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Sustainable Aquafeeds: Using Aquafarmer Preference to Inform a Multi-criteria Decision Analysis

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ABSTRACT: Aquafeed is a major contributor to the sustainability of food production using aquaculture. Therefore, improving the environmental, economic, and societal performance of aquafeeds provides an opportunity to significantly enhance the sustainability of aquaculture practices, which make up the fastest-growing food sector. Fish meal and fish oil are traditionally the main sources of essential nutrients (e.g., protein and fatty acids) in aqua diets. However, increases in supply prices and limited natural resources (e.g., forage fish) have encouraged some stakeholders to seek alternative nutrient-rich options. This work provides a multidimensional assessment of current and promising future aquafeeds, utilizing multi-criteria decision analysis. The considered parameters include cost, environmental impacts, and nutrient inclusion. The results based on varying stakeholders' perspectives indicate that the replacements of fish meal with plant-based soybean meal and fish oil with plant-based canola oil are the most favorable alternatives among those investigated to enhance the overall aquafeed performance in aquaculture food production.

KEYWORDS: *sustainable aquafeed, life cycle assessment (LCA), industrial ecology, producer preference, aquaculture, multi-criteria decision analysis (MCDA), decision making, aquafarming*

1. INTRODUCTION

It is anticipated that global fish consumption will increase from 111697 million tons in 2006 to 151771 million tons by 2030.[1] This increase will mainly be triggered by two root causes: the prospective global population increase and the change in humans' dietary habits.[2] Due to the limited capacity of commercial fishing through capture fisheries, aquaculture is an attractive food production technology to meet the growing demand for aquatic species.[3] Aquaculture is the practice of farming aquatic organisms (fish and seafood) by intervening rearing processes (e.g., stocking, feeding, protection from predators, etc.) to enhance production.[4] Strategies for sustainable industrial aquaculture need to be considered, analyzed, and implemented to address the prospective need.[5,6]

Aquafeed is one of the main drivers of material and energy flows in aquaculture systems, ascribing to it a significant role with regard to environmental, economical, and technical aspects of aquaculture food production.[2,7,8] The contribution of aquafeeds to the overall environmental impacts, economic performance, and production quality of aquaculture systems has been distinctly highlighted and investigated in many recent studies.[9−15] Forage-sourced fish meal and fish oil are the traditional main sources of essential nutrients in formulated aquafeeds, making them the major material and energy inflows in aquafeed production.[16] To prevent single-source dependency on a finite resource, there is a growing desire to implement alternative ingredients (to fish meal and fish oil) in aquafeed formulation to achieve acceptable production while mitigating the ecological burdens.[17−19] It is necessary to quantify the environmental trade-offs that may occur due to the usage of nonconventional aquafeed ingredients.

With respect to environmental implications, Ghamkhar and Hicks[2] investigated the comparative environmental impacts of various aquafeed formulations, including fish oil and meal free diets, in a midpoint life cycle assessment (LCA) using a holistic set of 12 relevant indicators (TRACI, biotic resource use, and water intake). The study suggests that replacement alternatives that incorporate (1) energy-efficient substitutions for fish oil (e.g., plant-based canola oil) and (2) less material-intensive substitutions for fish meal (e.g., poultry byproduct and soybean meal) are promising strategies for mitigating the overall ecological damage caused by aquafeeds. With respect to the economic implications, Arikan and Aral[20] have performed a comprehensive technical and economic analysis of seabream and seabass production, using small-scale, medium-scale, and large-scale aquaculture systems (n = 65). Their findings indicate that aquafeed contributes to >60% of total costs (variable and fixed) in all investigated systems. Strategies for decreasing the share of aquafeed cost (e.g., domestic fish meal production) need to be explored.[21] With respect to production performance, Adelizi et al.[22] analyzed the production of trout (growth and tissue analyses) utilizing nine formulated diets with varying levels of protein (∼37−51%) and fat (∼10−18%). The results suggest that the diet with the highest digestible protein content (fishmeal-based, soybean free) outperforms other diets in terms of fish weight gain, protein

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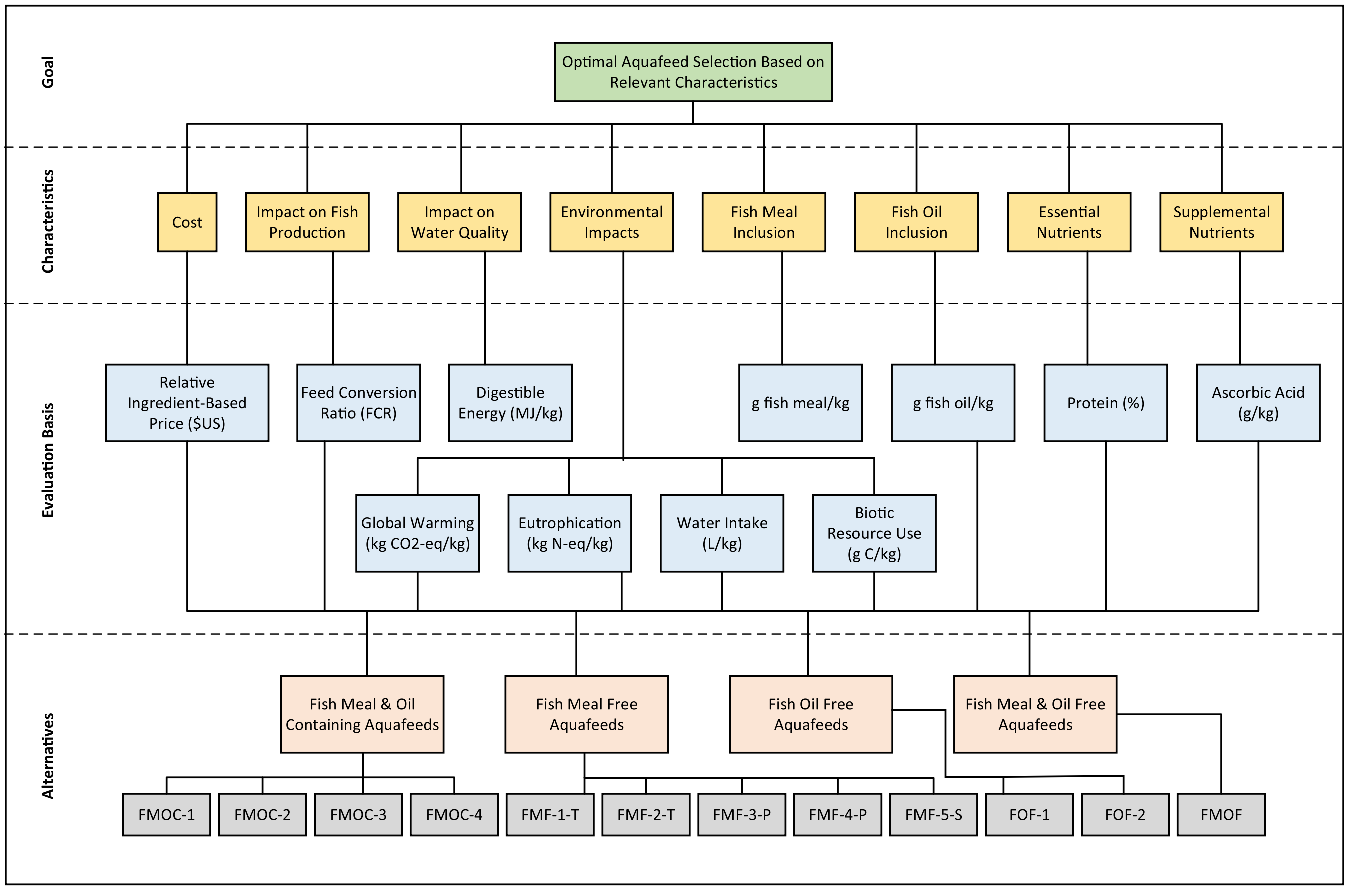

