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Article

# Comparative Sustainability of Essential Amino Acids from Rendering Animal Proteins and Vegetable Proteins Used in Three Aquaculture Species

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## Abstract

While productivity increases in the production of aquaculture have contributed to reductions in greenhouse gas emissions per unit of production, additional reductions in greenhouse gas emissions can be attained by modifying the ingredients in the selected studied species, i.e., Nile tilapia, salmon and shrimp diets. In this paper, a baseline diet, for a given studied species, was aggregated from at least four commercial diets to have a better representation of the real world. Then using the same list of feed ingredients, an alternative scenario was defined not only balancing the ration from energy, protein and fat nutrient requirements, and constraining the cap at 150% for individual feed ingredient from the baseline diet but also minimizing the greenhouse gas emission. For all three studied species, 8.4% less plant-based protein meals, 23.9% less grains, and 36.8% more animal protein meals were used in the scenario diet. In consequence, total greenhouse gas emissions was reduced by 15.3% from the baseline diet and total acres of land use was decreased by 20%.

**Keywords:** greenhouse gas emission; life cycle assessment; land use; Nile tilapia; salmon; shrimp; rendered animal protein meals; feed utilization

## 1. Introduction

Aquaculture makes an important contribution to food composition, due to its high protein profile and essential nutrients, such as essential fatty acids (omega-3s), vitamins (A, B, and D) and minerals (calcium, phosphorus, zinc, iron, selenium, and iodine), compared to other food commodities[1]. Global aquaculture production continues to expand maybe production chain since the COVID-19 pandemic. Over the last two decades, total global aquaculture production increased 191%, with a 5.0% average annual growth rate[2], mainly from Asia. For the last decade, aquaculture production growth in the United States was 13.9% from 420 thousand tons to 479 thousand tons (live weight)[3], while U.S. per capita consumption of seafood products increased from 16.8 pound per person in 2012 to 20.8 pound per person in 2022[4].

Feed is commonly used in aquaculture species. According to Naylor[5] et al., in 2017, 51.2 million tons of feed were consumed by farmed fish. And in 2022, a survey reported that 1.27 billion tons of aquaculture feed were produced worldwide[6]. In the early 2010s, a considerable controversy arose from what has been termed a “fish-in fish-out” feed type (which heavily relied on fishmeal, fish oil and wild caught fish) as aquaculture feed, unclear feed conversion ratio, and that the ratio itself depends on total catch of wild fisheries[7]. Also, “fish-in fish-out” feed may not be sustainable as a feed ingredient source. Therefore, a more holistic approach, from a feed perspective, was advocated

by increasing use and recycling of circular ingredients to reduce the carbon footprint and benefit the aquaculture sector from social, economic and environmental aspects[7–9].

Life cycle assessment (LCA) is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. LCA describes the life cycle as consecutive and interlinked stages of a product system extending from the acquisition of raw materials through materials processing, technology manufacturing, construction, technology use/maintenance/upgrade, and the technology retirement[10]. LCA also provides a framework for understanding economic and social impacts. In an LCA, data are collected at the unit process level, intended to represent a single industrial activity, which in this case is the food and agriculture industry. Each single industrial activity (a) produces products and sometimes co-products; (b) uses resources from the environment; (c) uses resources from other unit processes in the production chain; and (d) generates emissions to the environment[10,11].

An LCA analysis combines unit process data for the life cycle, and the impact assessment estimates the impact associated with activities and flows to and from the environment for the inventory. A precise estimate of LCA is calculating and assigning greenhouse gas emissions (GHGE) for different activities in different stages[10,12].

Therefore, it is important to recognize how much GHGE is currently in commercial aquaculture diets, and what potential substitutes could be used in a diet that to lower GHGE and still meet the nutritional requirements for aquaculture species. Few studies have discussed this topic. Hence, this study is interested in how commonly used protein feed ingredients, such as plant-based meals, rendered animal protein meals, and some grain products (i.e., wheat and wheat middlings) used in aquaculture diets (Nile tilapia, salmon and shrimp), affect the following:

1. GHGE estimates for production of selected feed ingredients
2. Essential Amino Acids (EAAs) composition and the GHGE of the EAAs fractions
3. availability of EAAs needed for aquaculture rations

These data were comprehensively analyzed to provide estimates of the environmental footprint associated with the production of specific amounts (per metric ton, MT) of these feed sources.

## 2. Data and Methods

Information on GHGE of feed ingredients is contained in the Global Feed LCA institute's (GFLI) database [13]. The GFLI database consists of the LCA of raw materials from various regions in the world. The system boundary is cradle-to-farm gate for cultivated products, which includes all life cycle stages up to the delivery of the feed to the farm, as well as feed mill operations and logistics; and a system boundary from cradle-to-processing gate for processed products, including the transport to processing plant and its processing. With three allocations at co-production, which are economic, mass dry matter, and energy content and supporting 15 impact categories, the database allows meaningful environmental assessment of animal nutrition products and stimulates continuous improvement of the environmental performance in the animal nutrition and food industry. The GFLI database was used to establish the GHGEs for the selected feed stuffs with factors converted to values per metric ton (and/or bushel).

Datasets have been developed for the LCA Commons in response to a national need for data representing U.S. operations. The LCA Commons database is an open access database developed by the United States Department of Agriculture (USDA) National Agricultural Library (NAL)[14] for use in LCAs to support policy assessment, technology implementation, decision-making, and publicly disclosed comparative product or technology assertions. The Ecoinvent database[15] also includes quality-assured comprehensive datasets from a variety of activities representing industrial and agricultural processes.

A wide-ranging literature and database review was carried out to determine the GHGE intensities associated with the production of selected animal and vegetable feed ingredients. GHGE in the production of feed ingredients can be influenced by many factors, such as feed type (crops and

their co-products versus animal species and their by-products), differences in genetics, cultivation, harvest and post-harvest conditions, processing, overall technology, production systems and location, to name a few. The main sources of data came from GFLI. To supplement data not available in this source, information contained in several reports from USDA NAL, Ecoinvent and other publications[16–21] were included.

From a feed consumption standpoint, related data sources used to estimate aquaculture feed consumption were Feedtables[22] and Feedipedia[23]. USDA National Animal Nutrition Program (NANP)[24] were used to obtain feed ingredients nutritional profiles. USDA NASS and USDA Census databases were used to estimate the studied aquaculture species' (Nile tilapia, salmon and shrimp) production. Other relevant publications[18,25–29] were also included. This study took into consideration several reasons for limiting the amount of a particular by-product feed in rations, including palatability, moisture content of the total diet, energy content, protein balance, carbohydrate balance, fiber levels and fat concentrations.

From the relevant databases, data summaries were created for total production of crops that are important for the feeding and production of aquaculture in the U.S., total land use footprint, and GHGE footprint for each crop and fractions that are used for each studied species of aquaculture.

To have a better understanding of commercial aquaculture diets for the studied species, and confidentiality agreements with these commercial diets' providers, a more representative baseline diet, for a given species, was composed of at least four commercial diets (Nile tilapia: 4 commercial diets; salmon: 5 commercial diets; shrimp: 10 commercial diets). Major protein ingredients were defined as those ingredients that are protein resources to the studied species, and the inclusion rate of the ingredient was greater than 1%, defined as major feed ingredients. For a given species, all the selected feed ingredients were broken out from all the commercial diets, then the average of these ingredients was calculated to create the baseline diet. Note that feed additives, such as minerals, vitamins, antioxidants, cholesterol, BHT, etc., were aggregated and identified as "feed additives" and were not estimated individually.

Once the baseline diet was created for a given species, a GHGE value was assigned to each corresponding protein feed ingredient. Then the GHGE for the ingredients and the GHGE for EAAs fractions from the selected feed ingredients by species were estimated. Apparent digestibility (AD) of EAAs from animal proteins and vegetable proteins for studied species was also considered in this study.

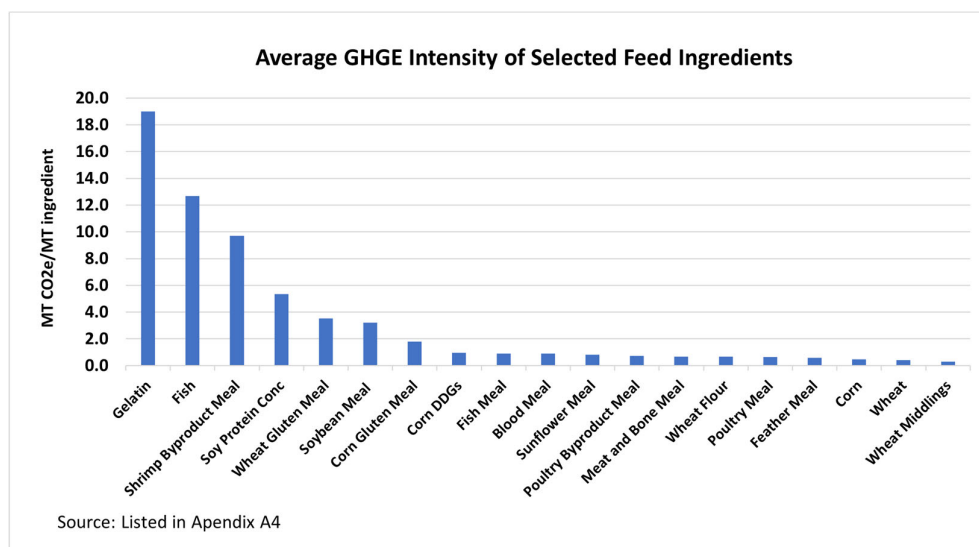
Using the same list of feed ingredients, an alternative scenario was defined as to how the EAA needs for aquaculture diets could be met if there were greater use of animal-based EAAs and what the effect of that change would be on the GHGE of aquaculture production using the best mix of EAAs from the perspective of GHGE while still being subject to other considerations such as limits on any particular feedstuff's inclusion in a ration due to energy content, protein balance, fiber levels and fat concentrations. By doing this, the ration was balanced on energy, protein and fat requirements including amino acid fractions on a digestibility basis and minimized for GHGE by feed ingredients. To make the scenario diets realistic, the ingredient constraints of feed ingredients were capped at 150% of the baseline diet for a given ingredient.

Of note, a feed ingredient was only used in a ration if it was found in the baseline ration for a given species. For instance, "poultry meal" was only used in baseline salmon diets; therefore, under the scenario diet, poultry meal would only be used in salmon diet and was not used in Nile tilapia or shrimp diets. Additionally, the feed additives were not considered in the scenario diet because their inclusion was beyond the scope of the study. The scenario diets were estimated by using Solver in Excel. Then, following the same steps as from the baseline analysis, the GHGE for the selected ingredients, and for the EAAs fractions from these ingredients by species would be established.

### 3. Results

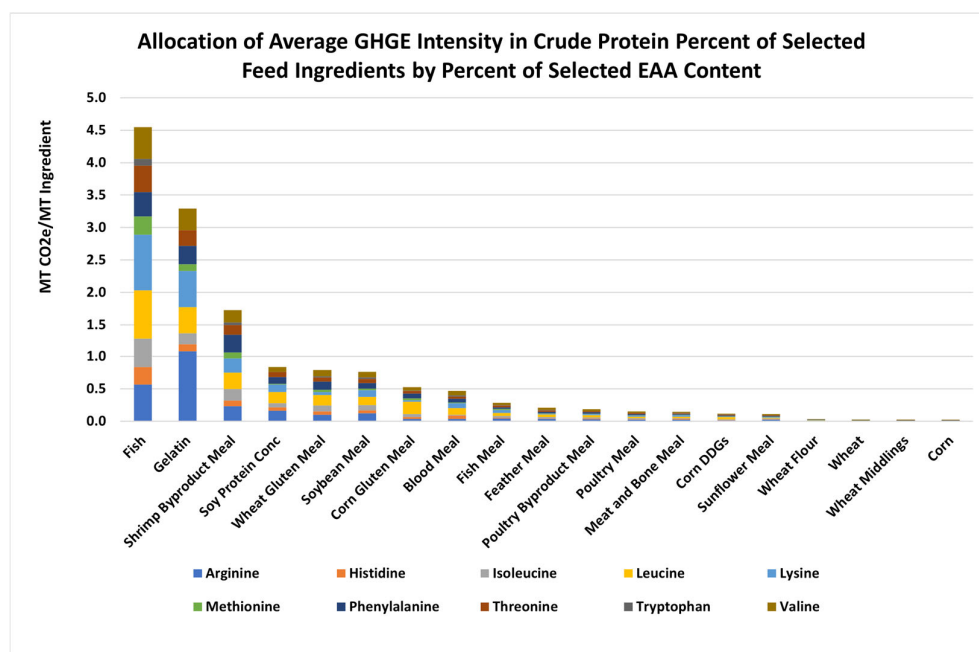
GHGE intensities in the production of feed ingredients used for the aquaculture industry included in this study are presented in Figure 1. GHGE intensities ranged from 19.0 metric tons of

CO<sub>2</sub> equivalent per metric ton of ingredient (MT CO<sub>2</sub>e/MT ingredient) for gelatin to 0.3 MT CO<sub>2</sub>e/MT ingredient for wheat middlings. Source details for the selected ingredients are shown in Appendix Table A4.



**Figure 1.** Average GHGE Intensity of Selected Feed Ingredients in Aquaculture Diets.

Data on the amino acid fractional content of the feed ingredients was used to allocate the GHGE intensity for each feed ingredient in the study to its amino acid fraction and taking the crude protein content in each ingredient, with quantities stated in MT CO<sub>2</sub>e/MT ingredient. The allocations for selected ingredients used in this study are shown in Figure 2.



**Figure 2.** Allocation of Average GHGE Intensity in Crude Protein of Selected Feed Ingredients by Percent of Selected EAA Content.

Figures 3–12 show the metric tons of GHGE per Kg of selected EAA in the major plant and animal protein meal ingredients. Besides the GHGE, the percentage of crude protein in each

ingredient and its corresponding percent content of each EAA was taken into consideration in these estimates. Due to the range of GHGE per amino acids for the different feed ingredients, GHGE can be reduced by changing the ingredients used in aquaculture.

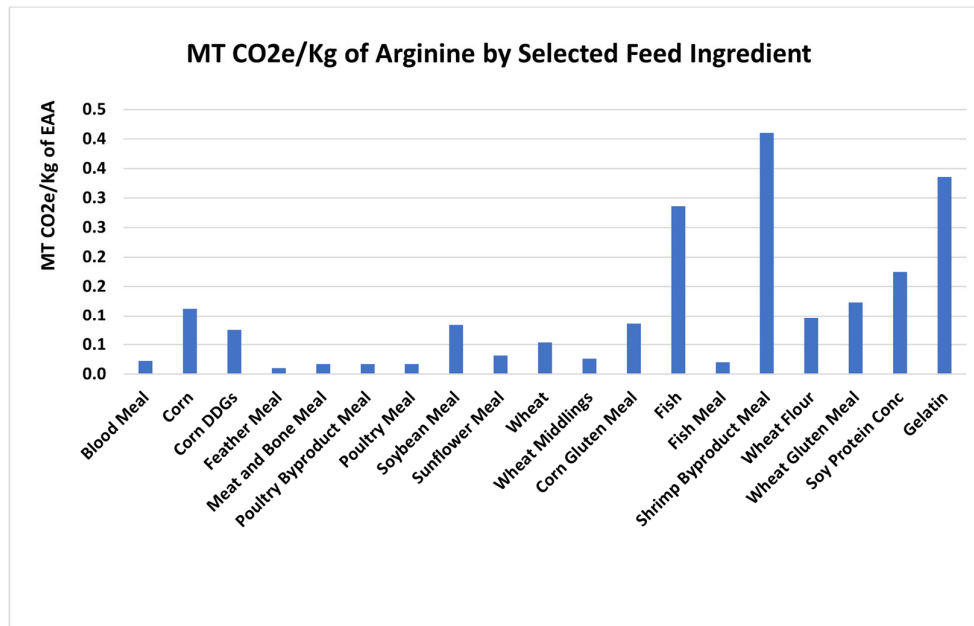


Figure 3. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Arginine.

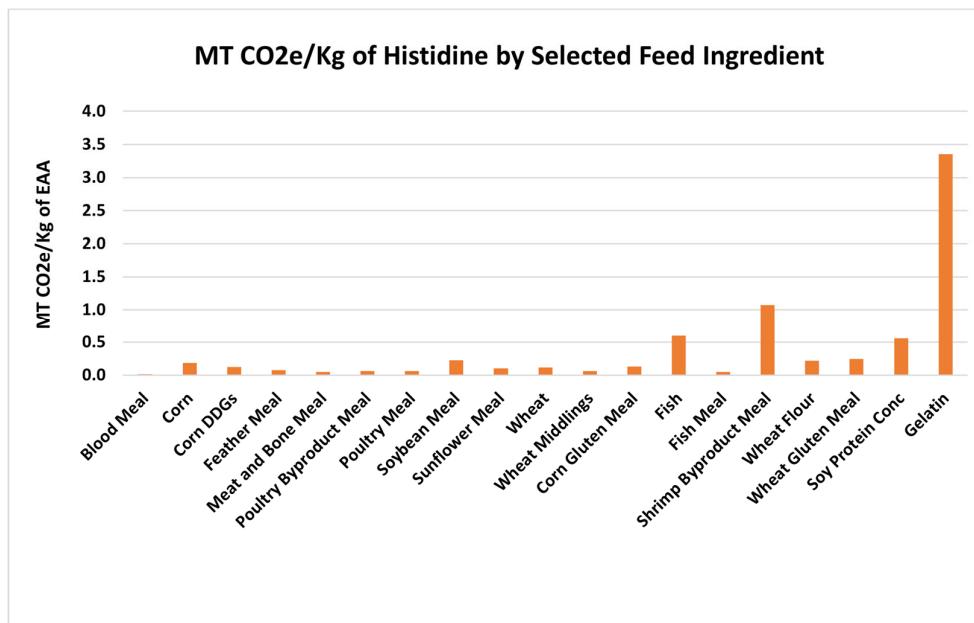


Figure 4. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Histidine.

