases. (2016). https://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/

Jiang, W., Zhao, Y., Wu, X., Du, Y., & Zhou, W. (2023). Health inequalities of global protein-energy malnutrition from 1990 to 2019 and forecast prevalence for 2044: Data from the Global Burden of Disease Study 2019. *Public Health*, *225*, 102–109. https://doi.org/10.1016/j.puhe.2023.10.003

MEXT. (2015). *Standard Tables of Food Composition in Japan* (Version Seventh Revised Version) [Dataset]. https://www.mext.go.jp/en/policy/science_technology/policy/title01/detail01/1374030.htm

Passarelli, S., Free, C. M., Shepon, A., Beal, T., Batis, C., & Golden, C. D. (2024). Global estimation of dietary micronutrient inadequacies: A modelling analysis. *The Lancet Global Health*, *12*(10), e1590–e1599. https://doi.org/10.1016/S2214-109X(24)00276-6

Program, H. F. (2024). Daily Value on the Nutrition and Supplement Facts Labels. *FDA*. https://www.fda.gov/food/nutrition-facts-label/daily-value-nutrition-and-supplement-facts-labels

SDG Goal 2: Zero Hunger. (n.d.). UNICEF DATA. Retrieved December 30, 2024, from https://data.unicef.org/sdgs/goal-2-zero-hunger/

Swanson, D., Block, R., & Mousa, S. A. (2012). Omega-3 Fatty Acids EPA and DHA: Health Benefits Throughout Life1. *Advances in Nutrition*, *3*(1), 1–7. https://doi.org/10.3945/an.111.000893

The National Food Institute, & Technical University of Denmark. (2024). *Frida—The Danish Food Composition Database* (Version Version 5.3) [Dataset]. https://frida.fooddata.dk/data?

Trade and foreign fishing mediate global marine nutrient supply | PNAS. (n.d.). Retrieved May 26, 2025, from https://www.pnas.org/doi/abs/10.1073/pnas.2120817119

University, D., & WorldFish. (2023). *Illuminating Hidden Harvests*. FAO ; Duke University ; WorldFish ; https://openknowledge.fao.org/handle/20.500.14283/cc4576en

USDA Agricultural Resarch Service. (1975). *USDA Agriculture Handbook No. 102*. USDA ARS. https://www.fao.org/uploads/media/USDA_handbook_no8_02.pdf

USDA, ARS. (2024). *USDA Food and Nutrient Database for Dietary Studies 2021-2023*. Food Surveys Research Group Home Page. http://www.ars.usda.gov/nea/bhnrc/fsrg

Viana, D. F., Zamborain-Mason, J., Gaines, S. D., Schmidhuber, J., & Golden, C. D. (2023). Nutrient supply from marine small-scale fisheries. *Scientific Reports*, *13*(1), 11357. https://doi.org/10.1038/s41598-023-37338-z

Weffort, V. R. S., & Lamounier, J. A. (2023). Hidden hunger – a narrative review. *Jornal de Pediatria*, *100*(Suppl 1), S10–S17. https://doi.org/10.1016/j.jped.2023.08.009

Willer, D. F., Newton, R., Malcorps, W., Kok, B., Little, D., Lofstedt, A., de Roos, B., & Robinson, J. P. W. (2024). Wild fish consumption can balance nutrient retention in farmed fish. *Nature Food*, *5*(3), 221–229. https://doi.org/10.1038/s43016-024-00932-z

Supplementary Figures:

Supplementary Table 1: Classification of Aquatic Foods

Phylum, Subphylum, or Biological Distinction	Zone	Family or Order	Species grouping	Species in uFISH (Common names)
Finfish	**Demersal**		**Bass**	European sea bass
			Catfish	Torpedo-shaped catfish, Philippine catfish, North African catfish, Bighead catfish, Channel catfish, Striped catfish
			Pike	Northen Pike
		Cods	**Cod**	Atlantic cod, pacific cod
	Pelagic		**Mackerel**	Atlantic horse mackerel
	Pelagic (migratory)	**Salmonid**	**Salmon**	Atlantic salmon
			Trout	Rainbow trout
	Variable	**Cichlid**	**Sole**	Common sole
			Tilapia	Nile tilapia
Crustacean	Class		Species grouping	Species in uFISH (Common names)
	Malacostraca		**Crab**	Rock crab, Dungeness crab, Edible crab, Tanner crab, Swimming crab, Blue crab, Blue swimming crab, Indo-Pacific swamp crab, King crab, Red king crab
			Crayfish	Oceanian crayfish
			Lobster	Lobsterettes, American lobster, European lobster, Norway lobster, Spiny lobster, Red rock lobster
			Shrimp/ Prawn	Common shrimp, Pandalus shrimp, Penaeid shrimp, Endeavour shrimp, Eastern school shrimp, Speckled shrimp, Whiteleg shrimp, Sergestid shrimp, Palaemonid shrimp; River prawn, Monsoon River prawn, Giant River prawn, Northen prawn, Brown tiger prawn, Western king prawn, Banana prawn, Giant tiger prawn, Green tiger prawn
Mollusk	**Bivalve**		**Clams**	Venus clams
			Mussels	Mytilus mussel, Korean mussel, Blue mussel, Mediterranean mussel, Perna mussel, New zealand mussel, Green mussel
			Oysters	Cupped oyster, Flat oyster
			Scallops	Scallops, Giant Atlantic scallop
	Cephalopod		**Octopus**	Common octopus
			Squid	Inshore squid, European squid, Ommastrephidae squids, Cuttlefish
	Gastropod		**Abalone**	Abalone
			Conch	Conch shells

Supplementary Table 2: Price data by species groupings

Species Grouping	Globefish Species	Cost/kg (EU)	Cost/kg (USD)	Yield	Cost/ Kg/ Yield	(Cost/Kg/ Yield)$^{-1}$	Price Index NRF6.2	Price Index NRF9.2b
Bass	(whole) European seabass	6.18	6.74	0.39	17.28	0.06	6.13	8.10
Catfish	(whole) Wolffishes or Atlantic catfish	5.96	6.50	0.19	34.19	0.03	2.42	3.10
Clams	(whole) Donax clams, imperial surf clam	13.50	14.72	0.20	73.58	0.01	2.75	3.78
Cod	(whole) Atlantic cod	6.91	7.53	0.38	19.82	0.050	3.50	7.72
Conch	(whole) Conch	6.51	7.09	0.68	10.48	0.10	7.24	15.74
Crab	(whole) Crab, edible crab, spinous spider crab, velvet swim crab	12.23	13.33	0.25	53.32	0.02	3.00	3.43
Lobster	(whole) Common spiny lobster, European lobster, Norway lobster	31.60	34.44	0.28	123.01	0.01	0.70	1.41
Mackerel	(whole) Atlantic horse mackerel	4.07	4.44	0.54	8.22	0.12	12.54	35.18
Mussels	(whole) Mediterranean mussel	3.22	3.51	0.51	6.88	0.15	24.70	33.13
Octopus	(whole) Common octopus	12.03	13.11	0.79	16.60	0.06	9.46	12.47
Oysters	(whole) Oysters	16.47	17.95	0.11	163.15	0.01	1.40	1.49
Pike	(whole) Pike perch	9.00	9.81	0.38	25.82	0.04	4.46	6.35
Salmon	(whole) Atlantic salmon	7.85	8.56	0.65	13.16	0.08	6.38	12.31
Scallops	(whole) Great Atlantic scallop	4.87	5.30	0.13	40.79	0.03	3.11	3.16
Shrimp/Prawn	(whole) Common prawn, giant tiger prawn, common shrimp, scarlet shrimp	25.65	27.96	0.46	60.78	0.02	1.88	2.57
Sole	(whole) Common sole, wedge sole, lemon sole	18.08	19.71	0.60	32.85	0.03	2.51	4.23
Squid	(whole) European squid, Indian squid, longfin squid, opalescent inshore squid, patagonian squid, squid	6.77	7.38	0.78	9.46	0.11	12.58	21.99
Tilapia	(fillet) Nile tilapia	4.68	5.10	1.00	5.10	0.20	14.79	42.90
Trout	(whole) Rainbow trout	6.60	7.19	0.66	10.9	0.09	9.17	12.48
Abalone	No data available	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Crayfish	No data available	N/A	N/A	N/A	N/A	N/A	N/A	N/A