Figure 1. Multi-criteria decision hierarchy for aquafeed selection. FMOC-1, FMOC-2, FMOC-3, and FMOC-4 refer to fish meal- and oil-containing diets. FMF-1-T and FMF-2-T refer to fish meal free (but fish oil-containing) diets with terrestrial replacements (poultry byproduct and blood meal, respectively). FMF-3-P and FMF-4-P refer to fish meal free (but fish oil-containing) diets with plant-based replacements (peanut meal and soybean meal, respectively). FMF-5-S refers to fish meal free diet with seafood byproduct replacement. FOF-1 and FOF-2 refer to fish oil free (but fish meal-containing) diets with vegetable (canola) and vegetable and protist-based replacements, respectively. Finally, FMOF refers to fish meal and oil free diet with terrestrial, seafood byproduct, and plant-based replacements.

intake efficiency, and fillet flavor. Davidson et al.[23] compared the production of post-molt Atlantic salmon using different formulated aquafeeds (fishmeal-based vs fishmeal free) with similar levels of protein and crude fat (42% and 27%, respectively) and found that the growth, survival, and feed conversion ratios (FCRs) were unaffected by the level of fishmeal in diets, when protein and fat levels are kept similar.

Considering the implications of aquafeeds in varying relevant dimensions (environmental, economic, and technical), the selection of the most sustainable aquafeed is a challenge for decision makers and seafood producers. To accomplish that, it is necessary to consolidate many factors (e.g., the overall cost of aquafeed, its impact on final fish product, its impact on water quality, etc.). These factors are usually conflicting, and if the decision makers want to incorporate all of the influencing dimensions, they may face the dilemma of which option to select on the basis of the available commercial choices.[24]

Multi-criteria decision analysis (MCDA), which is an integrated sustainability evaluation methodology, can be used as a platform to compare the relative sustainability of aquafeeds with respect to the pertinent features and characteristics.[25,26] In MCDA, a multidimensional decision making approach is used to tackle complex problems, entailing varying forms of data, antagonistic objectives, and multiple interests and perspectives.[25,27,28] For example, Yin et al.[29] have performed a MCDA to identify the most suitable coastal aquaculture sites in the Menai Strait (U.K.), incorporating environmental and socioeconomic factors. Considering the wide variety of potential functions for the investigated coastal areas (e.g., transportation, recreation, leisure fishing, etc.), this study has considered the minimization of stress on ecosystems, productive harvest improvement, and conflict mitigation among coastal water users to select the most suitable locations. Safarian et al.[30] conducted a MCDA among bioethanol production systems (i.e., agricultural vs agricultural waste biomass) in Iran, using seven relevant economic, energy, and environmental factors. Their results indicate that despite most agricultural systems, agricultural waste systems (e.g., sugar cane) are suitable feedstock for bioethanol production in Iran, because they are cost-effective, renewable, and abundant.

This work seeks to implement MCDA to evaluate the sustainability of varying formulated aquafeeds (e.g., fish meal and oil free diets) based on their relevant economic, environmental, commercial, and technical characteristics. To accomplish that, the following three steps are performed. First, a survey is developed and distributed among the licensed commercial aquafarmers in the State of Wisconsin to obtain real-world characteristic scores (weightings). Second, a holistic set of formulated aquafeeds (12) with varying levels of ingredients (e.g., fish meal and fish oil) have been obtained

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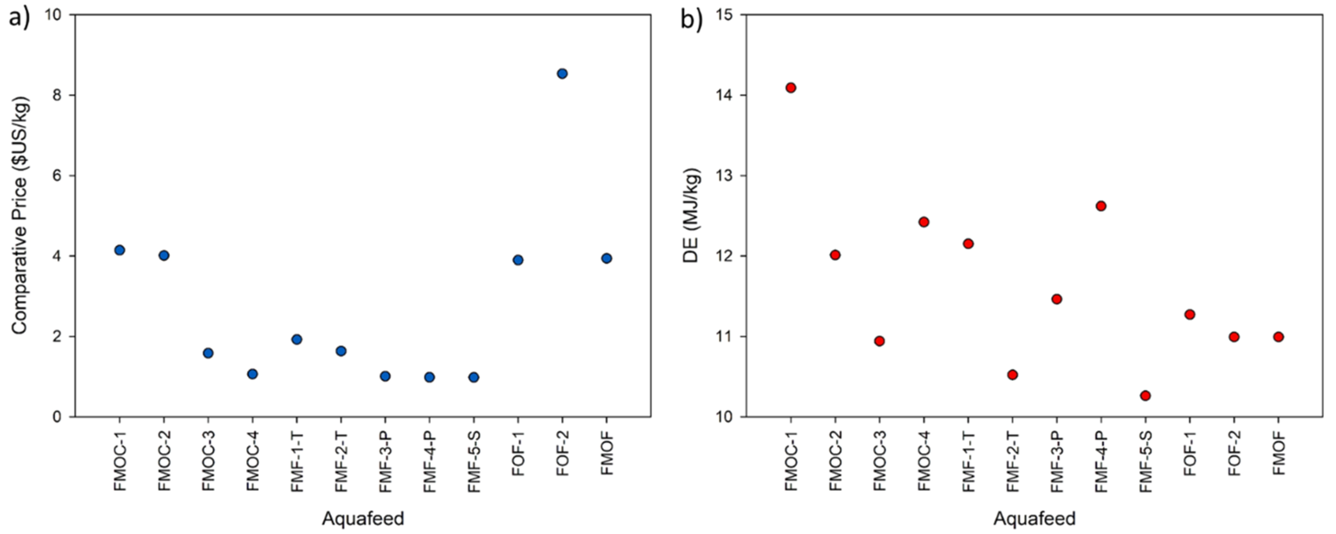