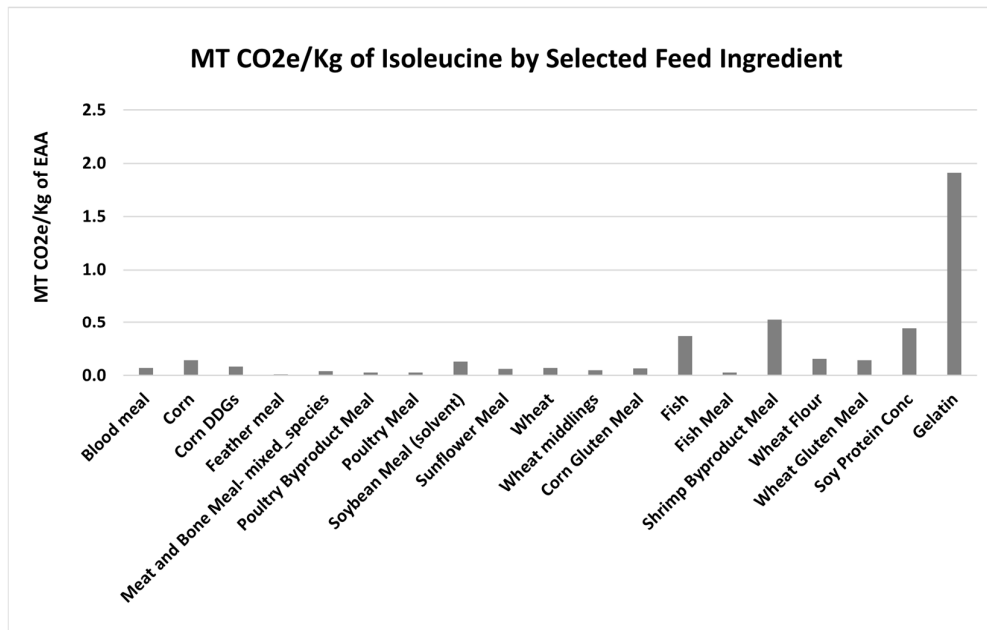


Figure 5. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Isoleucine.

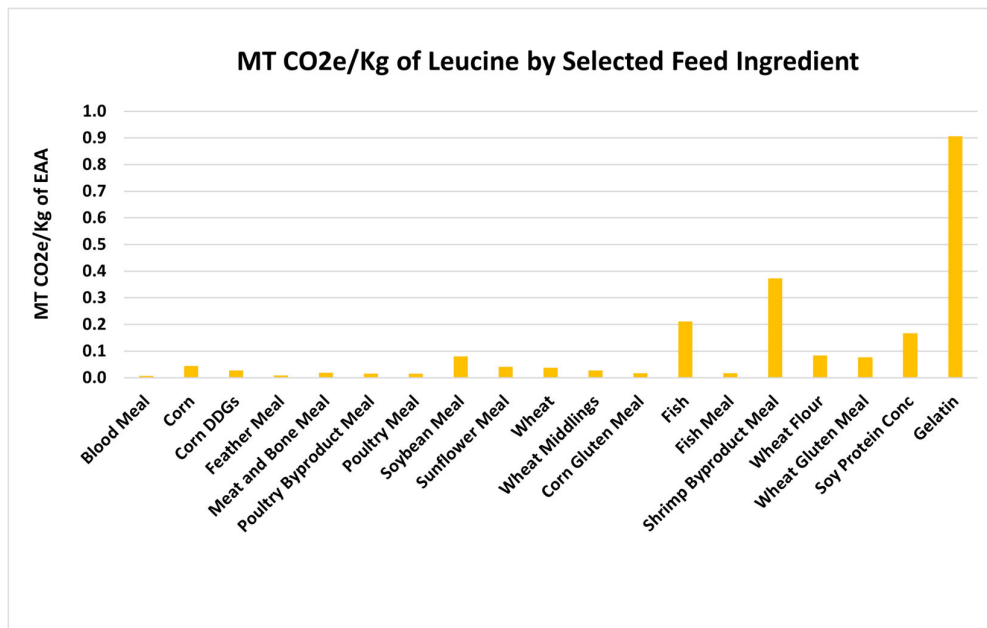


Figure 6. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Leucine.

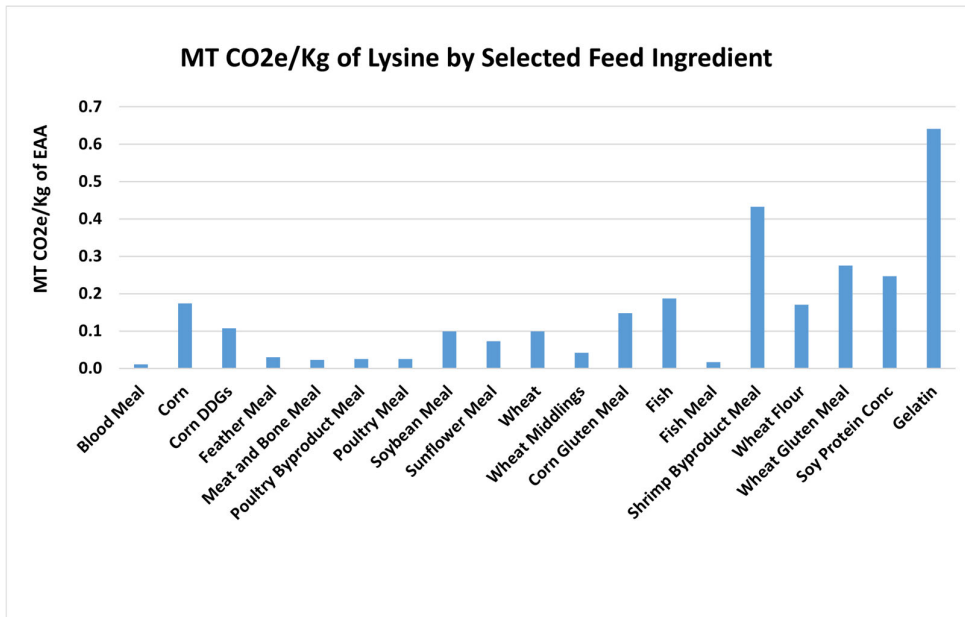


Figure 7. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Lysine.

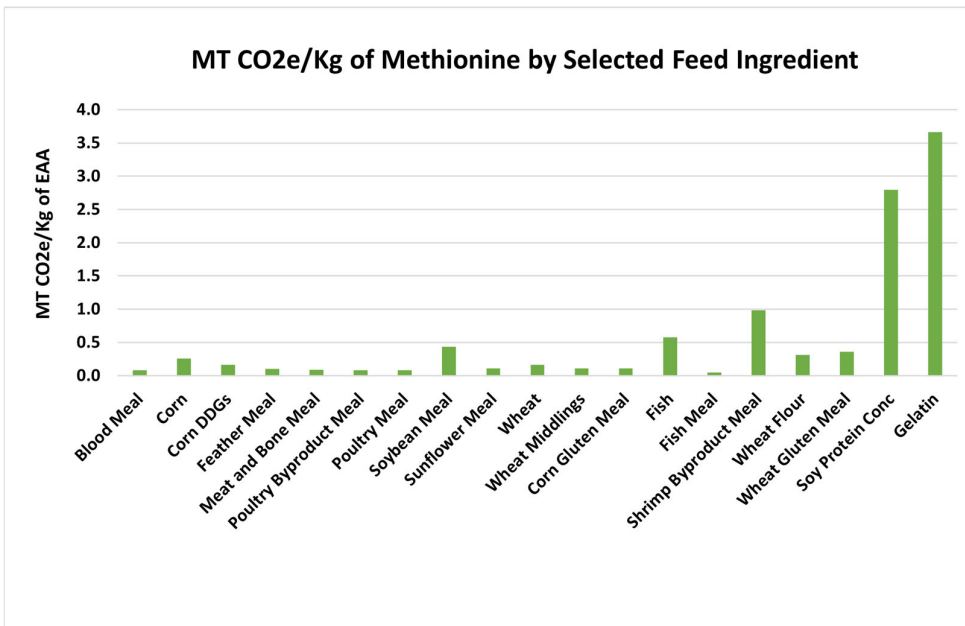


Figure 8. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Methionine.

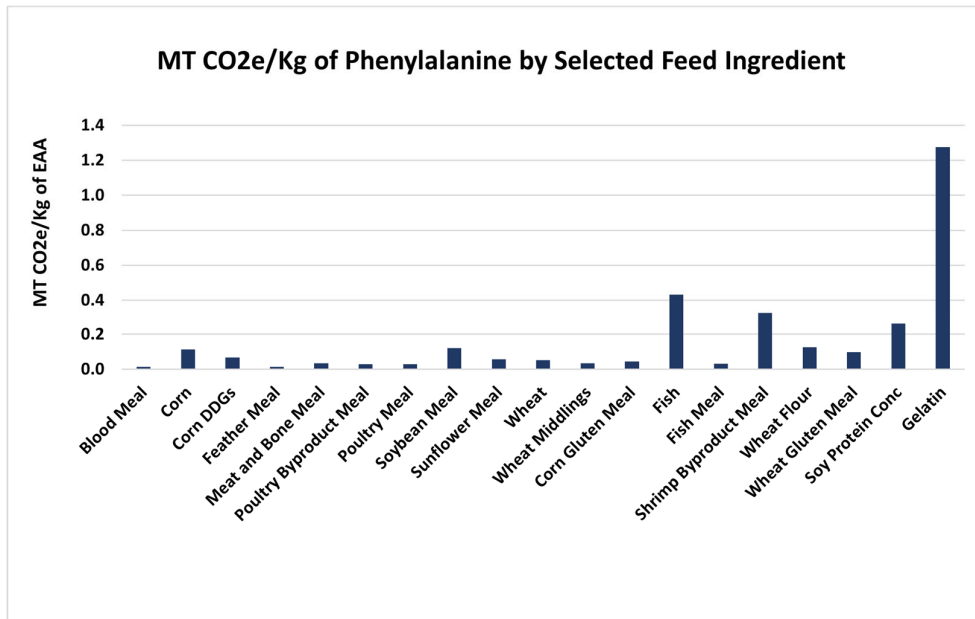


Figure 9. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Phenylalanine.

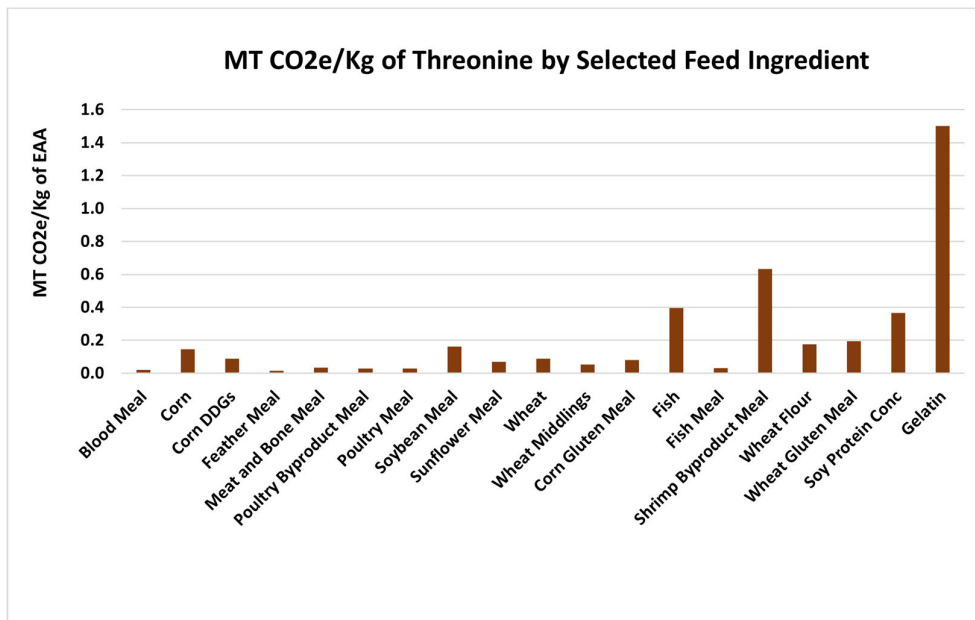


Figure 10. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Threonine.

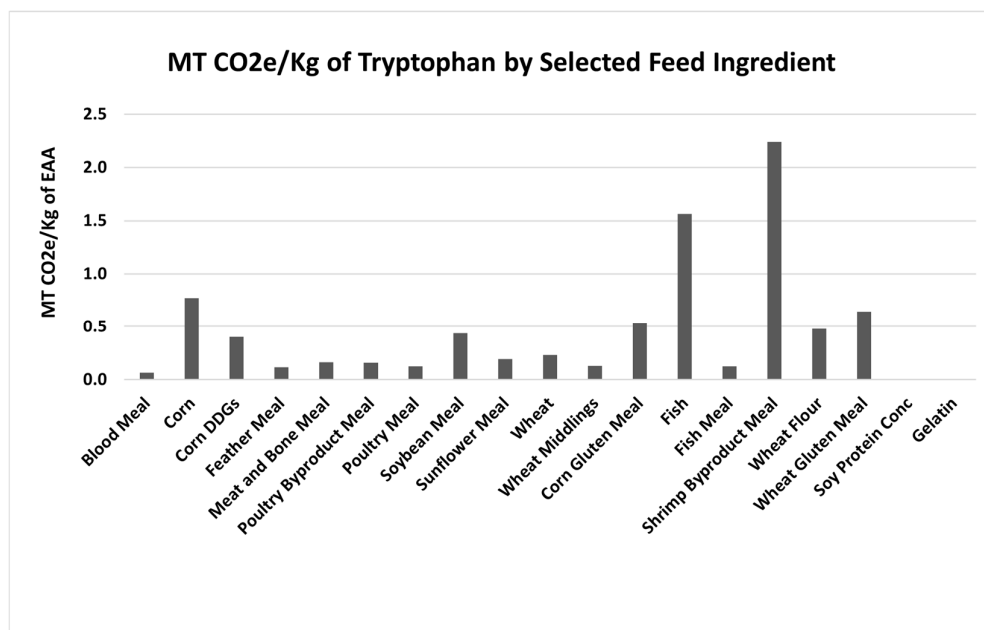


Figure 11. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Tryptophan.

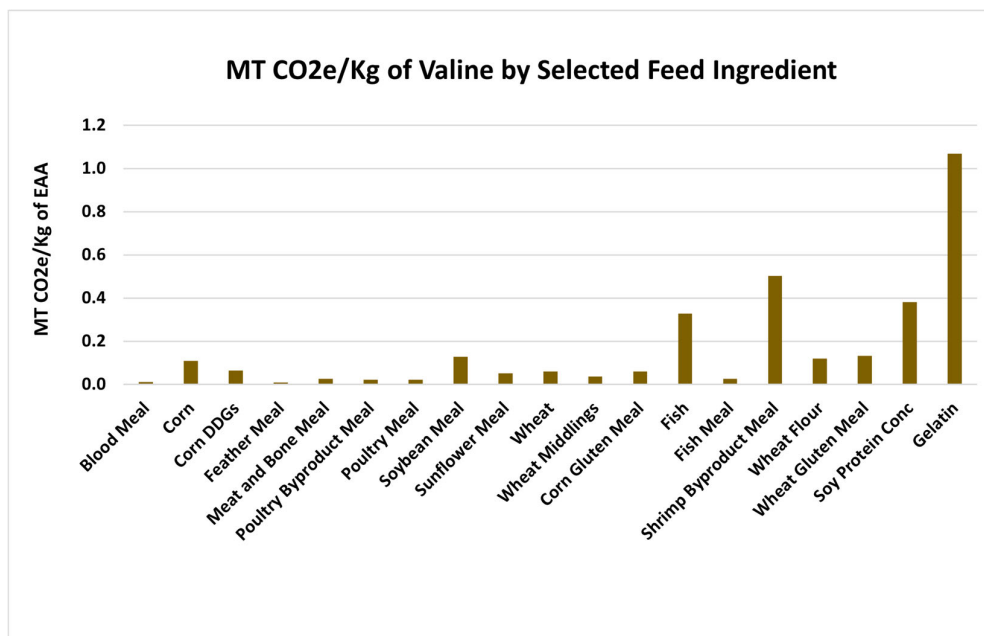


Figure 12. Aquaculture Ingredients: MT of CO<sub>2</sub>e/Kg of Valine.

For the three studied aquaculture species, analysis included a baseline and a scenario.

### 3.1. Nile Tilapia

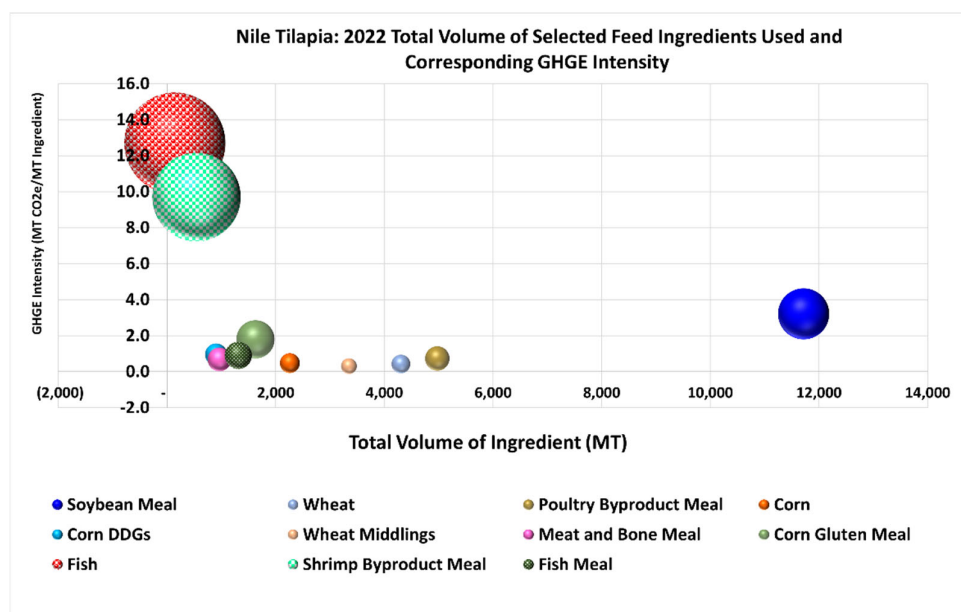
Based on information from Nile tilapia feed suppliers, four commercial feeds were provided. The average of these ingredients was calculated to create the baseline diet for Nile tilapia, shown in Table 1. Animal protein meals were led by poultry byproduct meal (13.8%), followed by fish meal (3.6%) and meat and bone meal (2.7%). Plant-based protein meals were led by soybean meal (32.4%), followed by corn gluten meal (4.5%) and corn dried distillers grains (corn DDGs) (2.5%).