Figure 2. (a) Comparative cost estimation of aquafeeds. Relative costs for the investigated aquafeeds based on the ingredient components. (b) Impact of aquafeeds on water quality estimation: digestible energy (DE, megajoules per kilogram) values for the investigated aquafeeds.

from the authors' previous work.[2] These aqua diets span a wide domain of levels of ingredients and consequent biological and nutritional characteristics. Thus, they will provide an acceptable range of prospective feeding formulations that can be successfully used for aquafarming. Third, MCDA is performed on the basis of the elicited rankings and aquafeed options. A MCDA hierarchy for this research is illustrated in Figure 1. Four hypothetical scenarios (aquafarmers with prime considerations of environmental impact mitigation, final product maximization, cost minimization, and fish meal substitution) have also been further evaluated and discussed.

2. MATERIALS AND METHODS

MCDA is defined as "an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi-interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems".[25,31] To develop a MCDA, the following steps are required: the collection of the existing (or potential) options to select as a decision (section 2.1), the elicitation of decision characteristics, including their relative importance (sections 2.2 and 2.3), the assignment of comparative values to the characteristics (section 2.4; subsections 2.4.1−2.4.5), and the selection of the proper analysis methodology (section 2.5). The following sections will elaborate on the aforementioned steps undertaken in this work, as well as the methodological approaches for graphical analysis for interactive assistance (GAIA, section 2.6) and hypothetical scenario analysis (section 2.7).

2.1. Existing and Potential Options (decisions). Twelve different aquafeeds that have been successfully formulated and experimentally utilized to produce seafood (to ensure the practicality of diet usage) were extracted from previous work by the authors.[2] Four fish meal- and oil-containing diets, termed FMOC-1, FMOC-2, FMOC-3, and FMOC-4, with varying ingredients and protein contents were considered.[23,32,33] Two fish meal free diets (FMFs), in which fish meal is replaced with terrestrial poultry byproduct and terrestrial blood meal, were selected, which are termed FMF-1-T and FMF-2-T, respectively.[34,35] Two fish meal free diets, in which fish meal is replaced with plant-based peanut meal and soybean meal, were used, which are termed FMF-3-P and FMF-4-P, respectively.[22] A forage fish meal free diet, in which fish meal is replaced with fish processing industry byproducts, was considered and termed FMF-5-S.[36] FOF-1 and FOF-2 refer to the fish oil free (FOF) diets, in which fish oil is replaced with vegetable-based (canola) oil and both vegetable-based (canola) and single-cell protist-based (Thraustochytrid) oils, respectively.[32,37] Finally, a fish meal and fish oil free diet, termed FMOF, in which fish meal and oil is fully replaced with terrestrial meal (poultry byproduct), plant-based meal (mixed nuts), and seafood byproduct (whitefish trimming) ingredients is selected.[23] Specifications regarding the ingredients and amounts are provided in detail in the Tables S1−S12. Further detailing specifications regarding a corresponding life cycle impact database, assumptions, and comments can be found in another paper by the authors.[2]

2.2. Elicitation of Decision Characteristics. To evaluate the impact of input data on the MCDA model output, two approaches were undertaken.

(1) Four stylized scenarios were defined and evaluated, as the typical approach undertaken for MCDA,[38−40] representing hypothetical scenarios for prioritizing (a) environmental considerations, (b) initial cost minimization, (c) final product maximization, and (d) fish meal replacement (further described in section 2.7).

(2) To provide additional insight, a survey was developed and distributed among 40 aquafarmers, identified by the Wisconsin Department of Agriculture, Trade, and Consumer Protection's list of fish farms as commercial licensed aquafarms (school farms excluded).[41] Farmers are producing a range of aquatic species (e.g., tilapia, trout, salmon, and perch). Eight surveys have been received back fulfilled with an acknowledgment of performing research based on the provided data. It is important to highlight that the number of respondents depends on the survey goals. A 20% response rate for the purpose of this survey is a reasonable outcome, as it meets the purpose of incorporating producers' realistic scores within the analysis, which was often lacking in previous MCDA studies. We should also note that many fish farms are teetering on the brink of closure right now due to the COVID pandemic,[42,43] which means that there may be even fewer farms in Wisconsin than are listed on the permit registry. As many of the surveys were returned as undeliverable. Despite the aforementioned limitations, the structure of the analysis based on realistic scenarios is valuable for the purpose of this analysis because (a) incorporation of aquafarmers scores for decision characteristics (either harmonious or discordant) provides the opportunity to analyze outcomes based on potential variations affecting the producers' practice and (b) a majority of MCDA studies have been performed solely around hypothetical decision scores, in which potential real-case variations may exist.

In general, it is easier for the decision makers to rank their preferences rather than give weightings to them. Therefore, the survey has been developed in such a way to attribute ranking scores to different characteristics by the decision makers (i.e., aquafarmers). A copy of the survey instrument is provided in Table S13.