**Table 1.** Estimated Nile Tilapia Baseline Diet.

Feed Ingredient	Nile Tilapia Baseline Diet (%)
Soybean Meal	32.4
Poultry Byproduct Meal	13.8
Wheat	11.9
Wheat Middlings	9.3
Corn	6.3
Corn Gluten Meal	4.5
Fish Meal	3.6
Meat and Bone Meal	2.7
Corn DDGs	2.5
Shrimp Byproduct Meal	1.5
Soybean Oil	1.3
DL Methionine	0.5
Fish <sup>1</sup>	0.4
Fish Oil	0.3
Rice	0.3
Lecithin	0.3
Feed Additives	8.7
Total	100.0

<sup>1</sup> “Fish” ingredient refers to general marine fish and applies to all references to “fish” in this Results section.

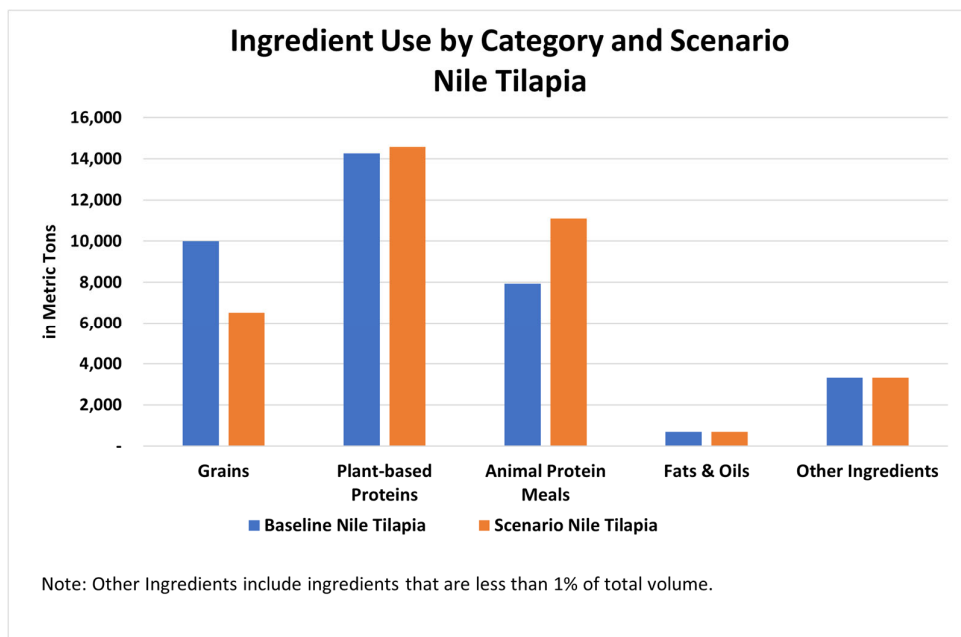
Figure 13 shows the total volume of selected feed ingredients used in Nile tilapia production in the U.S. based on baseline estimates and the corresponding GHGE intensities of those ingredients in the US. By far, soybean meal was the ingredient with the largest volume, with about 12,000 MT used in Nile tilapia baseline diet. The GHGE intensity of soybean meal was estimated at 3.2 MT CO<sub>2</sub>e/MT of soybean meal[13]. Poultry byproduct meal was in second place in terms of volume used in Nile tilapia (4,977 MT) in 2022. Note that, bubble size in Figure 13, Figure 21, Figure 29, and Figure 37 represents the GHGE intensity by ingredient. Source data are listed in Table A4 in Appendix A4.



**Figure 13.** 2022 Total Volume of Selected Feed Ingredients Used and Corresponding GHGE Intensity in Nile Tilapia Baseline Diet.

For Nile tilapia, the baseline scenario included 10.0 thousand MT of grains, 14.3 thousand MT of plant-based proteins, 7.9 thousand MT of animal protein meals, 681.7 MT of fats and oils and 3.3

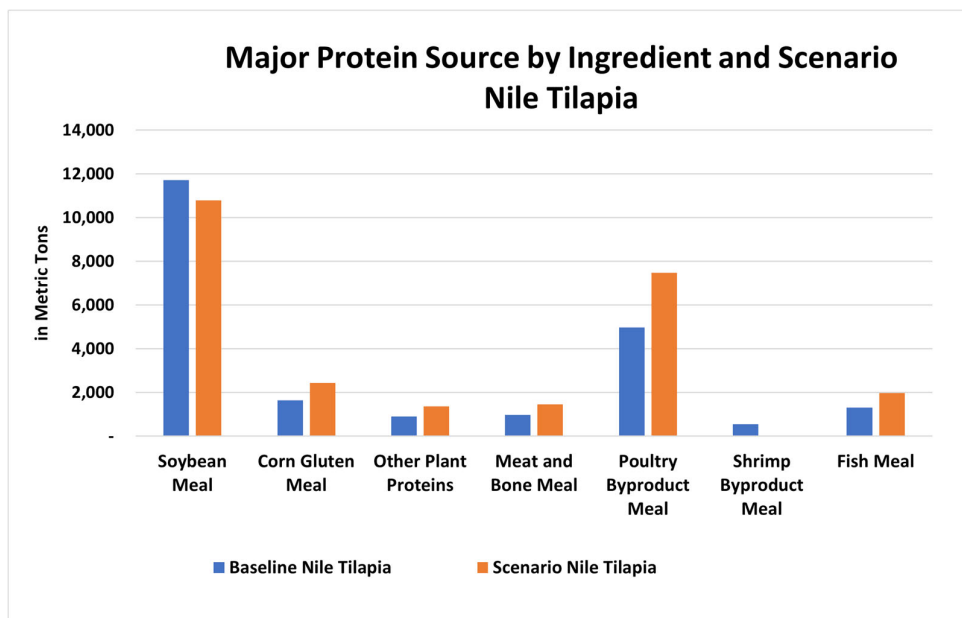
thousand MT of other ingredients. In the scenario for Nile tilapia, grains comprised 6.5 thousand MT of the Nile tilapia diet, plant-based proteins were 14.6 thousand MT, animal protein meals were 11.1 thousand MT, fats and oils were 681.7 MT, and 3.3 thousand MT of other ingredients, shown in Figure 14.



**Figure 14.** Ingredient Use by Category and Scenario in Nile Tilapia Diets.

Meeting Nile tilapia nutritional needs while minimizing GHGE results in a slight change in the mix of major protein meal sources used in Nile tilapia diets (Figure 15). In the baseline case, 11.7 thousand MT of soybean meal were included in the Nile tilapia diets, 1.6 thousand MT of corn gluten meal, 0.9 thousand MT of other plant-based protein meals, 9.6 thousand MT of Meat and Bone Meal, 5.0 thousand MT of poultry byproduct meal, 542.9 MT of shrimp byproduct meal, and 1.3 thousand MT of fish meal.

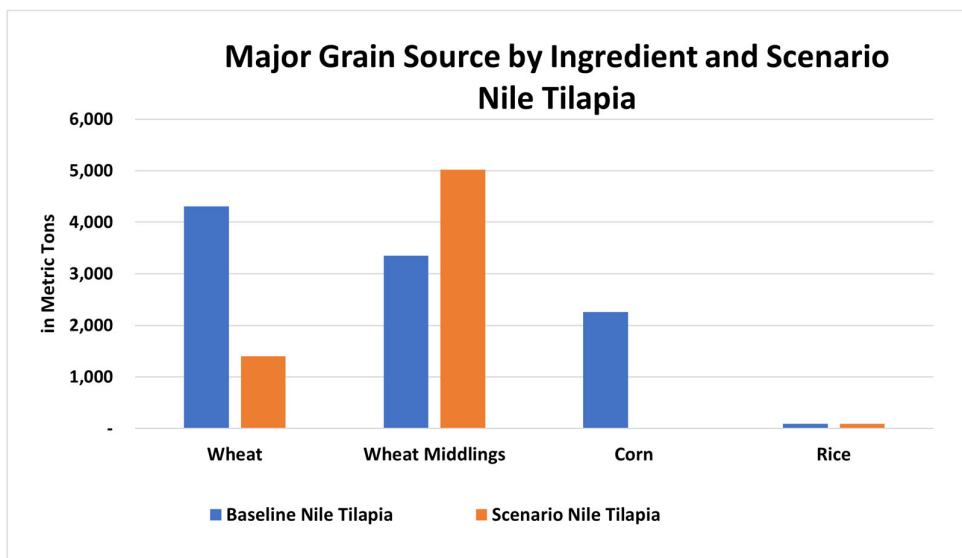
In the Nile tilapia scenario that minimizes GHGE, 10.8 thousand MT of soybean meal, a decline of 8.0%; 2.4 thousand MT of corn gluten meal, an increase of 50.0%; 1.4 thousand MT of other plant-based protein meals, an increase of 50.0%; 1.4 thousand MT of Meat and Bone Meal, an increase of 50.0%; 7.5 thousand MT of poultry byproduct meal, an increase of 50.0%; there was no shrimp byproduct meal included, a decline of 100%; and 2.0 thousand MT of fish meal, an increase of 50.0%.



**Figure 15.** Major Protein Meal Sources by Scenario in Nile Tilapia Diets.

Compared with major protein sources, minimizing GHGE results in a significant change in the mix of major grain sources used in Nile tilapia diets (Figure 16). In the baseline case, 4.3 thousand MT of wheat were included in the Nile tilapia diets, 3.3 thousand MT of wheat middlings, 2.3 thousand MT of corn and 90.5 MT of rice. In the Nile tilapia scenario that minimizes GHGE, 1.4 thousand MT of wheat were included in the Nile tilapia scenario diets, a decline of 67.4%; 5.0 thousand MT of wheat middlings, an increase of 50.0%; there was no corn included, a decline of 100%; and 90.5 MT of rice, with no change.

Nile tilapia is the only species that reduced GHGE from grains, while salmon and shrimp reduced GHGE from protein sources.



**Figure 16.** Major Grain Sources by Scenario in Nile Tilapia Diets.

Feed ingredient usage for both baseline and scenario of Nile tilapia are shown in Appendix Table A1. The GHGE for selected feed ingredients by scenario of Nile tilapia are shown in Appendix Table

A2. GHGE by EAA by ingredient aggregation and by scenario of Nile tilapia are shown in Appendix Table A3.

Total GHGE by EAA and scenario for Nile tilapia are shown in Figure 17. For Arginine, the scenario GHGE decreased by 2.8% compared to the baseline. Percentage change in GHGE for the other EAAs for the scenario are respectively: Histidine -2.1%, Isoleucine -2.5%, Leucine +3.0%, Lysine -2.6%, Methionine -0.2%, Phenylalanine -5.6%, Threonine -1.0%, Tryptophan -18.1%, and Valine -0.5%. Data is also shown in Table 1.

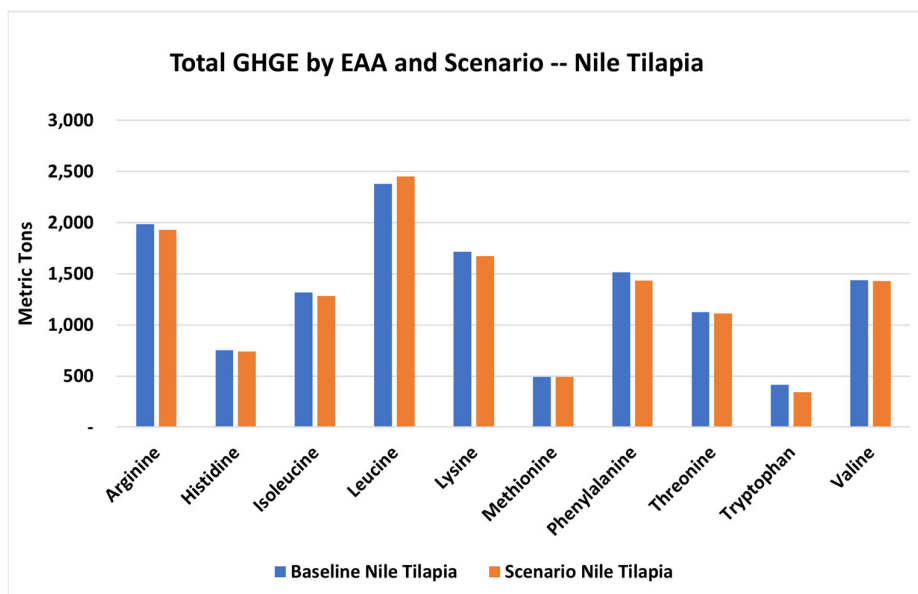


Figure 17. Total GHGE by EAA and Scenario in Nile Tilapia Diets.

GHGE by EAA for the grains portion of the Nile tilapia rations are shown in Figure 18, for the plant-based meals in Figure 19, and for the animal protein meals portion of the Nile tilapia rations in Figure 20.

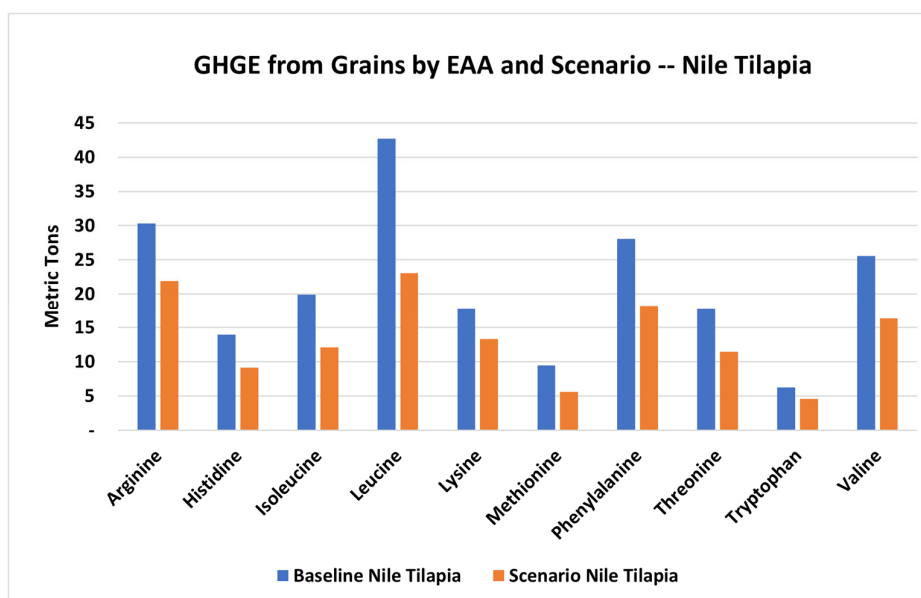


Figure 18. GHGE from Grains by EAA and Scenario in Nile Tilapia Diets.

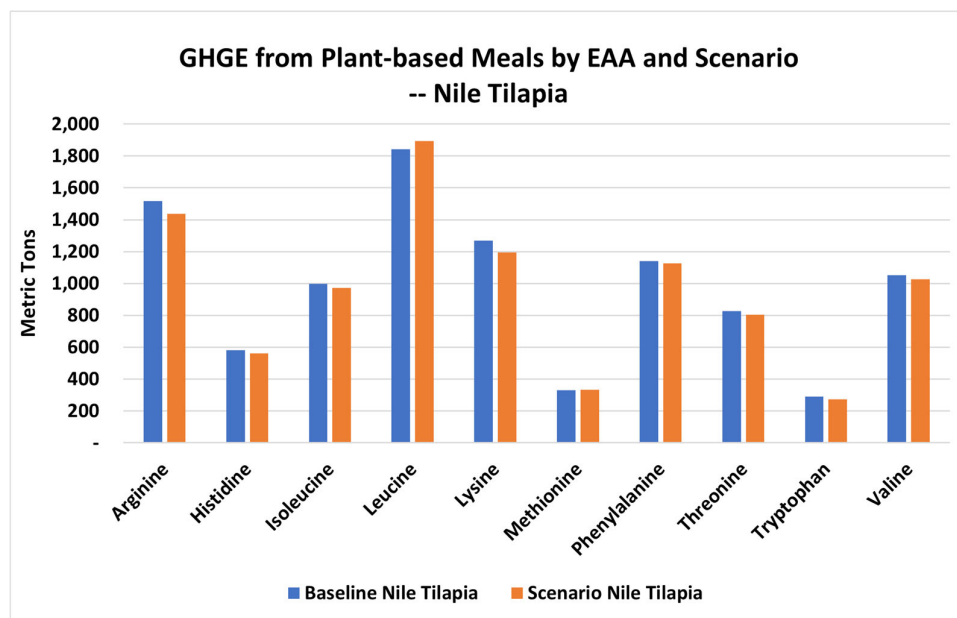


Figure 19. GHGE from Plant-based Meals by EAA and Scenario in Nile Tilapia Diets.

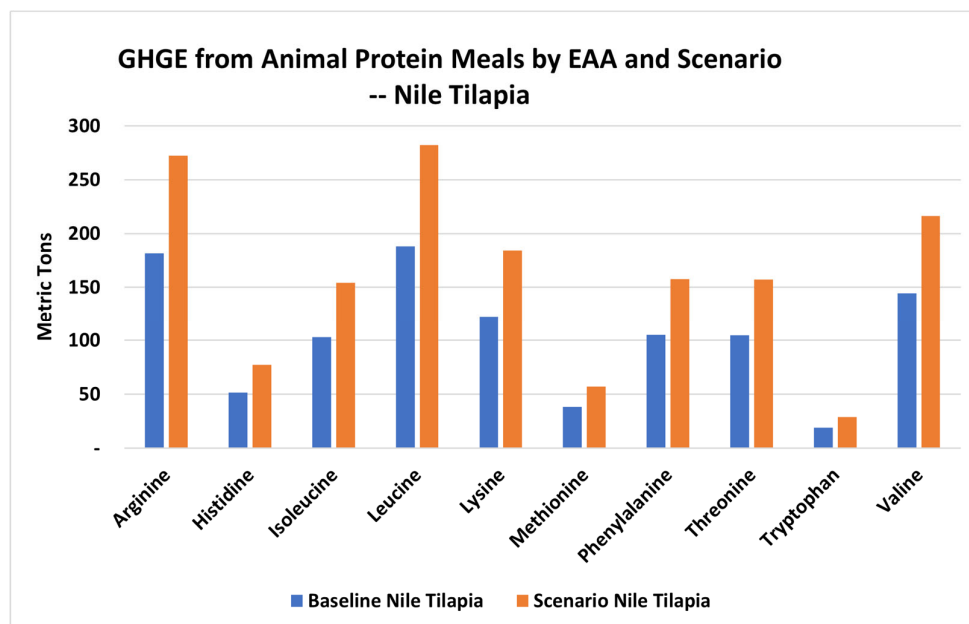


Figure 20. GHGE from Animal Protein Meals by EAA and Scenario in Nile Tilapia Diets.

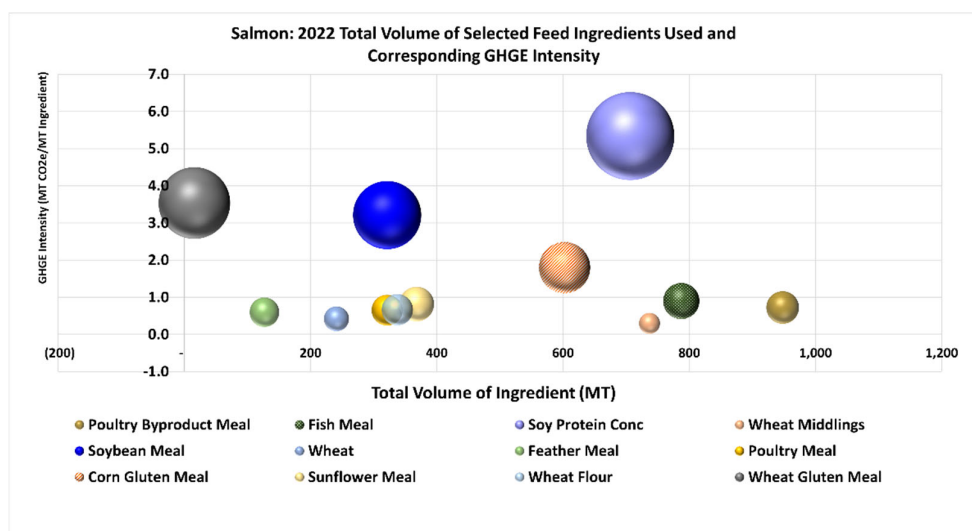
### 3.2. Salmon

Five commercial salmon feeds were provided by feed suppliers. The average of these ingredients was calculated to create the baseline diet for salmon, shown in Table 2. Animal protein meals were led by poultry byproduct meal (11.8%), followed by fish meal (9.8%) and poultry meal (4.0%). Plant-based protein meals were led by soy protein conc (8.8%), followed by corn gluten meal (7.5%) and sunflower meal (4.6%).

**Table 2.** Estimated Salmon Baseline Diet.

Feed Ingredient	Salmon Baseline Diet (%)
Soybean Oil	11.9
Poultry Byproduct Meal	11.8
Fish Meal	9.8
Wheat Middlings	9.2
Soy Protein Conc	8.8
Corn Gluten Meal	7.5
Fish Oil	6.5
Sunflower Meal	4.6
Wheat Flour	4.2
Poultry Meal	4.0
Soybean Meal	4.0
Wheat	3.0
Lecithin	2.3
Blood Meal	1.8
Poultry Fat	1.7
Lysine	1.6
Feather Meal	1.6
DL Methionine	0.5
Wheat Gluten Meal	0.2
Histidine	0.2
Threonine	0.1
Feed Additives	4.9
Total	100.0

Figure 21 shows the total volume of selected feed ingredients used in salmon baseline diet. The largest volume of ingredient used corresponded to poultry byproduct meal with 948.0 MT, followed by fish meal (787.6 MT). The GHGE intensity of poultry byproduct meal was estimated at 0.7 MT CO<sub>2</sub>e/MT of this feed ingredient.



**Figure 21.** 2022 Total Volume of Selected Feed Ingredients Used and Corresponding GHGE Intensity in Salmon Baseline Diet.

For salmon, the baseline scenario included 1.3 thousand MT of grains, 2.0 thousand MT of plant-based proteins, 2.3 thousand MT of animal protein meals, 1.8 thousand MT of fats and oils and 0.5 thousand MT of other ingredients. In the scenario for salmon, grains comprised 1.7 thousand MT of the salmon diet, plant-based proteins were 0.8 thousand MT, animal protein meals were 3.2 thousand

MT, fats and oils were 1.8 thousand MT, and 0.5 thousand MT of other ingredients, shown in Figure 22.

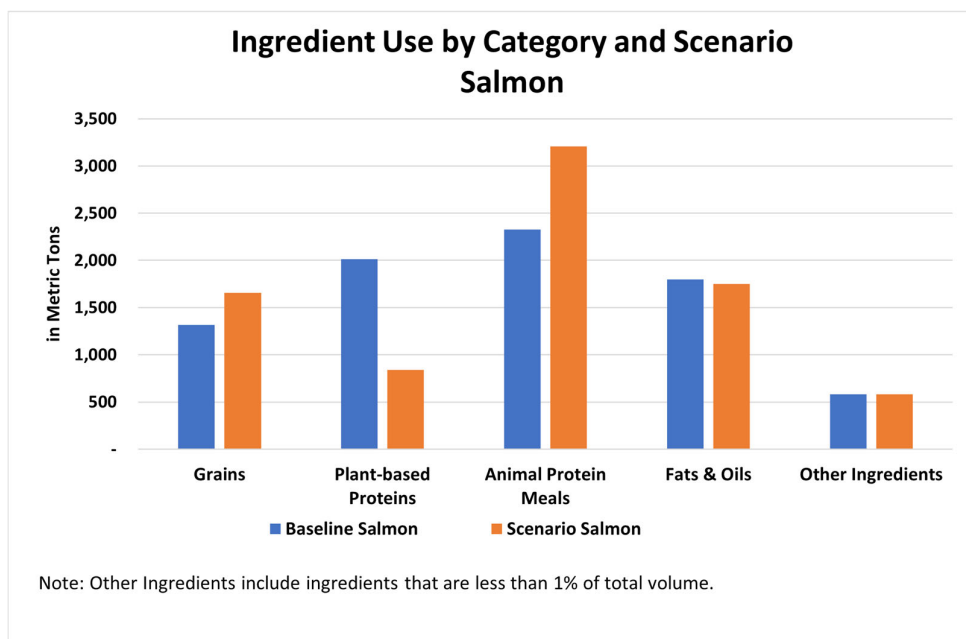


Figure 22. Ingredient Use by Category and Scenario in Salmon Diets.

Meeting salmon nutritional needs while minimizing GHGE results in a significant change in the mix of major protein meal sources used in salmon diets (shown in Figure 23).

In the baseline case, 321.5 MT of soybean meal were included in the salmon diets, 602.6 MT of corn gluten meal, 1.1 thousand MT of other plant-based protein meals, 0.9 thousand MT of poultry byproduct meal, and 0.8 thousand MT of fish meal. In the salmon scenario that minimizes GHGE, there was no soybean meal included, a decline of 100%; 0.4 thousand MT of corn gluten meal, a decline of 37.3%; 0.5 thousand MT of other plant-based protein meals, a decline of 57.8%; 1.4 thousand MT of poultry byproduct meal, an increase of 50.0%; and 1.2 thousand MT of fish meal, an increase of 50.0%.

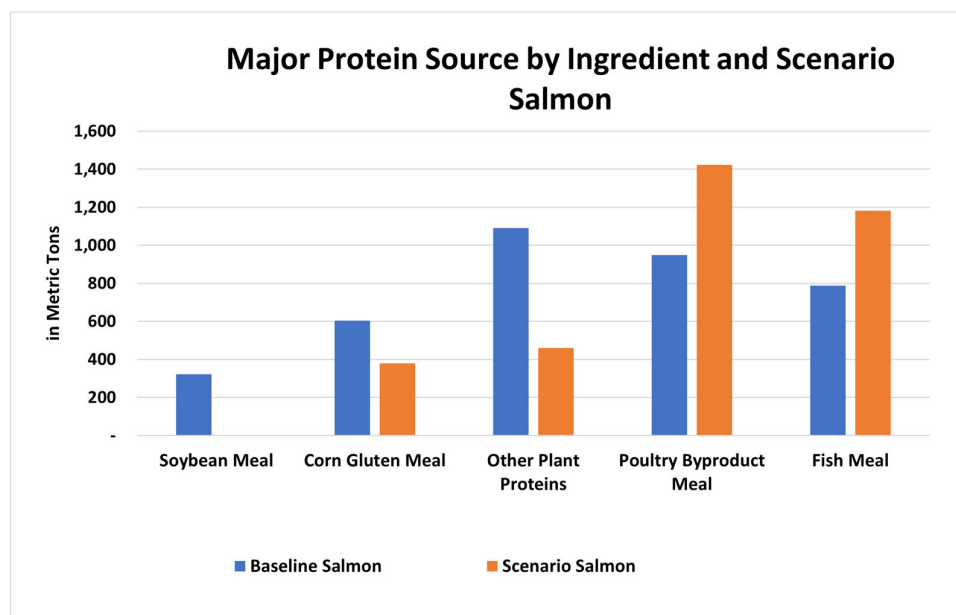


Figure 23. Major Protein Meal Sources by Scenario in Salmon Diets.

Compared with major protein sources, minimizing GHGE results in a significant change in the mix of major grain sources used in salmon diets (Figure 24). In the baseline case, 241.1 MT of wheat were included in the salmon diets, 0.7 thousand MT of wheat middlings, 337.6 MT of wheat flour. In the salmon scenario that minimizes GHGE, 231.9 MT of wheat were included in the salmon scenario diets, a decline of 3.8%; 1.1 thousand MT of wheat middlings, an increase of 50.0% 320.0 MT of wheat flour, a decline of 5.2%; there was no corn or rice included in either diet.

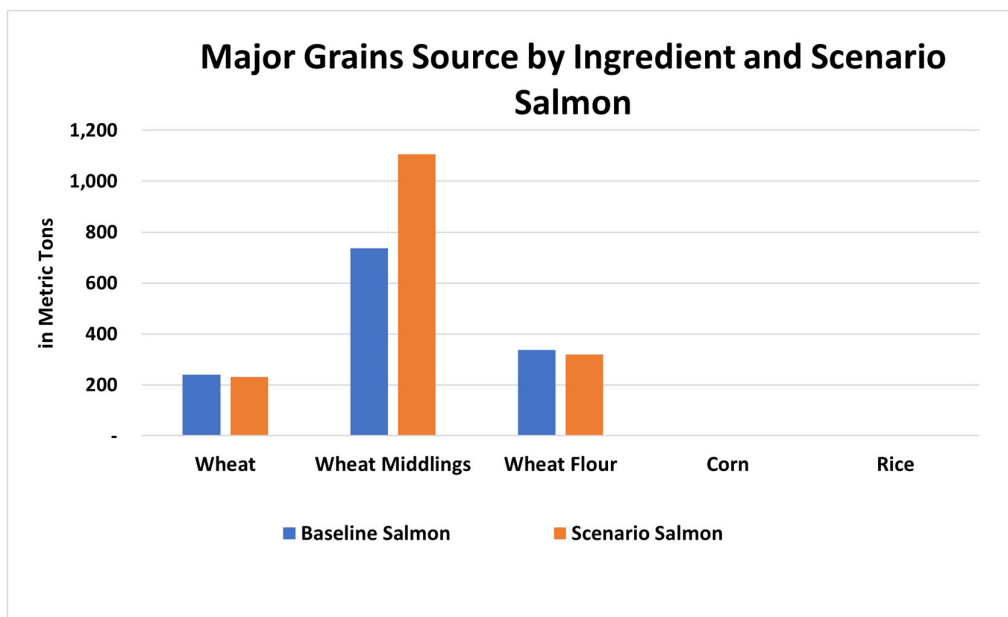


Figure 24. Major Grain Sources by Scenario in Salmon Diets.

Feed ingredient usage for both baseline and scenario of salmon are shown in Appendix Table A1. The GHGE for selected feed ingredients by scenario of salmon are shown in Appendix Table A2. GHGE by EAA by ingredient aggregation and by scenario of salmon are shown in Appendix Table A3.

Total GHGE by EAA and scenario for salmon are shown in Figure 25. For Arginine, the scenario GHGE decreased by 48.0% compared to the baseline. Percentage change in GHGE for the other EAAs for the scenario were respectively: Histidine -42.1%, Isoleucine -39.6%, Leucine -42.5%, Lysine -41.5%, Methionine -18.2%, Phenylalanine -46.6%, Threonine -39.8%, Tryptophan -72.8%, and Valine -31.9%. Data is also shown in Table 1.

GHGE by EAA for the grains portion of the salmon rations are shown in Figure 26, for the plant-based meals in Figure 27, and for the animal protein meals portion of the salmon rations in Figure 28.

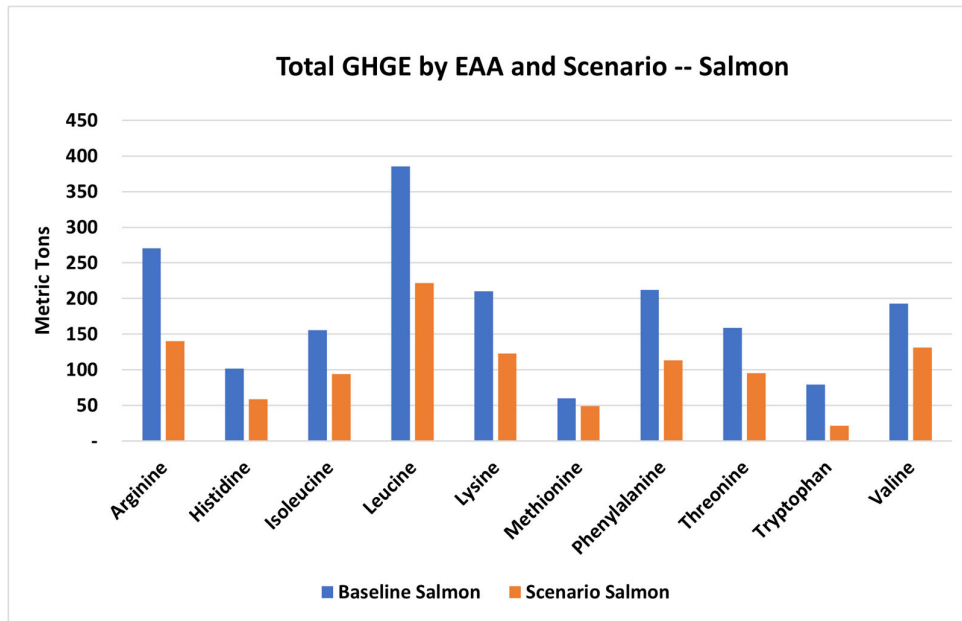


Figure 25. Total GHGE by EAA and Scenario in Salmon Diets.

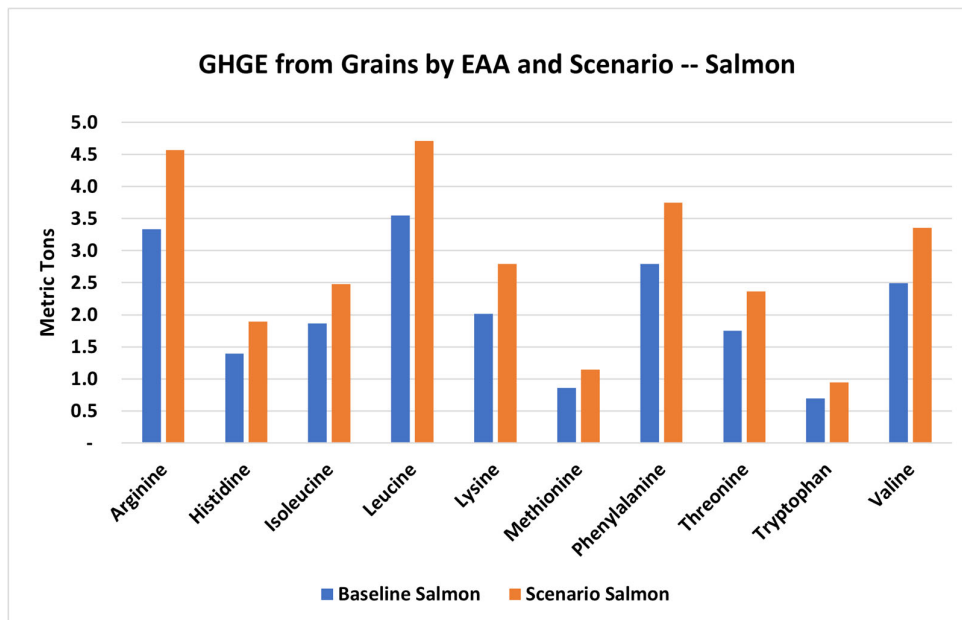


Figure 26. GHGE from Grains by EAA and Scenario in Salmon Diets.

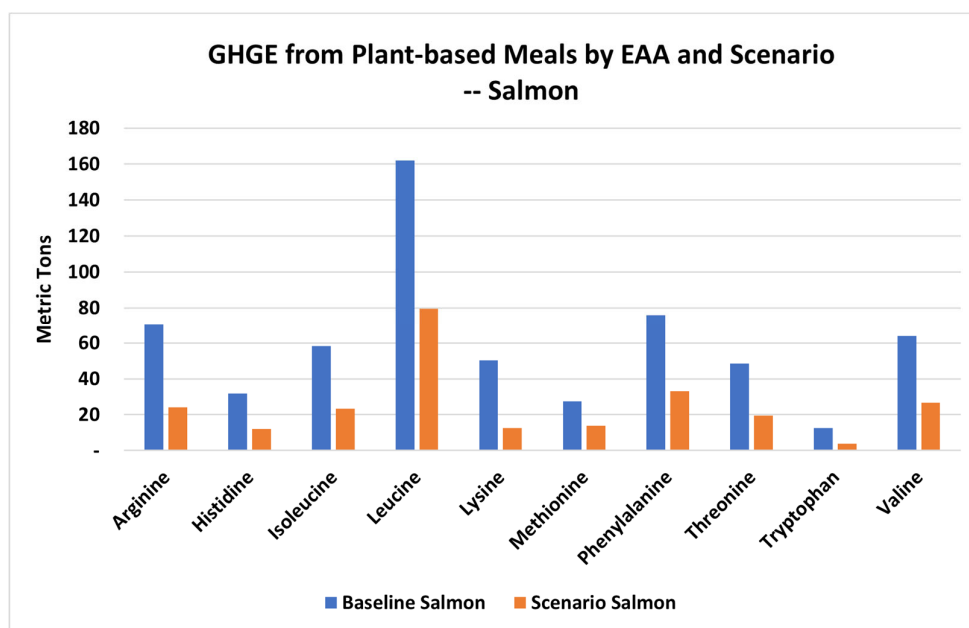


Figure 27. GHGE from Plant-based Meals by EAA and Scenario in Salmon Diets.