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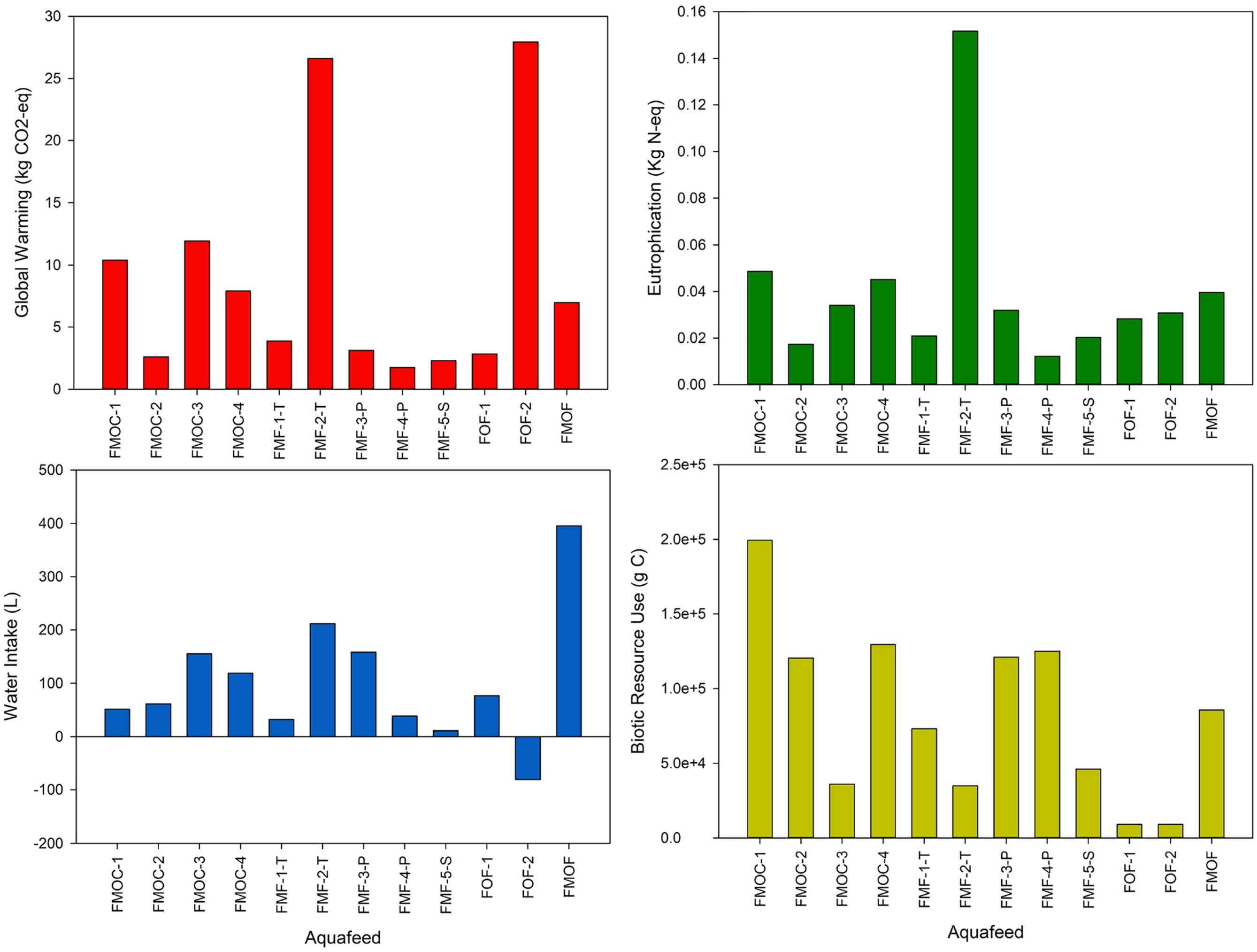

Figure 3. Quantified environmental impacts of aquafeeds based on unit mass (1 kg) of protein provision.

2.3. Weightings. To attribute appropriate weightings to different characteristics that influence producers' decisions on the selection of aquafeeds, eight farmers ranked the relevant characteristics on the basis of their level of importance (survey). The characteristics are "cost", "impact on fish production", "impact on water quality", "impact on the environment", "use of fish meal", "use of fish oil", "inclusion of essential nutrients", and "inclusion of supplemental nutrients". The elicited rankings have been converted to weightings using the rank-order centroid (ROC) method, which is known as one of the best performing rank-to-weighting conversion methods due to the nonlinear function of weights.[44] Weightings to different ranked characteristics based on ROC can be attributed using the following algorithm:

$$W_i = \frac{1}{M}\sum_{n=i}^{M}\frac{1}{n} \tag{1}$$

where W_i is the attributed weighting to the characteristic ranked i and M is the total number of characteristics (items). A summary of the survey results regarding the rankings attributed to different characteristics (by decision makers) as well as the associated calculated ROC weightings is provided in Table S14.

2.4. Assignments of Values to Characteristics. *2.4.1. Cost.* Assuming similar pellet production and product processing (e.g., grinding, extruding, drying, etc.) for the investigated aquafeeds,[2] we can directly correlate the comparative prices for different aquafeeds to the quantities and types of ingredient components. Comparative ingredient-based prices have been elicited on the basis of the component inclusion of varying ingredients for each diet.[45,46] The results are presented in Figure 2a.

The United Nations Food and Agricultural Organization (FAO) data set for monitoring and analysis of food prices is used to attribute the most accurate ingredient prices for different aquafeeds (most recent annual average international export prices from April 2019 to April 2020). For the ingredients that did not exist in the database, an online web search was used to elicit the best estimation for the merchandised price per gram of ingredient based on available products. Attributed price values based on each aquafeed's ingredient are provided in Table S15.

2.4.2. Impact on Fish Production. To evaluate the impact of using different aquafeeds on the quantity of produced fish (gained live weight product), the feed conversion ratio (FCR) is used as the common quantification approach to characterize the efficiency of intake of nutrients by species.[2,47] FCR is defined as the amount of consumed dry weight aquafeed per unit of gained live weight product. A lower FCR for an aquafeed indicated a larger gain of the ultimate product (e.g., fish) using the investigated aquafeed. The attributed FCRs for the investigated aquafeeds are listed in Table S16.

2.4.3. Impact on Water Quality. The dietary-origin waste is reported as the major contributor to the final waste in aquaculture systems.[48,49] The undigested portion of ingested feed (=ingested portion − digested portion) can be attributed to the decrease in water quality.[48,50] In an effort to quantify the comparative digestibility of the investigated aquafeeds, the values for the digestible energy (DE, megajoules per kilogram) have been elicited with respect to different ingredients for rainbow trout.[51] The results are shown in Figure 2b (Table S17). A higher overall DE for an aquafeed indicates a smaller

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undigested feeding portion and less waste and, consequently, higher rearing water quality.

2.4.4. Impact on the Environment. Life cycle assessment (LCA) is a methodology for quantifying and assessing the environmental impacts of products or processes over their entire or partial life cycle (based on the defined system boundaries). A standardized LCA follows the four steps defined by the International Standard Organization (ISO14040):[52,53] (1) goal and scope definition, in which the system's boundary and evaluation methods are defined; (2) life cycle inventory, in which all of the material and energy flows (inflows and outflows) to the system are quantified;[54] (3) life cycle impact assessment, in which the quantified environmental impacts are calculated and evaluated; and (4) interpretation, in which conclusions and recommendations are made. For this study, the quantified environmental impacts of different aquafeeds are elicited from a previous LCA, in which the U.S. Environmental Protection Agency's TRACI 2.1 is used as the midpoint impact characterization tool, along with the stand-alone categories of biotic resource use and water intake.[2,55] The main impact categories that have been considered for this study are global warming (GW), eutrophication (EU), biotic resource use (BRU), and water intake (WI). The selected impact categories are recognized as the most relevant categories in terms of resource extraction (biotic and water resources) and emissions (eutrophication and global warming potential) with respect to aquafeeds.[2,24] Quantified impacts are provided in Figure 3 and Table S19.