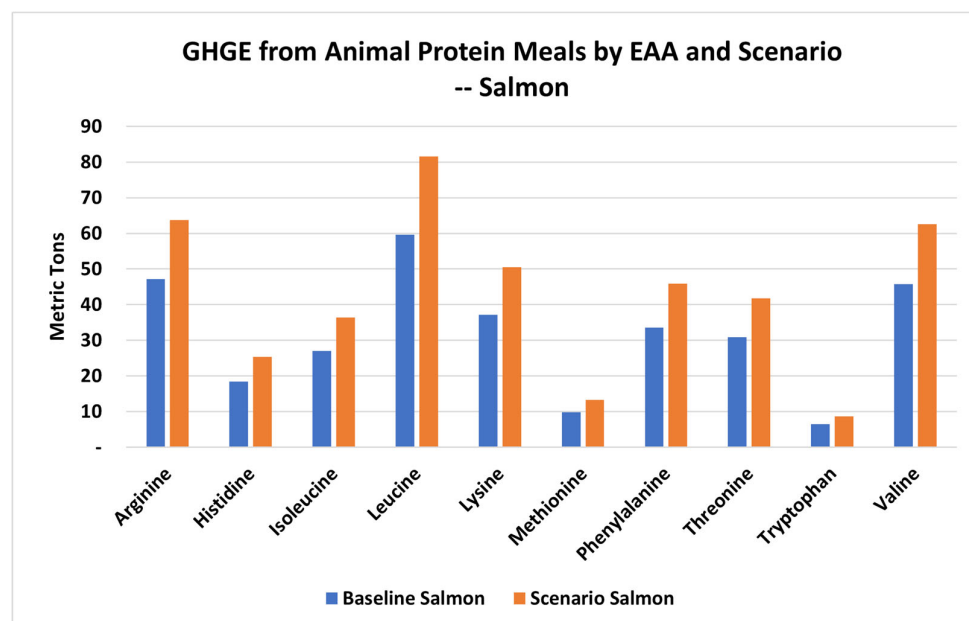


Figure 28. GHGE from Animal Protein Meals by EAA and Scenario in Salmon Diets.

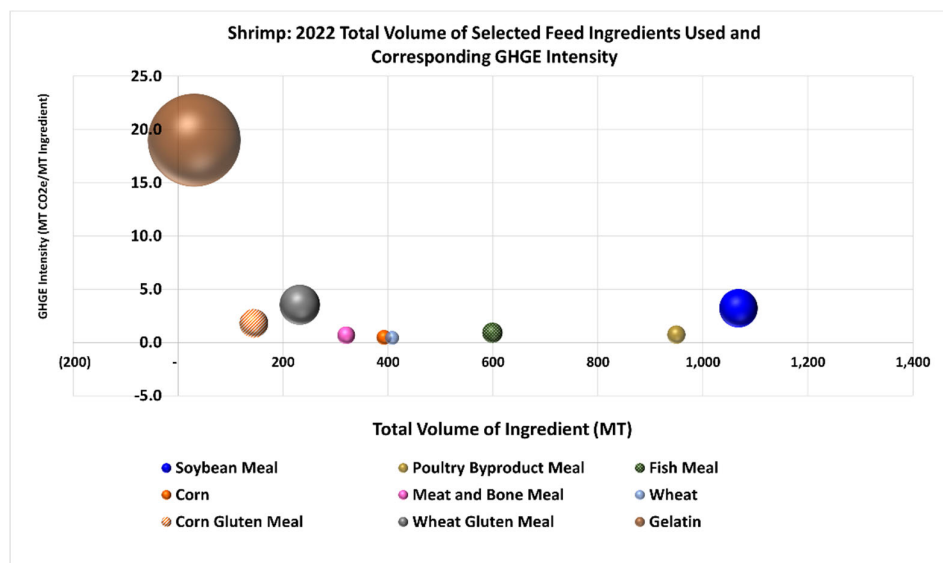
### 3.3. Shrimp

Based on information from shrimp feed suppliers, ten commercial feeds were provided. The average of these ingredients was calculated to create the baseline diet for shrimp, shown in Table 3. Animal protein meals were led by poultry byproduct meal (20.5%), followed by fish meal (12.9%) and meat and bone meal (6.9%). Plant-based protein meals were led by soybean meal (23.0%), followed by wheat gluten meal (5.0%) and corn gluten meal (3.1%).

**Table 3.** Estimated Shrimp Baseline Diet.

Feed Ingredient	Shrimp Baseline Diet (%)
Soybean Meal	23.0
Poultry Byproduct Meal	20.5
Fish Meal	12.9
Wheat	8.8
Corn	8.5
Meat and Bone Meal	6.9
Wheat Gluten Meal	5.0
Corn starch	4.2
Corn Gluten Meal	3.1
Fish Oil	1.6
Soybean Oil	1.0
Lecithin	0.9
Gelatin	0.7
Inedible Tallow	0.2
Feed Additives	2.8
Total	100.0

Figure 29 shows the total volume of selected feed ingredients used in shrimp baseline diet for U.S. production. Soybean meal was the ingredient with the largest volume used in the diet, with the estimated tonnage of 1,067.8 MT. Poultry byproduct meal, with 949.4 MT, was in second place in terms of volume used in the shrimp diet in 2022.



**Figure 29.** 2022 Total Volume of Selected Feed Ingredients Used and Corresponding GHGE Intensity in Shrimp Baseline Diet.

For shrimp, the baseline scenario included 1.0 thousand MT of grains, 1.4 thousand MT of plant-based proteins, 1.9 thousand MT of animal protein meals, 174.9 MT of fats and oils and 129.0 MT of other ingredients. In the scenario for shrimp, grains comprised 1.2 thousand MT of the salmon diet, plant-based proteins were 0.8 thousand MT, animal protein meals were 2.3 thousand MT, fats and oils were 174.9 MT, and 129.0 MT of other ingredients, shown in Figure 30.

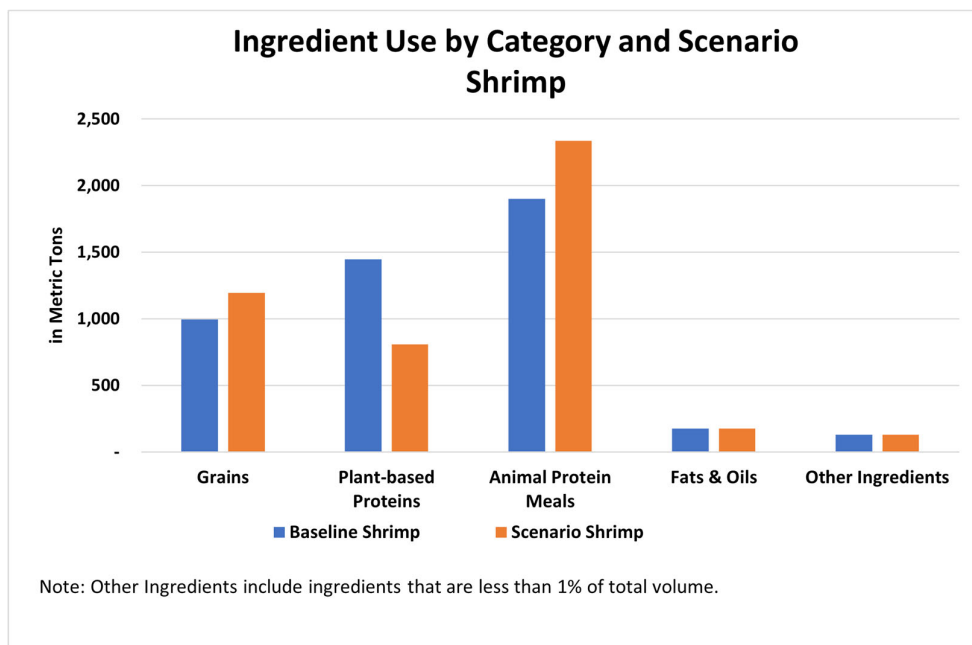


Figure 30. Ingredient Use by Category and Scenario in Shrimp Diets.

Meeting shrimp nutritional needs while minimizing GHGE results in a significant change in the mix of major protein meal sources used in shrimp diets (shown in Figure 31).

In the baseline case, 1.1 thousand MT of soybean meal were included in shrimp diets, 144.4 MT of corn gluten meal, 232.1 MT of other plant-based protein meals, 320.3 MT of meat and bone meal, 0.9 thousand MT of poultry byproduct meal, and 0.6 thousand MT of fish meal. In the shrimp scenario that minimizes GHGE, there was 0.6 thousand MT soybean meal included, a decline of 41.2%; 180.5 MT of corn gluten meal, an increase of 25.0%; other plant-based protein meals were removed in scenario diets, a decline of 100%; 400.4 MT of meat and bone meal, an increase of 25.0%; 1.2 thousand MT of poultry byproduct meal, an increase of 25.0%; and 0.7 thousand MT of fish meal, an increase of 25.0%.

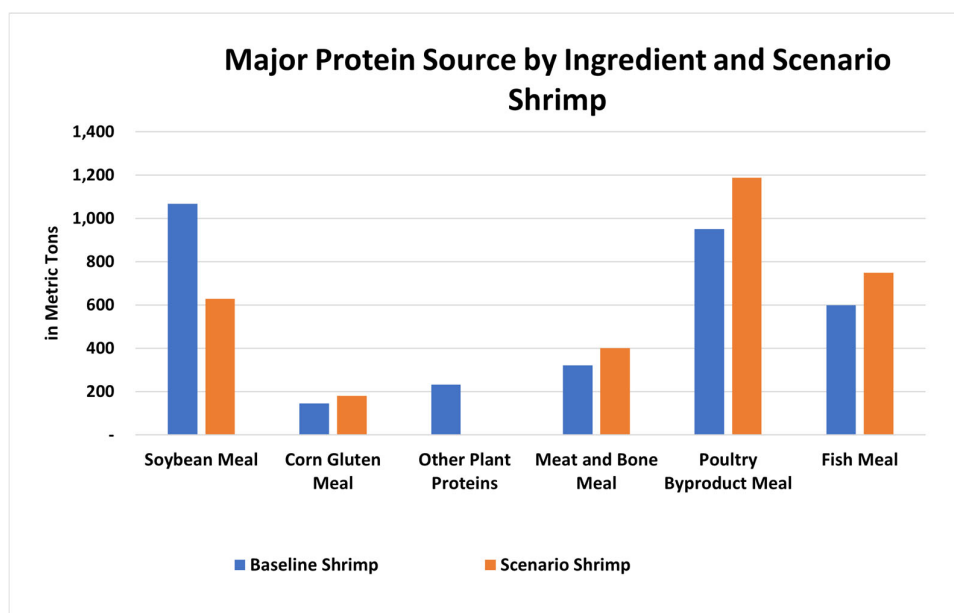


Figure 31. Major Protein Meal Sources by Scenario in Shrimp Diets.

Compared with major protein sources, minimizing GHGE results in a significant change in the mix of major grain sources used in shrimp diets (Figure 32). Only wheat and corn were included in the baseline shrimp diets. In the baseline case, 407.9 MT of wheat were included in the shrimp diets, and 392.3 MT of corn. In the shrimp scenario that minimizes GHGE, 509.9 MT of wheat and 490.4 MT of corn were included in the shrimp scenario diets, with both ingredients increasing by 25.0%.

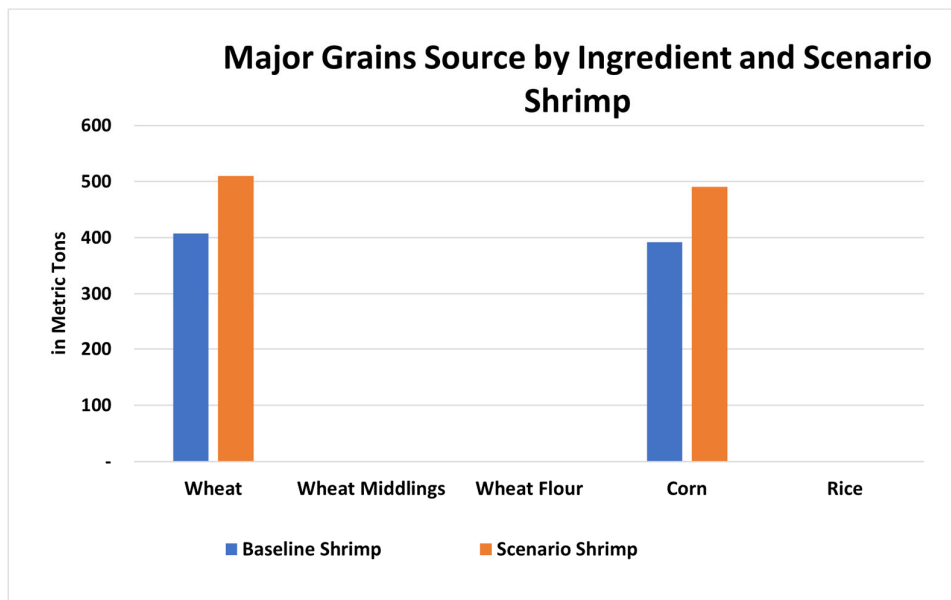


Figure 32. Major Grain Sources by Scenario in Shrimp Diets.

Feed ingredient usage for both baseline and scenario of shrimp are shown in Appendix Table A1. The GHGE for selected feed ingredients by scenario of shrimp are shown in Appendix Table A2. GHGE by EAA by ingredient aggregation and by scenario of shrimp are shown in Appendix Table A3.

Total GHGE by EAA and scenario for shrimp are shown in Figure 33. For Arginine, the scenario GHGE decreased by 36.4% compared to the baseline. Percentage change in GHGE for the other EAAs for the scenario are respectively: Histidine -32.5%, Isoleucine -31.7%, Leucine -28.7%, Lysine -29.8%, Methionine -26.3%, Phenylalanine -35.5%, Threonine -29.2%, Tryptophan -51.8%, and Valine -6.7%. Data is also shown in Table 1.

GHGE by EAA for the grains portion of the shrimp rations are shown in Figure 34, for the plant-based meals in Figure 35, and for the animal protein meals portion of the shrimp rations in Figure 36.

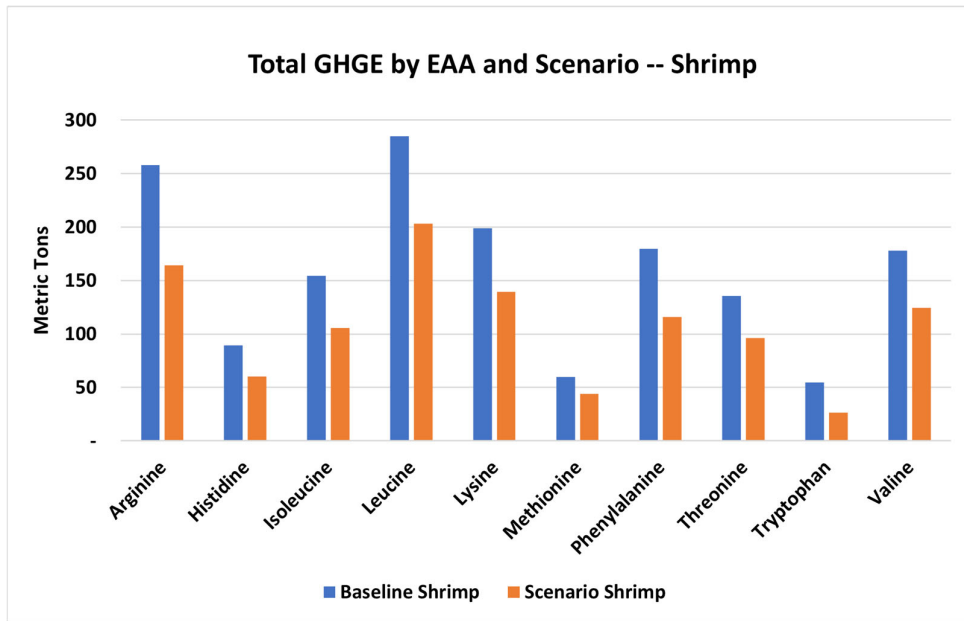


Figure 33. Total GHGE by EAA and Scenario in Shrimp Diets.

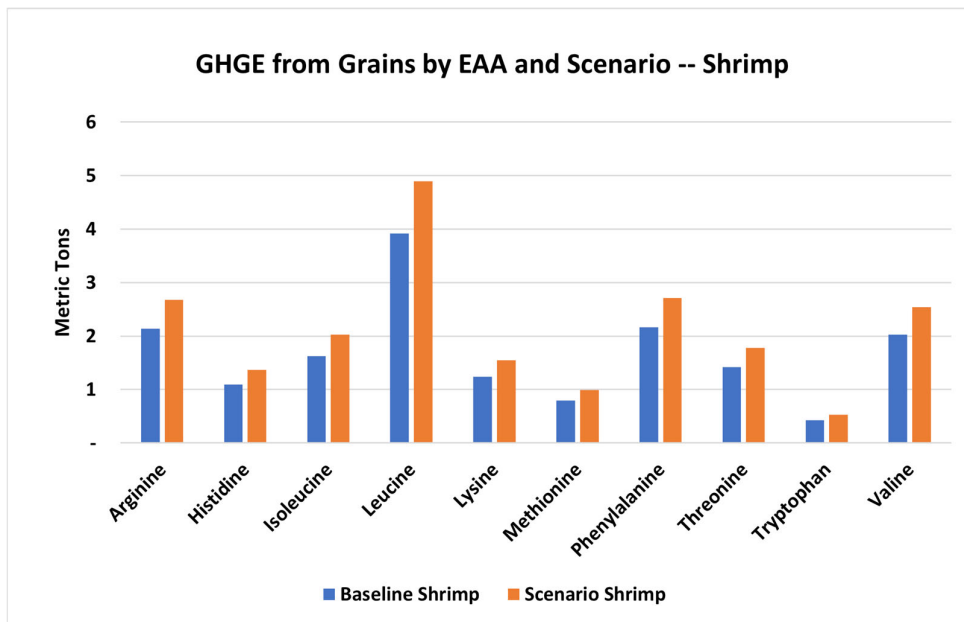


Figure 34. GHGE from Grains by EAA and Scenario in Shrimp Diets.

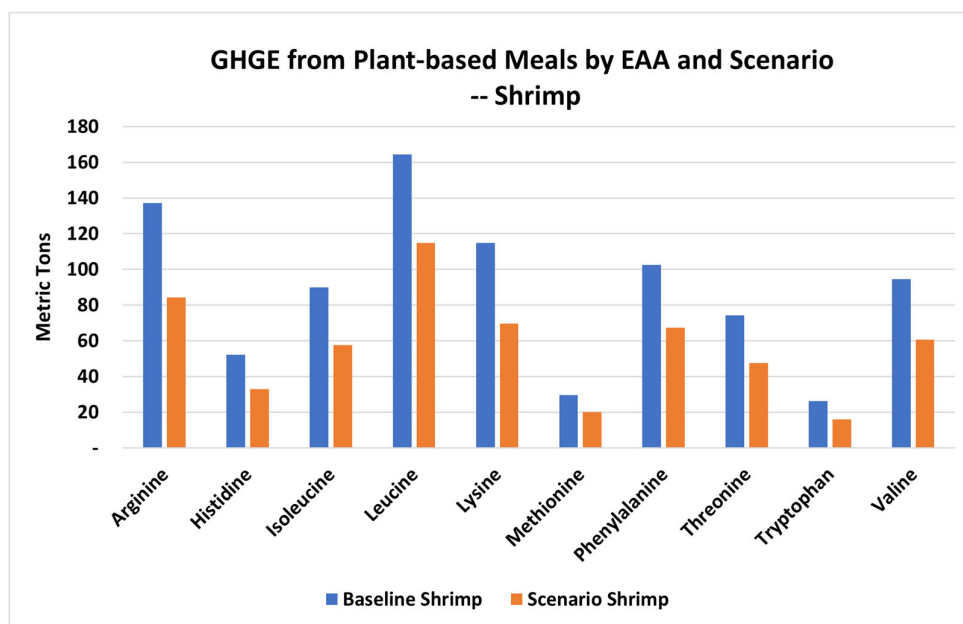


Figure 35. GHGE from Plant-based Meals by EAA and Scenario in Shrimp Diets.

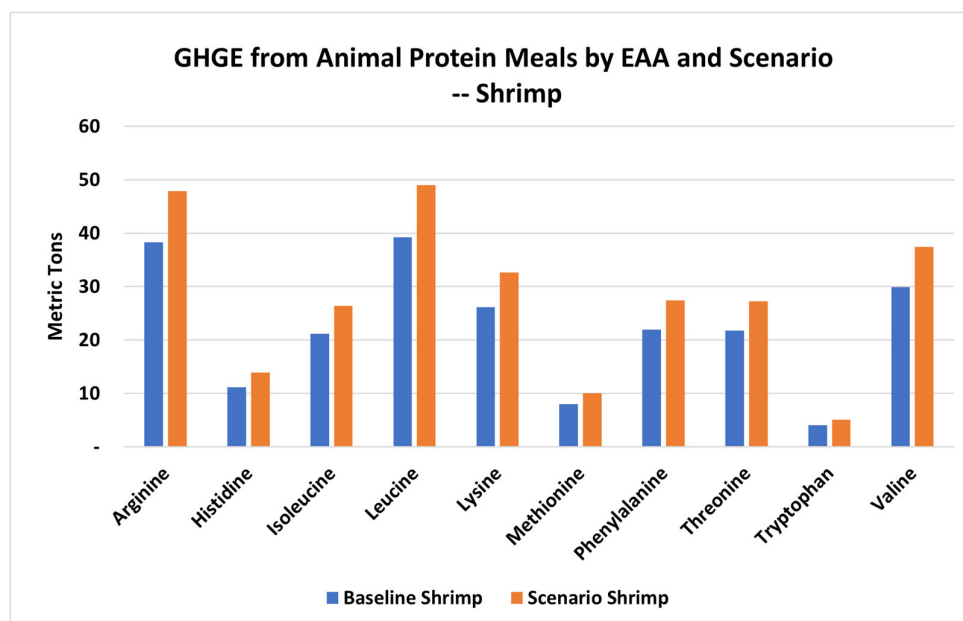


Figure 36. GHGE from Animal Protein Meals by EAA and Scenario in Shrimp Diets.

### 3.4. Studied Aquaculture Total

Total volume of selected feed ingredients used in the studied species, based on baselient estimates and the corresponding GHGE intensities of those ingredients, is shown in Figure 37. The tonnage used of soybean meal was the largest (13,107.8 MT) compared with all the other ingredients due to the large consumption in Nile tilapia feed. In addition, the ingredient with the second largest usage volume across all species was poultry byproduct meal with 6,874.4 MT. Gelatin, the feed ingredient with the highest GHGE value (19.0 MT CO<sub>2</sub>e/MT ingredient) among all the ingredients used in this study for aquaculture, had the lowest volume used with 31.0 MT. Gelatin was only used in shrimp production.

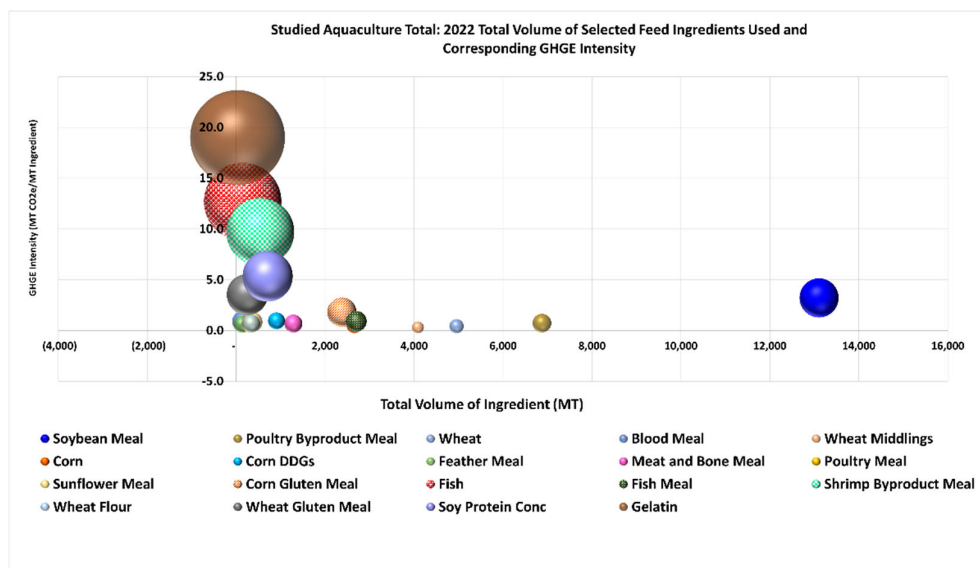


Figure 37. Total Volume of Selected Feed Ingredients Used and Corresponding GHGE Intensity in 2022 from Baseline Diets.

Based on the volume of each feed ingredient used in 2022 (according to the baseline analysis) for Nile tilapia, salmon and shrimp, the total land used (number of acres) to produce the corresponding volume of ingredient was estimated (in MT). The sources of land use data for aquaculture ingredients came from the GFLI database. Figure 38 shows the land used for the volumes of ingredients consumed in 2022 according to baseline analysis. Since soybean meal is the top feed ingredient used (in terms of volume) in aquaculture diets, it requires the largest land area. For the 13,107.8 MT of soybean used in aquaculture diets, 11,807 acres of land were required. Although the volume of poultry byproduct meal (6,874.4 MT) used in aquaculture was larger than that of wheat (4,957.6 MT), land use estimation (acres) was much larger for wheat (4,114 acres) than that of poultry byproduct meal (1,128 acres) due to the former having a higher land use factor (0.83 acres / MT ingredient) than poultry byproduct meal (0.16 acres / MT ingredient).

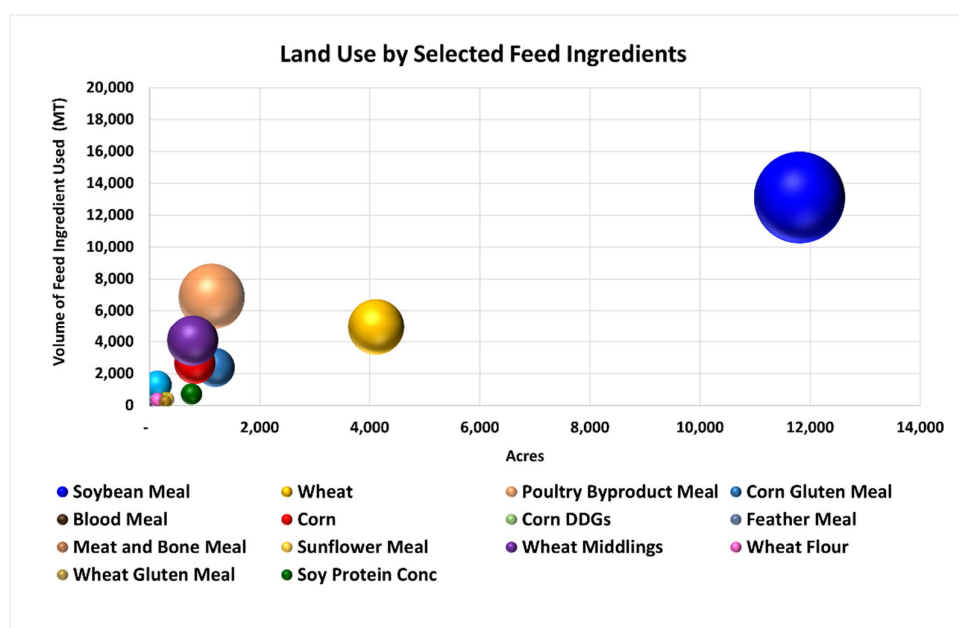
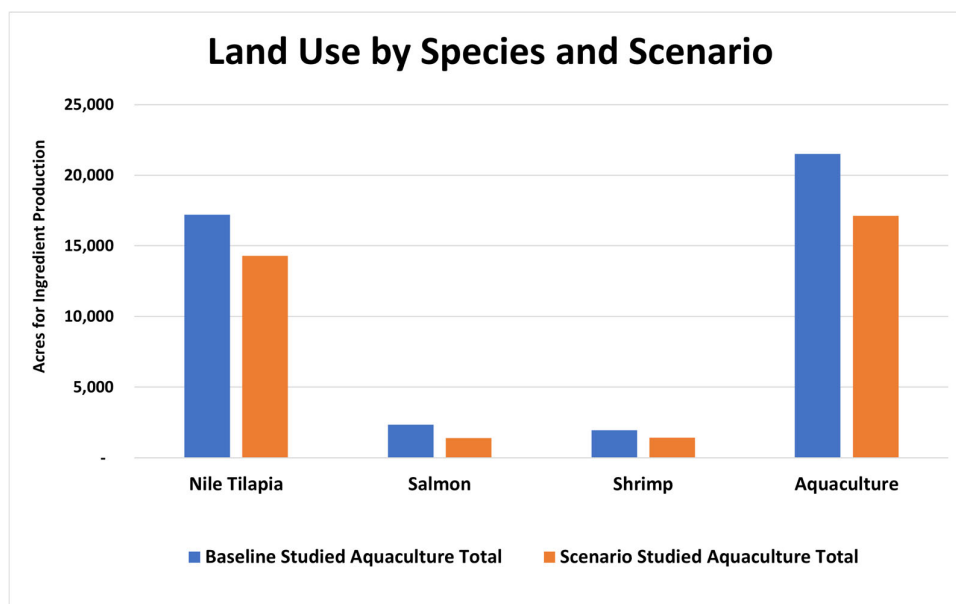


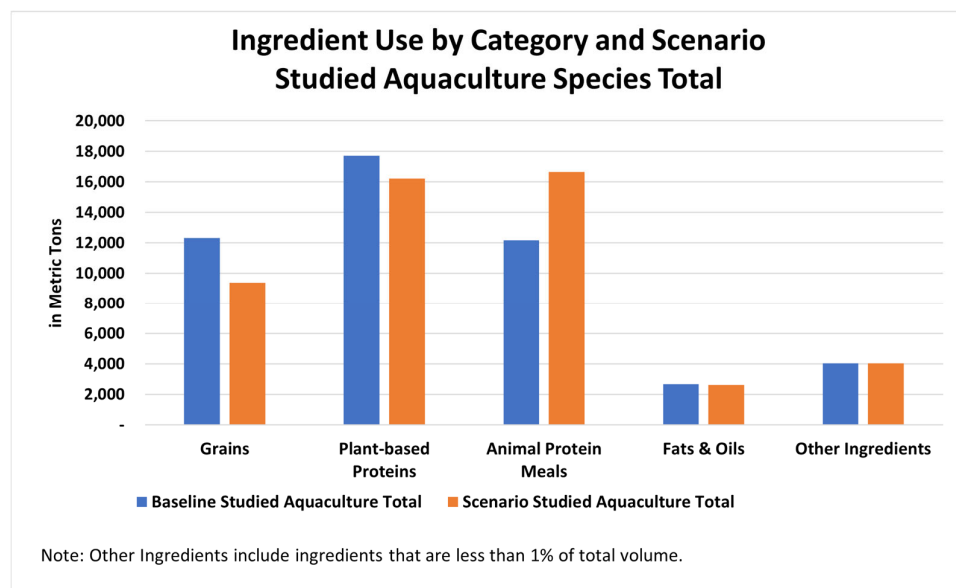
Figure 38. Land Use by Selected Ingredients used in Baseline Diets.

Land use impacts of the scenario result in a 20% overall reduction in land use for aquaculture rations compared with the baseline. Land use for Nile tilapia rations is 16% less than the baseline. For salmon and shrimp, there is a 40% and 27% reduction in land use, respectively, shown in Figure 39.



**Figure 39.** Total Land Use by Species and Scenario.

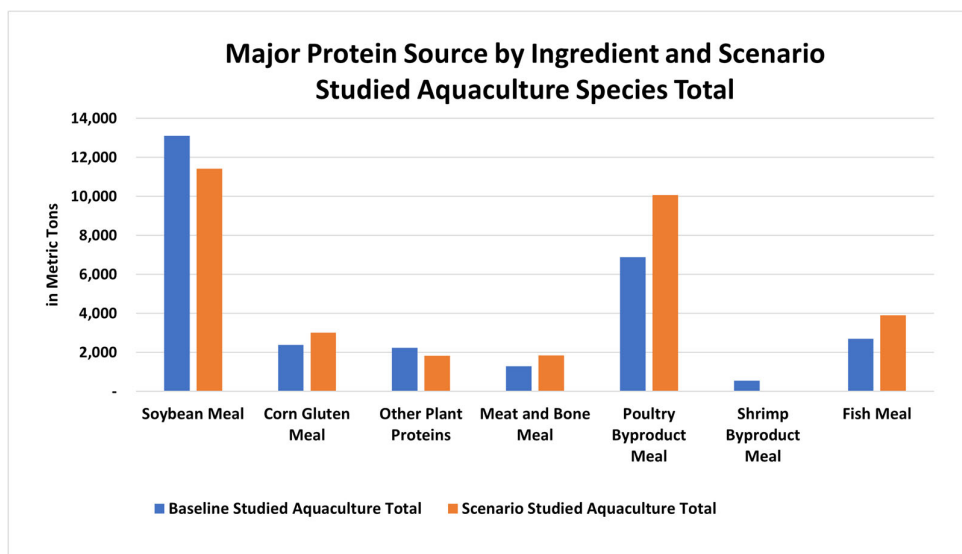
For the studied aquaculture total, the baseline scenario included 12.3 thousand MT of grains, 17.7 thousand MT of plant-based proteins, 12.2 thousand MT of animal protein meals, 2.7 thousand MT of fats and oils and 4.0 thousand MT of other ingredients. In the scenario for the studied aquaculture total, grains comprised 9.4 thousand MT, plant-based proteins were 16.2 thousand MT, animal protein meals were 16.6 thousand MT, fats and oils were 2.6 thousand MT, and 4.0 thousand MT of other ingredients, shown in Figure 40.



**Figure 40.** Ingredient Use by Category and Scenario, 3 Studied Aquaculture Species Total.

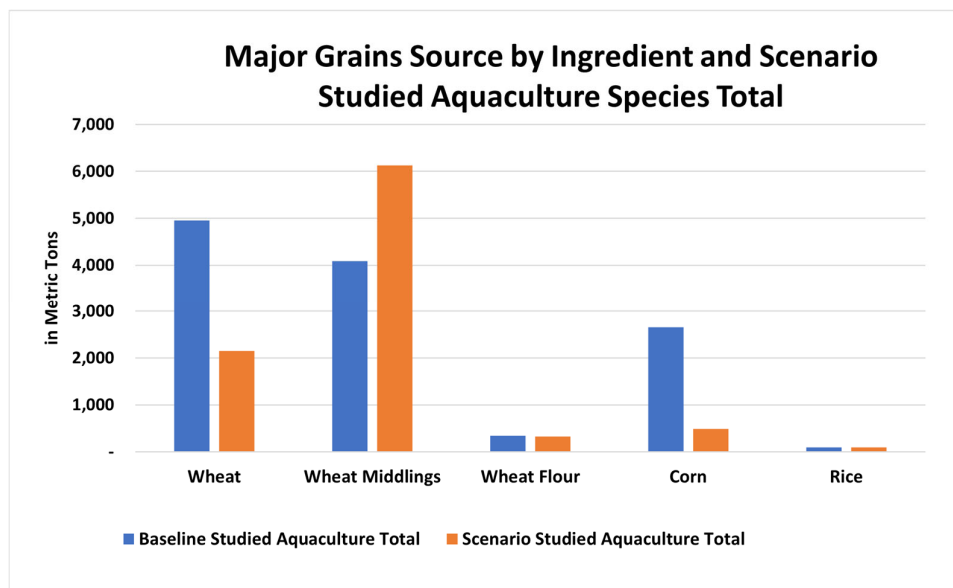
The major protein sources by ingredient and scenario for all 3 studied aquaculture species combined are shown in Figure 41. In the baseline case, soybean meal comprised 13.1 thousand MT of the total studied aquaculture diets, corn gluten meal was 2.4 thousand MT, other plant-based protein meals was 2.2 thousand MT, meat and bone meal was 1.3 thousand MT, poultry byproduct meal was 6.9 thousand MT, shrimp byproduct meal was 542.9 MT, and 2.7 thousand MT of fish meal.