To provide a comparative score for this criterion, the environmental impacts in each of the impact categories are first normalized (1 being the highest) and then considered as equally important with respect to other impact categories (i.e., the overall weighting for environmental impacts is equally distributed among all indicators).

2.4.5. Inclusion of Essential and Supplemental Nutrients. To quantify the incorporation of essential nutrients in the aquafeeds (rather than the use of supplements to make up deficits), protein inclusion (in terms of crude protein percentage) is selected as the major consideration in aqua diet formulations.[2,56,57] To specify the incorporation of supplemental (subessential) nutrients in the aquafeeds, supplemental vitamin C (ascorbic acid, Stay C) has been selected as the necessary nutrient that is required to be supplied to aquatic animals to acquire optimal growth and health.[58,59] The attributed protein inclusions (in percent) and supplemental vitamin C (in grams per kilogram) for the investigated aquafeeds are listed in Table S16.

2.5. Analysis Methodology (multi-criteria decision). The preference ranking organization method for enrichment evaluation (PROMETHEE II) has been selected as a standard and widely used method for MCDA.[60−62] PROMETHEE II is performed using the following procedure.[38]

The first step is to provide comparative, unitless, and harmonized values among varying criteria (evaluation matrix normalization). Equation 2 is used to normalize direct criteria (where maximizing is desired), and eq 3 is used for indirect (where minimizing is desired) criteria.

$$R_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}\ (i = 1, 2, ..., m; j = 1, 2, ..., n) \tag{2}$$

$$R_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})}\ (i = 1, 2, ..., m; j = 1, 2, ..., n) \tag{3}$$

where X_{ij} is the performance measure of the ith alternative with respect to the jth criterion (characteristic).

The second step is calculation of pairwise evaluative differences. In this step, the difference of each alternative with respect to other alternatives is calculated.

The third step is the calculation of the preference function. The difference between the evaluations obtained in the second step is translated into a preference degree, ranging from 0 to 1, using the following formulae (eqs 4 and 5).[60,63]

$$P_j(i, i') = 0;\ \text{if}\ R_{ij} \le R_{i'j} \tag{4}$$

$$P_j(i, i') = R_{ij} - R_{i'j};\ \text{if}\ R_{ij} > R_{i'j} \tag{5}$$

where R_{ij} and $R_{i'j}$ are the normalized values for two selected alternatives (ith and i'th) with respect to the jth criterion (characteristic).

In the fourth step in the calculation of aggregated preference, the criteria weights are taken into account using the following formula (eq 6).[64]

$$\pi(i, i') = \frac{\sum_{j=1}^{m}[W_j P_j(i, i')]}{\sum_{j=1}^{m} W_j} \tag{6}$$

where W_j is the weight attributed to the jth criterion (characteristic) and $P_j(i,i')$ is the preference function of the two selected alternatives (ith and i'th) with respect to the jth criterion.

The fifth step is determination of the leaving and entering flows. In this step, the extent to which an alternative dominates the other alternatives (leaving flow, eq 7) or an alternative is dominated by other alternatives (entering flow, eq 8) is expressed using the following formulae (eqs 7 and 8).

$$\varphi^+(i) = \frac{1}{n-1}\sum_{i'=1}^{n}\pi(i, i')\ (i \ne i') \tag{7}$$

$$\varphi^-(i) = \frac{1}{n-1}\sum_{i'=1}^{n}\pi(i', i)\ (i \ne i') \tag{8}$$

where n is the total number of alternatives and $\pi(i,i')$ is the aggregated preference of alternatives i and i'.

The sixth and final step is calculation of the net outranking flows (φ) and ranking determination. In this step, the net outranking flows are calculated using the following formula (eq 9). Then, alternatives are ranked from the most preferred (highest net outranking flow) to the least preferred (lowest net outranking flow).

$$\varphi(i) = \varphi^+(i) - \varphi^-(i) \tag{9}$$

2.6. Graphical Analysis for Interactive Assistance (GAIA). To perform further analysis regarding MCDA results, a GAIA plane for each real case and hypothetical scenario is plotted using Visual PROMETHEE version 1.5.[65] The aim of using GAIA in this MCDA is to provide the most possible information from a two-dimensional representation.[62] Four main types of information are provided by the GAIA plane:[66] (1) alternatives (actions) represented by points [alternatives with similar profiles will be closer to each other (and vice versa)], (2) characteristics (criteria) represented by axes [characteristics with similar preferences have axes close to each other (and vice versa)], (3) decision axis (the red axis), which represents all criteria values and weights (the orientation of the decision axis indicates the relative contribution of characteristics to the final outranking), and (4) the orthogonal projection of each alternative (action) on each criterion (characteristic) axis that will illustrate the performance of each alternative with respect to each characteristic.

2.7. Alternative Scenario Analysis. To evaluate the MCDA results in varying scenarios, four hypothetical stakeholder perspectives have been further evaluated. In the first perspective, the stakeholder (decision maker) values mitigating environmental impacts (EIMs) the most. Thus, the overall environmental impact criterion weight is equal to all other criteria combined (50:50, weighting ratios for other criteria are equal). In the second perspective, the stakeholder (decision maker) values maximizing fish production (FPM) the most. Then, the overall "impact on fish production" criterion weight is equal to all other criteria combined (50:50, weighting ratios for other criteria are equal). In the third perspective, the stakeholder (decision maker) values minimizing feeding costs (CM) the most. For this reason, the overall "aquafeed cost" criterion weight is equal to all

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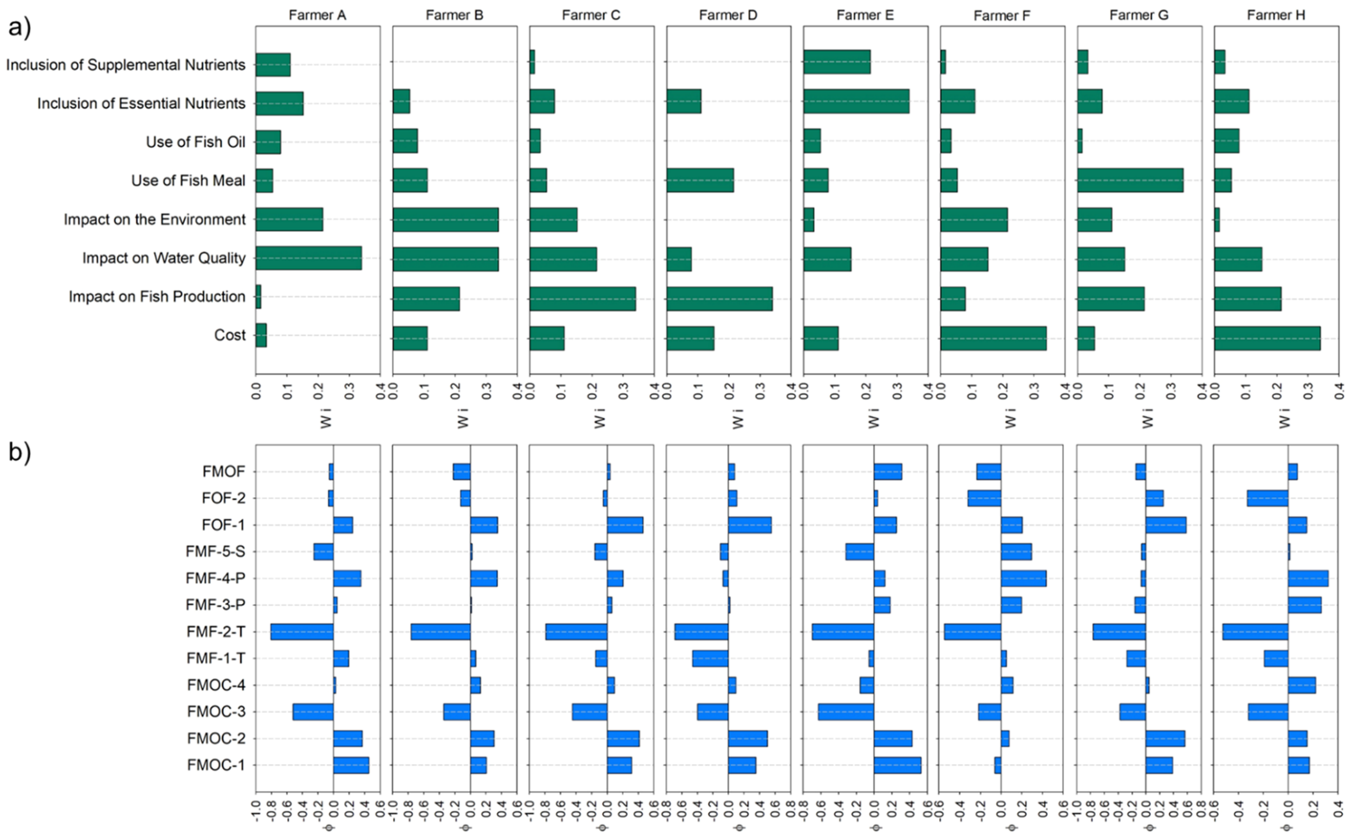

Figure 4. (a) Survey-based weightings (green bars) for the investigated characteristics based on farmers' ranking assignment using the ROC methodology. (b) Net outranking φ values for the investigated aquafeeds (blue bars). Aquafeeds with the highest φ values are most preferred and vice versa.

other criteria combined (50:50, weighting ratios for other criteria are equal). In the fourth perspective, the stakeholder (decision maker) values replacement of fish meal with alternative ingredients in the utilized aquafeed (FMR) the most. The aquafeeds (actions) with fish meal as an existing component are eliminated from the analysis, and only fish meal free diets are incorporated in the analysis. Furthermore, the "use of fish meal" criterion is assigned to the weighting of zero (equal weighting for all other criteria).

3. RESULTS

3.1. MCDA. A quantitative MCDA, attributed to the different criteria weighting scenarios, is performed on the basis of aquafarmer survey results (presented as farmers A–H). The assigned weightings and consequent MCDA results are shown in Figure 4 with green and blue bar graphs, respectively.

In four of eight scenarios, FOF-1 (the diet in which fish oil is replaced by canola oil) has resulted in the highest net outranking flow. Furthermore, it has ranked among the top four in seven of eight scenarios. Hence, FOF-1 can be stated as the most promising aquafeed based on the real-case scenarios. In addition, FMOC-2 has also performed as the second favorable aquafeed. Despite it not being ranked first in any of the scenarios, it has ranked among the top four in six of eight scenarios. Thus, FMOC-2 can be stated as the second most favorable aquafeed based on the real-case scenarios. On the contrary, FMF-2-T has resulted in the lowest net outranking flow in all investigated (12 of 12) scenarios. As a consequence, compiling all pertinent characteristics and attributed weightings, we can identify it as the least favorable aquafeed to be selected. Compiling all of the rankings based on different scenarios, we can rank the investigated aquafeeds (actions) as follows: (1) FOF-1, (2) FMOC-2, (3) FMOC-1, (4) FMF-4-P, (5) FMOC-4, (6) FMF-3-P, (7) FMOF, (8) FMF-5-S, (9) FOF-2, (10) FMF-1-T, (11) FMOC-3, and (12) FMF-2-T. Overall rankings are assigned on the basis of each aquafeed's average ranking over all investigated scenarios. The full results regarding the ranking flows for different aquafeeds under different scenarios are provided in Table S19.

Upon examination of the role of diet formulation in the aquafeeds, the results based on the integration of pertinent characteristics indicate that the substitution of fish oil with plant-based canola oil is a promising strategy for achieving a desirable aquafeed (FOF-1). This aquafeed has not only exhibited a relatively acceptable inclusion of nutrients and feed conversion ratio but also mitigated the environmental impacts associated with fish oil production.[2] Moreover, the aquafeeds with the supplemental nutrients have mostly resulted in the diet formulations, in which the ultimate production efficiencies (FCR improvement) outperform the relative costs increase (e.g., FMOC-2). Accordingly, the inclusion of supplemental nutrients (Stay C) is another approach for practically increasing aquafeed favorability. On the contrary, the substitution of fish meal with terrestrial alternatives (e.g., blood meal) has resulted in a significant decline in the ranking of the corresponding aquafeeds (i.e., FMF-1-T and FMF-2-T). Therefore, the replacement of fish meal with the investigated terrestrial alternatives is not an effective strategy for improving the desirability of aquafeeds.