In the scenario analysis which minimizes GHGE, 11.4 thousand MT of soybean meal was used in the studied aquaculture diets, with a decline of 12.9%; 3.0 thousand MT of corn gluten meal, with an increase of 26.4%; 1.8 thousand MT of other plant-based protein meals, a decline of 18.4%; 1.8 thousand MT of meat and bone meal, an increase of 43.8%; 10.1 thousand MT of poultry byproduct meal, an increase of 46.6%; shrimp byproduct meal was removed, a decline of 100%; and 3.9 thousand MT of fish meal, an increase of 44.4%.



**Figure 41.** Major Protein Meal Sources by Scenario, 3 Studied Aquaculture Species Total.

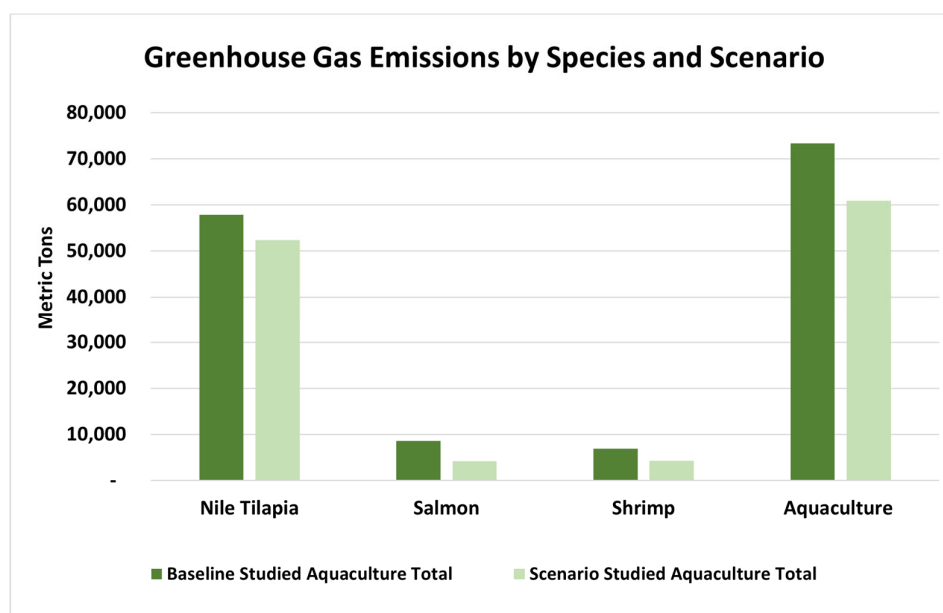
The major grain sources by ingredient and scenario for all 3 studied aquaculture species combined are shown in Figure 42. In the baseline case, 5.0 thousand MT of wheat were utilized by the total studied aquaculture species, 4.1 thousand MT of wheat middlings, 2.7 thousand MT of corn, 337.6 MT of wheat flour and 90.5 MT of rice. In the scenario analysis that minimizes GHGE, 2.1 thousand MT of wheat was used in the studied aquaculture diets, a decline of 56.7%; 6.1 thousand MT of wheat middlings, an increase of 50.0%; 0.5 thousand MT of corn, a decline of 81.5%; 320.0 MT of wheat flour, a decline of 5.2%; and 90.5 MT of rice, with no change.



**Figure 42.** Major Grain Sources by Scenario, 3 Studied Aquaculture Species Total.

Feed ingredient usage for both baseline and scenario of studied aquaculture species are shown in Appendix Table A1. The GHGE for selected feed ingredients by scenario and species are shown in Appendix Table A2. GHGE by EAA by ingredient aggregation and by scenario of the total studied aquaculture are shown in Appendix Table A3.

The GHGE for the studied species by scenario are shown in Figure 43. In the baseline case, Nile tilapia feed accounted for 57.8 thousand MT of CO<sub>2</sub> emissions, salmon feed accounted for 8.6 thousand MT of CO<sub>2</sub> emissions, shrimp feed accounted for 6.9 thousand MT of CO<sub>2</sub> emissions, and the total for the 3 species is 73.3 thousand MT of emissions. In the scenario, Nile tilapia feed accounted for 53.3 thousand MT of CO<sub>2</sub> emissions, salmon feed accounted for 4.2 thousand tons of CO<sub>2</sub> emissions, and shrimp feed accounted for 4.6 thousand MT of CO<sub>2</sub> emissions. The total studied aquaculture species in the scenario minimized GHGE to 62.1 thousand MT of CO<sub>2</sub> emissions, a decrease of 15% relative to the baseline.



**Figure 43.** GHGE by Species by Scenario.

Total GHGE by EAA and scenario for all three studied aquaculture species are shown in Figure 44, and the percentage change in GHGE by EAA and species from the baseline are shown in Table 4.

For Arginine, scenario GHGE are decreased by 11.1% compared to the baseline. Percentage change in GHGE for the other EAAs for the scenario are respectively: Histidine -9.3%, Isoleucine -8.8%, Leucine -5.7%, Lysine -9.0%, Methionine -4.5%, Phenylalanine -13.0%, Threonine -8.0%, Tryptophan -29.3%, and Valine -6.7%.

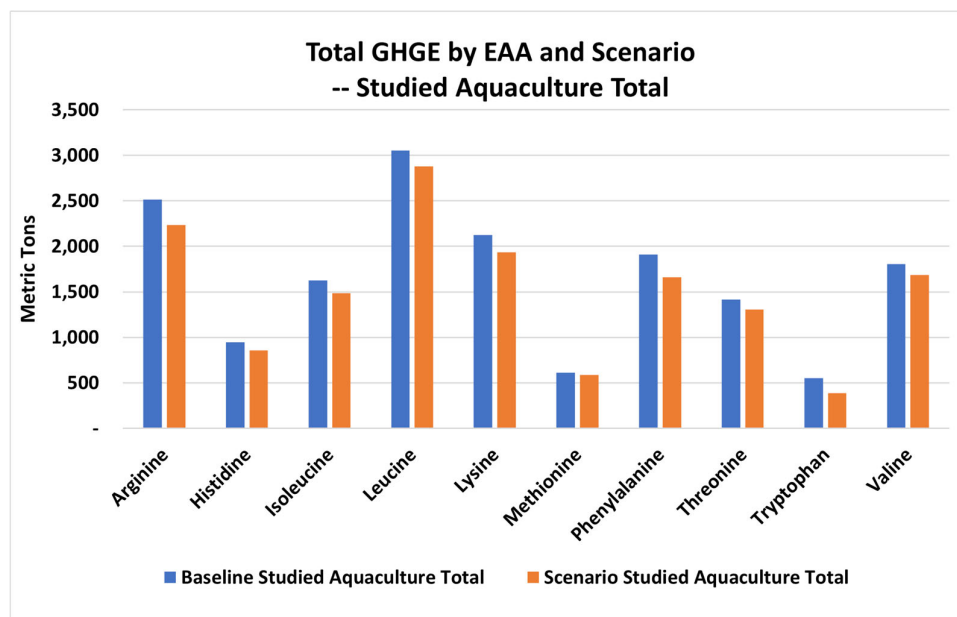


Figure 44. Total GHGE by EAA and Scenario, 3 Studied Aquaculture Species Total.

Table 4. Percentage Change in GHGE by EAA and Species from Baseline Diets.

Species	Arginine	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine
Nile Tilapia	-2.8%	-2.1%	-2.5%	3.0%	-2.6%	-0.2%	-5.6%	-1.0%	-18.1%	-0.5%
Salmon	-48.0%	-42.1%	-39.6%	-42.5%	-41.5%	-18.2%	-46.6%	-39.8%	-72.8%	-31.9%
Shrimp	-36.4%	-32.5%	-31.7%	-28.7%	-29.8%	-26.3%	-35.5%	-29.2%	-51.8%	-30.0%
Studied Aqua Total	-11.1%	-9.3%	-8.8%	-5.7%	-9.0%	-4.5%	-13.0%	-8.0%	-29.3%	-6.7%

GHGE by EAA for the grains portion of all three studied aquaculture species are shown Figure 45, for the plant-based meals in Figure 46, and for the animal protein meals portion of all three studied aquaculture species in Figure 47.

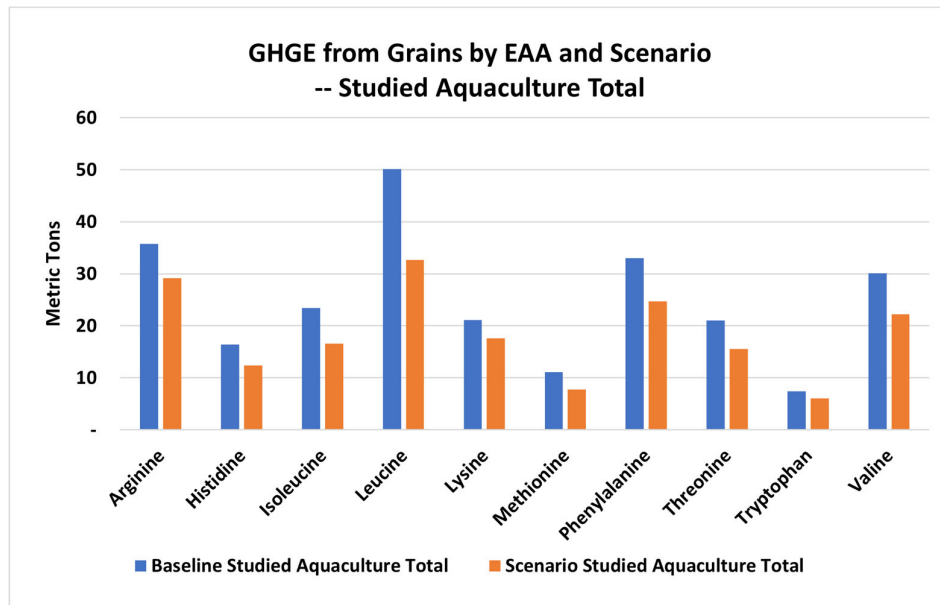


Figure 45. GHGE from Grains by EAA and Scenario, 3 Studied Aquaculture Species Total.

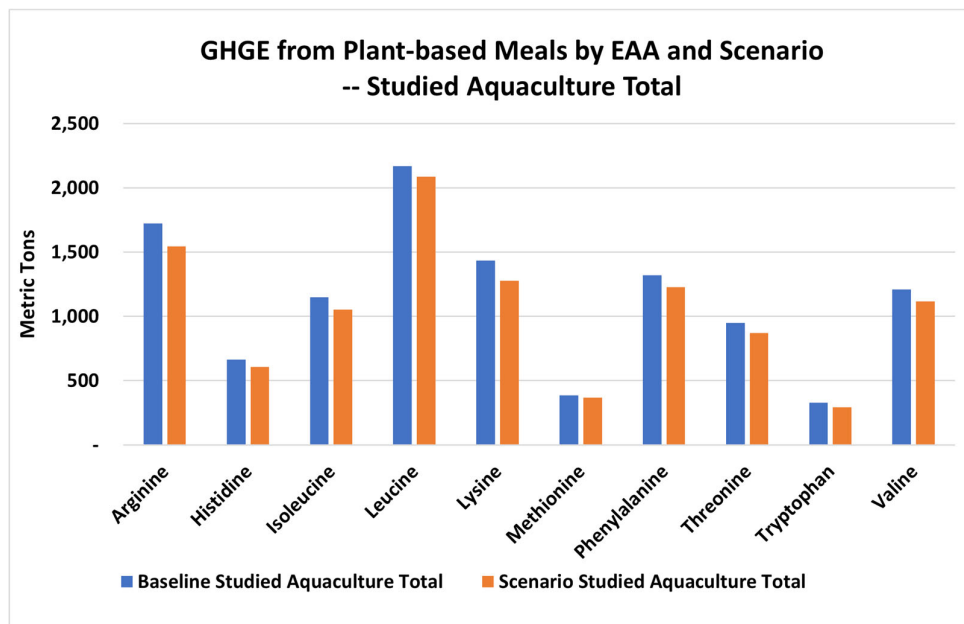


Figure 46. GHGE from Plant-based Meals by EAA and Scenario, 3 Studied Aquaculture Species Total.

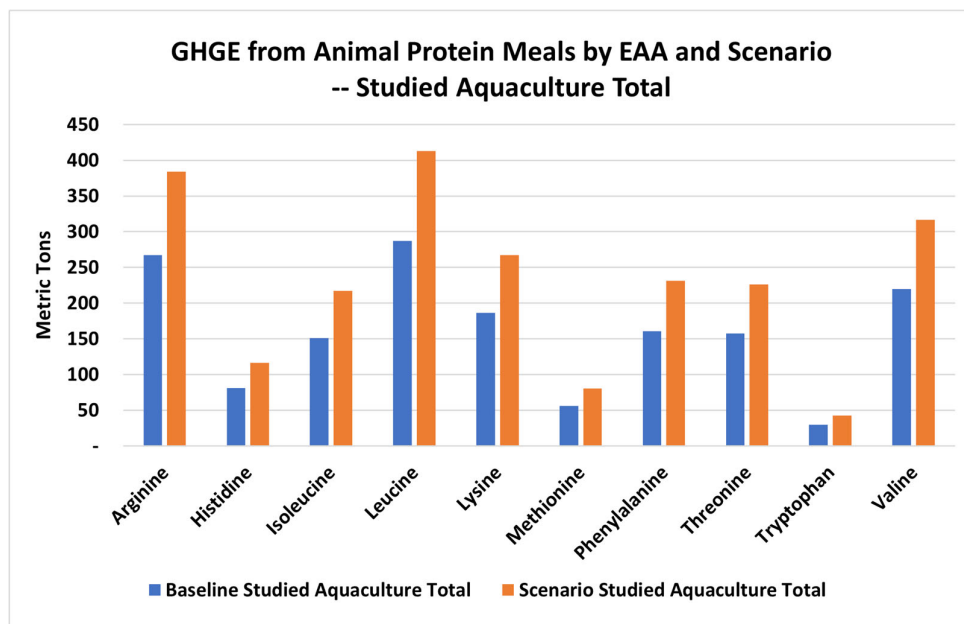


Figure 47. GHGE from Animal Protein Meals by EAA and Scenario, 3 Studied Aquaculture Species Total.

#### 4. Discussion and Conclusions

In this study, baseline ingredients used by the studied aquaculture species were estimated for U.S. production in 2022. For this baseline feed ingredient use, estimates were made for GHGE at the ingredient level and for each of the essential amino acids in those ingredients. Then a scenario was analyzed in which the nutrient requirements of each species were met, and in the meantime, minimizing the greenhouse gas emissions from the ration for each species. Also, to make the scenario diets realistic, the ingredient constraints of feed ingredients were capped at 150% of the baseline diet for a given ingredient.

For all studied species (Nile tilapia, salmon and shrimp), the primary ration adjustments were seen in a substitution of animal-based protein meals for grains and plant-based protein meals. Nile tilapia is the only species that reduced GHGE from grains, while salmon and shrimp reduced GHGE from protein sources. In the scenario, for all studied species, the GHGE minimizing scenario resulted in a 13% reduction in soybean meal use, 26% more corn gluten meal, 18% less other plant-based proteins, 44% increase in meat and bone meal use, 47% increase in poultry byproduct meal, 44% increase in fish meal, and shrimp byproduct meal was removed in the scenario result.

Moreover, for all studied aquaculture species, total GHGE were reduced by 15.3%: 73.3 thousand MT of GHGE in the baseline vs 62.1 thousand MT of GHGE in the scenario. Scenario total GHGE were reduced by 7.8%, 50.8% and 33.4% for Nile tilapia, salmon and shrimp, respectively. Impacts on the GHGE for each essential amino acid were substantially reduced in the scenario rations for all EAAs. For all studied species, the reductions by EAA ranged from 29.3% reduction for Tryptophan to 4.5% for Methionine.

Land use impacts of the scenario result in a 20% overall reduction in land use for aquaculture rations compared with the baseline. Estimates for land used for Nile tilapia rations is 16% less than the baseline. For salmon and shrimp, 40% and 27% reduction in land use, respectively, was estimated.

Therefore, from an environmentally friendly perspective, using rendered animal protein meals has a lower CO<sub>2</sub> emission intensity and requires fewer acres of total land compared to using plant-based meals in the studied aquaculture species diets.

**Author Contributions:** Conceptualization, D.L.M.; data, J.T. and S.P.B.M.; methodology, D.A.M.; formal analysis, J.T. and S.P.B.M.; visualization, J.T. and S.P.B.M.; writing-original draft preparation, J.T.; writing-review and editing, J.T., D.A.M., and C.S.; funding acquisition, C.S. and D.L.M. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The feed utilization and calculated GHGE data supporting the conclusions of this article will be made available by the authors on request. The raw GHGE data from the data sources listed in Data and Methods section may only be available as of the time of this research. And some data sources may require membership for access.