3.2. GAIA. To provide the most possible information from a two-dimensional representation, the GAIA plane is developed for all of the MCDA scenarios (Figure 5). As mentioned in

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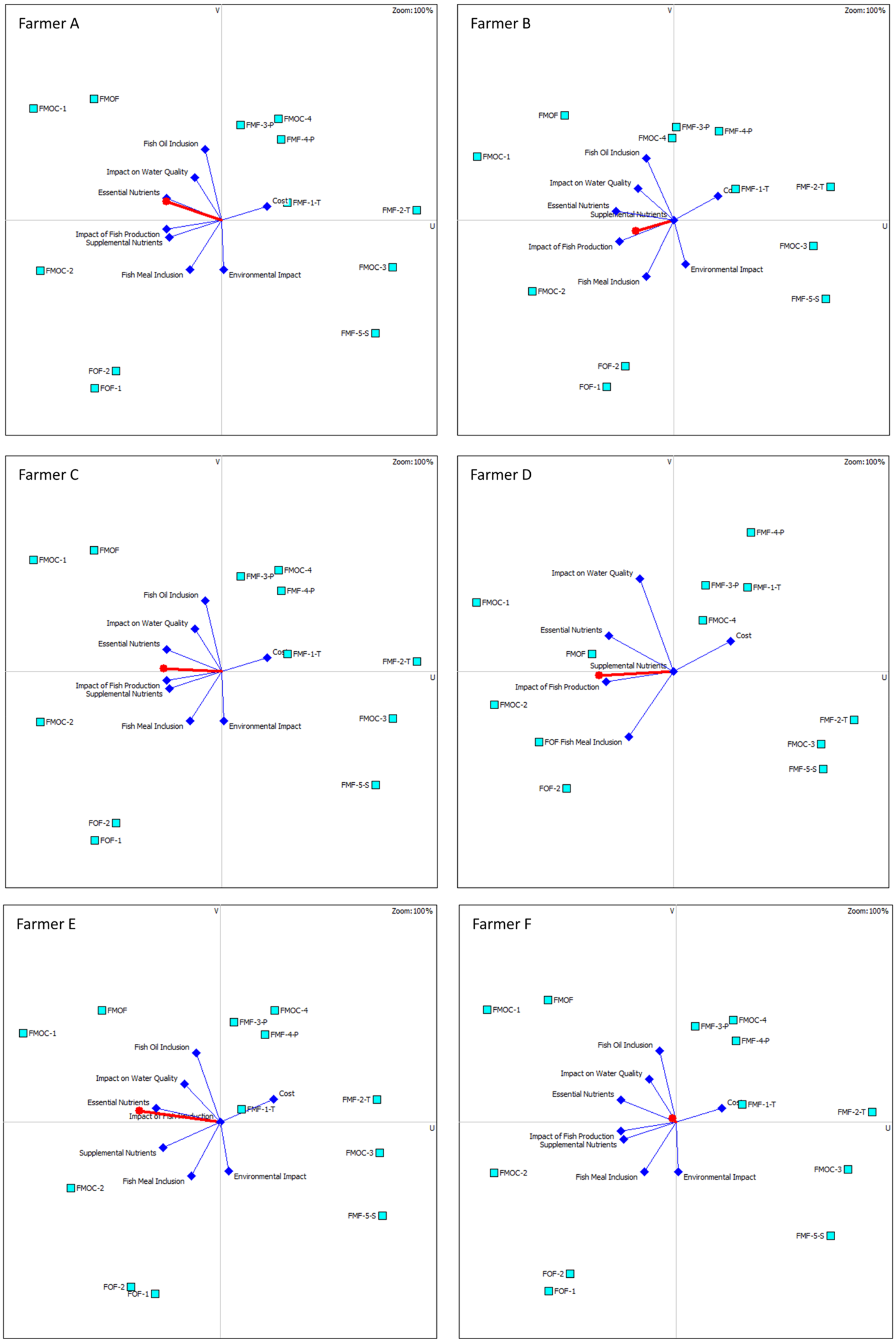

Figure 5. continued

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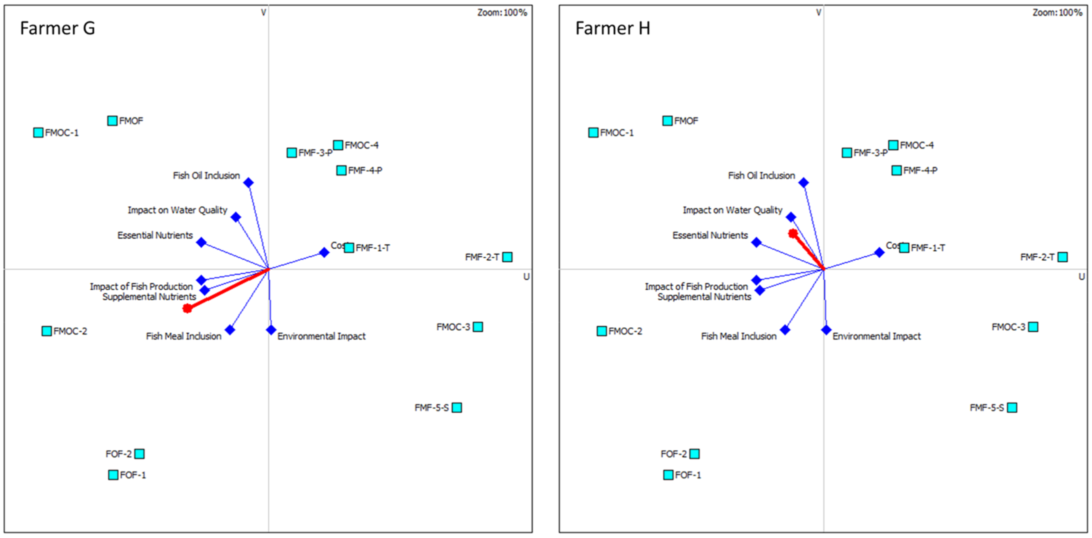

Figure 5. GAIA planes based on different scenarios.

Materials and Methods, alternatives (represented by light-blue points) with similar profiles are closer to each other in the GAIA plane. For example, FOF-1 and FOF-2 have many similar characteristics (regardless of their relative discrimination; both are fish oil free diets with similar FCRs and levels of protein). Consequently, they are located close to each other in most of the GAIA planes. Furthermore, characteristics with similar axis orientation represent how in-line they are with respect to each other. Thus, on the basis of the data and the investigated characteristics, the following statements could be made for most of the scenarios. First, aquafeeds with higher levels of essential and supplemental nutrients also have a better impact on fish production (lower FCR). Hence, the most practical way to improve fish production for an aquafarmer is to improve the inclusion of both essential and supplemental nutrients in the utilized diet formulation. Second, the cost and environmental impacts are the conflicting characteristics regarding most of the other characteristics. Consequently, if the aquafarmer selects the cheapest aquafeed or the aquafeed with the least environmental impact, the selected aquafeed will not perform as desirably in other discriminatory dimensions. Third, the inclusion of fish oil is mostly correlated with an improved impact on water quality. This suggests that the fish oil replacements are highly prone to decreasing the quality of rearing water. In addition, the vertical projection of each aquafeed on each characteristic line will demonstrate the relative performance of that aquafeed regarding the selected characteristic. For FOF-1, the positively contributing parameters are fishmeal inclusion, environmental impacts, and the impact on fish production. Consequently, aquafarmers who recorded high scores for those characteristics (targeting fishmeal-included, environmentally friendly, and efficient aquafeeds) can declare FOF-1 as the best option. For FMOC-2, the positively contributing parameters are the impact on fish production, inclusion of supplemental nutrients, and fishmeal inclusion. Consequently, aquafarmers who recorded high scores for those characteristics (targeting fishmeal and supplemental-included and efficient aquafeeds) can declare FMOC-2 as the best option. For FMF-2-T, the only characteristic that is relatively favorable for this alternative is cost. As aquafarmers mostly consider other conflicting factors as well when selecting an aquafeed (e.g., quality, ultimate efficiency, etc.), it has never posed a significant overall score.

4. DISCUSSION

Four hypothetical aquafarmer perspectives have been further analyzed to evaluate the MCDA results under varying scenarios. These scenarios include the perspective of stakeholders who outweigh one specific characteristic over the others, and those perspectives are (1) environmental impact mitigation (EIM), (2) final product maximization (FPM), (3) cost minimization (CM), and (4) fish meal replacement (FMR). MCDA is performed under hypothetical scenarios using PROMETHEE II. The results are illustrated in Figure 6 (and Table S20).

As shown in Figure 6, in EIM and FPM scenarios, FOF-1 has resulted in the highest net outranking φ values. Therefore, this diet formulation (a diet in which fish oil is replaced by plant-based oil) is the best option for the aquafarmers who are prioritizing either (1) obtaining the most fish per unit of utilized feed or (2) having the least environmental impacts. In CM and FMR scenarios, FMF-4-P has resulted in the highest net outranking φ values. Thus, FMF-4-P (a diet in which fish meal is replaced by soybean meal) is the best option for the aquafarmers who are prioritizing either (1) using the aquafeed with the least initial cost or (2) replacing the finite fish meal with other alternatives. In contrast, FMF-2-T (a diet in which fish meal is replaced by blood meal) has posed the least net outranking φ values for EIM, FPM, and FMR scenarios. Therefore, the selection of this diet would lead to the most unsought results for the aquafarmers who are seeking (1) to have the least environmental impact, (2) to obtain the most fish per unit of feed, and (3) to replace the finite fish meal with other alternatives. Expectedly, FOF-2 has resulted in the least desirable aquafeed for the CM scenario due to the relatively high cost of the utilized alga-based oil (protist-based Thraustochytrid oil).

In summary, considering the heterogenity of the opinions of the surveyed farmers as well as in the hypothetical weightings, and the consequent outranking results (Figures 4 and 6), it is relevant to mention that there is no diet that falls within the "one-size-fits-all" category. The selection of the most suitable aquafeed highly relies on the preference of the farmers for the

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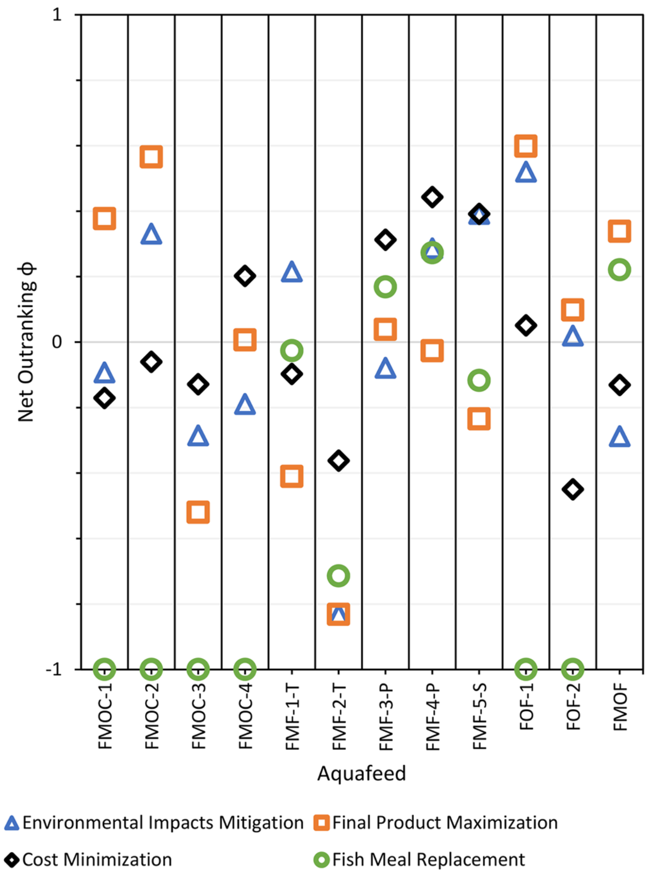

Figure 6. Comparison of MCDA results for different hypothetical scenarios (a higher φ value indicates greater desirability).

relevant characteristics. The prospective scarcity and price increase of marine-based fish meal and fish oil[67−69] are expected to result in the further preference of aquafeeds with alternative nutrition resources and lower ecological burdens.[2,70] From a decision making perspective, to recognize the most promising alternatives, it is important to integrate the relevant environmental, economic, and technical characteristics and implications of the aquafeeds using alternative ingredients. Our analyses based on the survey-based and hypothetical scenarios indicate that FOF-1 and FMF-4-P are the best fish meal and fish oil replacement strategies among investigated diets. Thereby, the replacement of fish oil by plant-based canola oil and the replacement of fish meal by soybean meal are potential approaches for obtaining desirable aquafeeds (specifically if the fish meal supply becomes limited or expensive). Upon examination of the alternatives with the lowest rankings, FMF-2-T was proposed to be the least favorable (net φ) in most scenarios. Accordingly, the replacement of fish meal with terrestrial blood meal is not recommended as a potentially desirable alternative, based on this modeling.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsagscitech.1c00053.

Aquafeed formulation details, farm survey form, aquafeed ingredient costs, aquafeed attributes, aquafeed digestible energy, aquafeed environmental impacts, MCDA aquafarmer results, MCDA hypothetical results, and science-based communication information (PDF)

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Notes

The authors declare no competing financial interest.

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