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

## Abbreviations

The following abbreviations are used in this manuscript:

AD	Apparent Digestibility
CO <sub>2</sub> e	Carbon Dioxide Equivalent
Corn DDGs	Corn Dried Distillers Grains
EAA	Essential Amino Acid
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GFLI	Global Feed LCA Institute
GHG	Green House Gas
GHGE	Green House Gas Emission
LCA	Life Cycle Assessment
LEAP	Livestock Environmental Assessment and Performance
MT	Metric Tons
NAL	National Agricultural Library
NANP	National Animal Nutrition Program
NARA	North American Renderers Association
NASS	National Agricultural Statistics Service
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
RCO	Ration Cost Optimization
U.S.	United States
USDA	United States Department of Agriculture

## Appendix A

### Appendix A.1 Ingredient Usage by Species and Scenario in Metric Tons

**Table A1.** Ingredient Usage by Species and Scenario (in Metric Tons).

Ingredient Aggregation	Ingredient	Nile Tilapia- Baseline	Nile Tilapia- Scenario	Salmon- Baseline	Salmon- Scenario	Shrimp- Baseline	Shrimp- Scenario	Studied	Studied
								Aquacul- ture Total- Baseline	Aquacul- ture Total- Scenario
	Meat and Bone Meal	965.5	1,448.3	-	-	320.3	400.4	1,285.9	1,848.7

	Poultry Byproduct Meal	4,977.0	7,465.5	948.0	1,422.1	949.4	1,186.7	6,874.4	10,074.2
Animal Protein Meals	Shrimp Byproduct Meal	542.9	-	-	-	-	-	542.9	-
	Fish Meal	1,312.1	1,968.2	787.6	1,181.4	598.9	748.6	2,698.6	3,898.2
	Fish*	144.8	217.2	-	-	-	-	144.8	217.2
	Poultry Meal	-	-	321.5	209.0	-	-	321.5	209.0
	Feather Meal	-	-	127.0	190.5	-	-	127.0	190.5
	Blood Meal	-	-	141.4	204.9	-	-	141.4	204.9
	Gelatin	-	-	-	-	30.9	-	30.9	-
	Soybean Meal	11,718.5	10,783.8	321.5	-	1,067.8	627.5	13,107.8	11,411.3
	Corn Gluten Meal	1,628.8	2,443.2	602.6	378.1	144.4	180.5	2,375.9	3,001.9
Plant-based Proteins	Wheat Gluten Meal	-	-	16.1	-	232.1	-	248.2	-
	Soy Protein Conc	-	-	706.7	-	-	-	706.7	-
	Sunflower Meal	-	-	368.1	459.7	-	-	368.1	459.7
	Corn DDGs	904.9	1,357.4	-	-	-	-	904.9	1,357.4
	Wheat	4,305.5	1,404.8	241.1	231.9	407.9	509.9	4,954.6	2,146.6
Grains	Wheat Middlings	3,348.1	5,022.2	737.3	1,105.9	-	-	4,085.4	6,128.1
	Wheat Flour	-	-	337.6	320.0	-	-	337.6	320.0
	Corn	2,262.3	-	-	-	392.3	490.4	2,654.5	490.4
	Rice	90.5	90.5	-	-	-	-	90.5	90.5
	Corn Starch	-	-	-	-	194.5	194.5	194.5	194.5
	Inedible Tallow	-	-	-	-	8.8	8.8	8.8	8.8
Fats & Oils	Poultry Fat	-	-	136.6	136.6	-	-	136.6	136.6
	Fish Oil	120.7	120.7	522.7	522.7	74.8	74.8	718.1	718.1
	Lecithin	90.5	90.5	185.1	185.1	43.8	43.8	319.4	319.4
	Soybean Oil	470.6	470.6	955.2	908.1	47.5	47.5	1,473.2	1,426.1
	DL Methionine	181.0	181.0	37.4	37.4	-	-	218.4	218.4
Other Ingredients	Lysine	-	-	128.2	128.2	-	-	128.2	128.2
	Threonine	-	-	10.9	10.9	-	-	10.9	10.9
	Histidine	-	-	13.4	13.4	-	-	13.4	13.4
	Feed Additives	3,132.5	3,132.5	391.1	391.1	129.0	129.0	3,652.5	3,652.5
	Total	36,196.2	36,196.2	8,036.9	8,036.9	4,642.5	4,642.5	48,875.5	48,875.5

\* "Fish" ingredient was referred to general marine fish.

#### Appendix A.2 GHGE by Selected Ingredient by Scenario in Metric Tons

**Table A2.** GHGE by Selected Ingredient by Scenario (in Metric Tons).

Ingredient Aggregation	Ingredient	Nile Tilapia- Baseline	Nile Tilapia- Scenario	Salmon- Baseline	Salmon- Scenario	Shrimp- Baseline	Shrimp- Scenario	Studied	Studied
								Aquacul- ture Total- Baseline	Aquacul- ture Total- Scenario
Animal Protein Meals	Meat and Bone Meal	654.1	981.2	-	-	217.0	271.3	871.1	1,252.4
	Feather Meal	-	-	75.8	113.7	-	-	75.8	113.7
	Poultry Meal	-	-	210.1	136.6	-	-	210.1	136.6

	Poultry								
	Byproduct Meal	3,613.3	5,419.9	688.3	1,032.4	689.3	861.6	4,990.8	7,313.9
	Blood Meal	-	-	126.9	183.8	-	-	126.9	183.8
	Fish *	1,837.3	2,756.0	-	-	-	-	1,837.3	2,756.0
	Fish Meal	1,180.1	1,770.2	708.4	1,062.6	538.6	673.3	2,427.1	3,506.1
	Shrimp								
	Byproduct Meal	5,266.5	-	-	-	-	-	5,266.5	-
	Gelatin	-	-	-	-	588.0	-	588.0	-
	Soybean Meal	37,615.0	34,614.7	1,031.9	-	3,427.4	2,014.3	42,074.3	36,628.9
	Corn DDGs	861.0	1,291.5	-	-	-	-	861.0	1,291.5
	Corn Gluten Meal	2,928.6	4,392.9	1,083.5	679.8	259.7	324.6	4,271.8	5,397.4
Plant-based	Sunflower								
Proteins	Meal	-	-	302.2	377.4	-	-	302.2	377.4
	Wheat Gluten Meal	-	-	56.9	-	821.2	-	878.1	-
	Soy Protein Conc	-	-	3,771.9	-	-	-	3,771.9	-
	Corn	1,075.3	-	-	-	186.5	233.1	1,261.7	233.1
	Wheat	1,811.6	591.1	101.4	97.6	171.6	214.5	2,084.6	903.2
	Wheat Middlings	1,003.9	1,505.9	221.1	331.6	-	-	1,225.0	1,837.5
	Wheat Flour	-	-	225.1	213.4	-	-	225.1	213.4
	Total	57,846.7	53,323.3	8,603.4	4,228.9	6,899.3	4,592.6	73,349.4	62,144.8

\* "Fish" ingredient was referred to general marine fish.

#### Appendix A.3 GHGE by EAA by Ingredient Aggregation and Scenario in Metric Tons

**Table A3.** GHGE by EAA by Ingredient Aggregation and Scenario (in Metric Tons).

Ingredient Aggregation	EAA	Nile Tilapia-Baseline	Nile Tilapia-Scenario	Salmon-Baseline	Salmon-Scenario	Shrimp-Baseline	Shrimp-Scenario	Studied	Studied
								Aquaculture Total-Baseline	Aquaculture Total-Scenario
Animal Protein Meals	Arginine	181.5	272.3	47.1	63.7	38.3	47.9	267.0	383.8
	Histidine	51.6	77.4	18.3	25.3	11.1	13.9	81.1	116.6
	Isoleucine	102.8	154.2	27.1	36.4	21.1	26.4	151.0	217.1
	Leucine	188.3	282.4	59.7	81.6	39.2	49.0	287.2	413.0
	Lysine	122.8	184.2	37.2	50.5	26.1	32.7	186.1	267.4
	Methionine	38.2	57.2	9.9	13.3	8.0	10.0	56.0	80.5
	Phenylalanine	105.1	157.6	33.6	45.9	21.9	27.4	160.6	230.9
	Threonine	104.7	157.1	30.8	41.8	21.8	27.2	157.3	226.1
	Tryptophan	19.2	28.8	6.4	8.6	4.0	5.0	29.6	42.4
	Valine	144.3	216.4	45.8	62.6	29.9	37.4	220.0	316.4
Plant-based Proteins	Arginine	1,516.3	1,437.1	70.3	24.2	137.1	84.2	1,723.7	1,545.4
	Histidine	580.8	561.5	31.7	12.2	52.2	33.0	664.7	606.6
	Isoleucine	999.2	971.2	58.4	23.4	90.0	57.5	1,147.5	1,052.1
	Leucine	1,842.9	1,892.6	161.9	79.5	164.5	114.9	2,169.3	2,086.9
	Lysine	1,270.1	1,193.9	50.3	12.6	114.9	69.7	1,435.3	1,276.1
	Methionine	329.7	334.0	27.5	13.9	29.5	20.1	386.7	368.0
	Phenylalanine	1,140.4	1,125.6	76.1	33.0	102.5	67.2	1,319.0	1,225.8
	Threonine	826.8	804.3	48.4	19.6	74.3	47.5	949.5	871.4
	Tryptophan	289.0	272.8	12.5	3.9	26.1	15.9	327.6	292.7
	Valine	1,052.0	1,027.4	63.9	26.7	94.5	60.8	1,210.4	1,114.9
Grains	Arginine	30.3	21.9	3.3	4.6	2.1	2.7	35.8	29.1

	Histidine	14.0	9.1	1.4	1.9	1.1	1.4	16.4	12.4
	Isoleucine	19.9	12.1	1.9	2.5	1.6	2.0	23.4	16.6
	Leucine	42.7	23.0	3.5	4.7	3.9	4.9	50.2	32.6
	Lysine	17.8	13.3	2.0	2.8	1.2	1.6	21.1	17.6
	Methionine	9.4	5.6	0.9	1.1	0.8	1.0	11.1	7.7
	Phenylalanine	28.1	18.2	2.8	3.8	2.2	2.7	33.0	24.7
	Threonine	17.9	11.4	1.7	2.4	1.4	1.8	21.0	15.6
	Tryptophan	6.3	4.6	0.7	0.9	0.4	0.5	7.4	6.0
	Valine	25.6	16.3	2.5	3.4	2.0	2.5	30.1	22.2
Total	Arginine	1,985.8	1,931.1	270.3	140.5	258.1	164.2	2,514.1	2,235.8
	Histidine	754.1	738.1	101.5	58.8	89.2	60.2	944.7	857.0
	Isoleucine	1,316.9	1,283.6	155.8	94.1	154.5	105.5	1,627.2	1,483.2
	Leucine	2,380.8	2,453.2	385.6	221.6	284.8	203.0	3,051.3	2,877.8
	Lysine	1,716.3	1,672.6	210.3	123.0	198.8	139.6	2,125.4	1,935.2
	Methionine	492.3	491.6	60.0	49.0	59.7	44.0	611.9	584.6
	Phenylalanine	1,515.5	1,431.1	212.0	113.1	179.7	115.9	1,907.2	1,660.1
	Threonine	1,123.5	1,112.6	158.6	95.4	135.6	96.0	1,417.6	1,304.1
	Tryptophan	416.4	341.0	79.5	21.6	54.5	26.3	550.4	389.0
	Valine	1,436.2	1,429.2	192.8	131.4	177.9	124.5	1,807.0	1,685.1

## Appendix A.4 GHGE by Ingredient with Sources

Table A4. GHGE by Ingredient with Sources.

Ingredient	MT CO <sub>2</sub> e/MT ingredient	Source
Gelatin	19.0	Carbon Cloud[30]
Fish*	12.7	Quantifying greenhouse gas emissions from global aquaculture[20]
Shrimp Byproduct Meal	9.7	Evaluation of Different Aquaculture Feed Ingredients in Indonesia Using Life Cycle Assessment[19]
Soy Protein Conc	5.3	GFLI[13]
Wheat Gluten Meal	3.5	GFLI[13]
Soybean Meal	3.2	GFLI[13]
Corn Gluten Meal	1.8	Feed Tables[22]
Corn DDGs	1.0	GFLI[13]
Fish Meal	0.9	GFLI[13]
Blood Meal	0.9	GFLI[13]
Sunflower Meal	0.8	GFLI[13]
Poultry Byproduct Meal	0.7	Life-cycle assessment of animal feed ingredients: Poultry by-product meal and hydrolyzed feather meal[17]
Meat and Bone Meal	0.7	GFLI[13]
Wheat Flour	0.7	GFLI[13]
Poultry Meal	0.7	Life-cycle assessment of animal feed ingredients: Poultry by-product meal and hydrolyzed feather meal[17]
Feather Meal	0.6	Life-cycle assessment of animal feed ingredients: Poultry by-product meal and hydrolyzed feather meal[17]
Corn	0.5	GFLI[13]
Wheat	0.4	GFLI[13]
Wheat Middlings	0.3	GFLI[13]

\* "Fish" ingredient refers to general marine fish.

## References

- Hua, K.; Cobcroft, J.M.; Cole, A.; Condon, K.; Jerry, D.R.; Mangott, A.; Praeger, C.; Vucko, M.J.; Zeng, C.; Zenger, K.; et al. The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets. *One Earth* **2019**, *1*, 316–329, doi:10.1016/j.oneear.2019.10.018.
- FAO The State of World Fisheries and Aquaculture 2024; FAO, 2024; ISBN 978-92-5-138763-4.

3. FAO FishStatJ Software for Fisheries and Aquaculture Statistical Time Series 2025.
4. Christopher G Davis Aquaculture. *Aquaculture* 2025.
5. Naylor, R.L.; Hardy, R.W.; Buschmann, A.H.; Bush, S.R.; Cao, L.; Klinger, D.H.; Little, D.C.; Lubchenco, J.; Shumway, S.E.; Troell, M. A 20-Year Retrospective Review of Global Aquaculture. *Nature* **2021**, *591*, 551–563, doi:10.1038/s41586-021-03308-6.
6. Boyd, C.E.; McNevin, A.A. Resource Use and Pollution Potential in Feed-Based Aquaculture. *Reviews in Fisheries Science & Aquaculture* **2024**, *32*, 306–333, doi:10.1080/23308249.2023.2258226.
7. Tacon, A.G.J.; Metian, M.; McNevin, A.A. Future Feeds: Suggested Guidelines for Sustainable Development. *Reviews in Fisheries Science & Aquaculture* **2022**, *30*, 135–142, doi:10.1080/23308249.2020.1860474.
8. Boyd, C.E.; D’Abramo, L.R.; Glencross, B.D.; Huyben, D.C.; Juarez, L.M.; Lockwood, G.S.; McNevin, A.A.; Tacon, A.G.J.; Teletchea, F.; Tomasso, J.R.; et al. Achieving Sustainable Aquaculture: Historical and Current Perspectives and Future Needs and Challenges. *J World Aquaculture Soc* **2020**, *51*, 578–633, doi:10.1111/jwas.12714.
9. Ghamkhar, R.; Hicks, A. Comparative Environmental Impact Assessment of Aquafeed Production: Sustainability Implications of Forage Fish Meal and Oil Free Diets. *Resources, Conservation and Recycling* **2020**, *161*, 104849, doi:10.1016/j.resconrec.2020.104849.
10. Life Cycle Assessment (LCA) Guide. *Life Cycle Assessment (LCA) Guide* 2024.
11. Guyomarc’h, F.; Héquet, F.; Le Féon, S.; Leconte, N.; Garnier-Lambrouin, F.; Auberger, J.; Malnoë, C.; Pénicaud, C.; Gésan-Guiziou, G. Life Cycle Assessment to Quantify the Environmental Performance of Multi-Products Food Processing Systems Such as Milk Fractionation: Importance of Subdivision and Allocation. *Journal of Food Engineering* **2024**, *380*, 112147, doi:10.1016/j.jfoodeng.2024.112147.
12. EPA Lifecycle Analysis of Greenhouse Gas Emissions under the Renewable Fuel Standard. *Lifecycle Analysis of Greenhouse Gas Emissions under the Renewable Fuel Standard* 2025.
13. Global Feed LCA Institute’s (GFLI) Database 2023.
14. National Renewable Energy Laboratory U.S. Life Cycle Inventory Database 2024.
15. Ecoinvent Database 2023.
16. Adom, F.; Maes, A.; Workman, C.; Clayton-Nierderman, Z.; Thoma, G.; Shonnard, D. Regional Carbon Footprint Analysis of Dairy Feeds for Milk Production in the USA. *Int J Life Cycle Assess* **2012**, *17*, 520–534, doi:10.1007/s11367-012-0386-y.
17. Campos, I.; Pinheiro Valente, L.M.; Matos, E.; Marques, P.; Freire, F. Life-Cycle Assessment of Animal Feed Ingredients: Poultry Fat, Poultry by-Product Meal and Hydrolyzed Feather Meal. *Journal of Cleaner Production* **2020**, *252*, 119845, doi:10.1016/j.jclepro.2019.119845.
18. Al Eissa, A.; Chen, P.; Brown, P.B.; Huang, J. Effects of Feed Formula and Farming System on the Environmental Performance of Shrimp Production Chain from a Life Cycle Perspective. *J of Industrial Ecology* **2022**, *26*, 2006–2019, doi:10.1111/jiec.13370.
19. Henriksson, P.J.G.; Mohan, C.V.; Phillips, M.J. Evaluation of Different Aquaculture Feed Ingredients in Indonesia Using Life Cycle Assessment. *IJoLCAS* **2016**, *1*, doi:10.52394/ijolcas.v1i1.4.
20. MacLeod, M.J.; Hasan, M.R.; Robb, D.H.F.; Mamun-Ur-Rashid, M. Quantifying Greenhouse Gas Emissions from Global Aquaculture. *Sci Rep* **2020**, *10*, 11679, doi:10.1038/s41598-020-68231-8.
21. Newton, R.W.; Maiolo, S.; Malcorps, W.; Little, D.C. Life Cycle Inventories of Marine Ingredients. *Aquaculture* **2023**, *565*, 739096, doi:10.1016/j.aquaculture.2022.739096.
22. The INRAE-CIRAD-AFZ Tables 2004.
23. Feedipedia 2012.
24. USDA National Animal Nutrition Program 2024.
25. Rahman, M.M.; Gunathilaka, B.E.; You, S.-G.; Kim, K.-W.; Lee, S.-M. Apparent Digestibility Coefficients of Plant Feed Ingredients for Olive Flounder (*Paralichthys Olivaceus*). *Fish Aquat Sci* **2023**, *26*, 87–96, doi:10.47853/FAS.2023.e7.
26. Vieira, C.C.F.; Pinto, R.C.C.; Diógenes, A.F.; Nunes, A.J.P. Apparent Digestibility of Protein and Essential Aminoacids from Commonly Used Feed Ingredients in Brazil for Juvenile Shrimp *Litopenaeus Vannamei*. *Revista Brasileira de Zootecnia* **2022**, *51*, e20210177, doi:10.37496/rbz5120210177.

27. Stein, H.H.; Fuller, M.F.; Moughan, P.J.; Sève, B.; Mosenthin, R.; Jansman, A.J.M.; Fernández, J.A.; De Lange, C.F.M. Definition of Apparent, True, and Standardized Ileal Digestibility of Amino Acids in Pigs. *Livestock Science* **2007**, *109*, 282–285, doi:10.1016/j.livsci.2007.01.019.
28. Nesara KM; Anand Prasad Paturi Nutritional Requirement of Fresh Water Prawn and Shrimp: A Review. *Journal of Entomology and Zoology Studies* **2018**, *6*, 1526–1532.
29. Ayisi, C.L.; Hua, X.; Apraku, A.; Afriyie, G.; Kyei, B.A. Recent Studies Toward the Development of Practical Diets for Shrimp and Their Nutritional Requirements. *HAYATI Journal of Biosciences* **2017**, *24*, 109–117, doi:10.1016/j.hjb.2017.09.004.
30. Technical Report - Climate Footprint of Bovine Gelatin 2023.

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