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Selecting Product Species for Aquaculture Companies: A Spherical Fuzzy Delphi–CRADIS Framework

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ABSTRACT

Developments in the aquaculture sector have broadened the commercial reach of products. Parallel to this expansion, seafood is becoming increasingly important in human nutrition due to its low cost and high protein content. This study seeks to identify marine aquaculture species that can be cultivated in the Eastern Black Sea Region. It also determines the criteria used in marine aquaculture species evaluation. In this regard, the importance of the criteria and the degree of preference for the management options are determined. To accomplish these objectives, the t-spherical fuzzy-Delphi-subjective weighting approach-compromise ranking of alternatives from distance to ideal solution (CRADIS) methodology is employed. The study finds that euryhaline capability, ecosystem effect, habitat suitability, and temperature tolerance are important determinants in seafood aquaculture production. Rainbow trout is the most ideal option, followed by Black Sea salmon, brown trout, seabass, and seabream. The study emphasizes the importance of environmental, sustainable, and customer-focused principles in marine aquaculture management.

1. Introduction

Aquatic products play a significant role in human nutrition. However, many factors, including the rapidly increasing human population, technological advancements, and global warming, are negatively impacting the survival of aquatic organisms [1,2]. The United Nations Food and Agriculture Organization (FAO) has reported a decrease in fish stocks ranging from 10.5% to 58.1% depending on the intensity of fishing [3,4]. Undoubtedly, one of the important solutions to alleviate this pressure is aquaculture [5]. In this context, determining the type of aquatic product to be cultivated is a crucial decision [6].

Aquaculture is the controlled cultivation of aquatic organisms such as fish, mollusks, crustaceans, and algae for feeding, growth, production, breeding, stocking, and conservation purposes [7]. These

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activities can be carried out from the beginning to the end of the organisms' lives, or only for a specific period. Aquaculture differs from fishing in terms of ownership, controlled environments, process, and quality control. Aquatic products can be cultivated for nutrition, sport, ornamental purposes, stock replenishment, or scientific research [8]. However, the production of aquatic products for nutritional purposes is the most significant commercial activity, directly impacting human lives. Developments in the aquaculture sector have also expanded the commercial scope of these products. Parallel to this expansion, aquatic products are increasingly gaining a significant share in human nutrition due to their low cost and high protein content [9]. In addition to cost, aquatic products also offer significant health advantages compared to other protein sources. For example, the consumption of fish, which holds a significant place among aquatic products, has many positive effects on humans. Depending on the species, fish contain vitamins A, B, C, D, E, and K, as well as fatty acids like Omega-3 and various minerals. Aquatic products can meet a significant portion of the vitamins and minerals that humans need. Fish consumption, in particular, is highly preferred as a source of vitamin B12 supplementation. For these reasons, the production, cultivation, and consumption of fish and aquatic products hold an important place today, considering both health and economic factors [10,11].

Türkiye is on its way to becoming a global player in aquaculture through the transformations and advancements it has experienced [10]. Examining the development of the aquatic products sector in Türkiye from the 1970s to the present day shows that significant progress has been made [12]. In addition to achieving technological progress, the shortage of qualified personnel has also been significantly solved [13,14]. On the other hand, it is known that economic crises in Türkiye negatively affect seafood consumption [9]. In this context, decisions to be made in aquaculture require the consideration of conflicting criteria.

On the other hand, one of the important markets for aquaculture companies in Türkiye is the European Union (EU) countries. The EU mandates the fulfillment of certain conditions in the supply of seafood. In addition, some transformations are necessary in Türkiye to ensure compliance within the framework of the EU membership process. These reasons have led Turkish aquaculture companies to follow and adopt the latest technologies. For example, the condition adopted by the EU within the framework of its goal to ensure environmentally friendly aquaculture, requiring cages to be located no less than 0.6 nautical miles from the shore, has also been implemented in Türkiye since 2007 [15,16]. In addition to the EU's regulatory influence on the sector, factors directly affecting seafood exports are also decisive in the strategic decisions to be taken. At this point, the price and quality of the product, export incentives, and market research play an important role in achieving a sustainable market share in the aquaculture sector [15].

Over the past few decades, significant increases have been observed in the consumption of farmed aquaculture products, both globally and locally. In Türkiye, in particular, aquaculture production has significantly surpassed wild-caught aquaculture production since 2020. Furthermore, approximately three-quarters of Türkiye's aquaculture production takes place in the seas. While 39% of marine-farmed products are produced in Muğla and 30.2% in İzmir, Muğla has the highest share in inland aquaculture with 18.2%. Artvin, a Black Sea province, has a significant share in inland aquaculture with 4.1% [17].

In Türkiye, per capita aquaculture consumption increased from 6.1 kg in 2018 to 7.3 kg in 2022. However, Türkiye is a net exporter in aquaculture foreign trade. Türkiye's aquaculture exports increased from 177,500 tons in 2018 to 251,416 tons in 2022. A similar increase can be seen in imports as well. The amount of seafood imports was 98,315 tons in 2018 and 115,189 tons in 2022.

While the revenue from seafood exports increased to 1.651 billion USD, approximately two-thirds of this trade took place with EU countries [17].

It has been suggested that one of the regions that can benefit Türkiye the most in the aquaculture sector is the Eastern Black Sea Region [10]. The history of aquaculture in the Black Sea Region begins with the production of rainbow trout in 1972 [18]. Due to its natural resources, the Eastern Black Sea Region provides opportunities for the establishment and operation of aquaculture facilities at low cost. In this context, a significant portion of the businesses engaged in aquaculture are clustered in the Eastern Black Sea Region [19]. It is stated that Gümüşhane, Rize, and Artvin in the Eastern Black Sea region have significant potential for organic aquaculture [9]. Considering the increasing importance of aquaculture production, the potential of the Eastern Black Sea region in this field, and its leading position, this study aims to identify suitable new product species for marine aquaculture in the Artvin and Rize provinces of the Eastern Black Sea region, and to determine the criteria to be considered in their selection.

This study will present a decision model proposal for determining new product species for businesses operating in freshwater and marine aquaculture in Artvin and Rize provinces. Within this framework, the scope of the study is the evaluation of commercially viable marine species that can be produced in seawater in the regions of Türkiye's continental shelf along the İyidere-Hopa line. Aquaculture in cages is currently carried out in the specified region. Furthermore, the region encompassing Artvin and Rize provinces is relatively unindustrialized compared to many other regions of Türkiye. This situation makes it possible to develop a suitable environment for environmentally friendly and sustainable aquaculture. Therefore, this study aims to contribute to sustainable seafood farming activities in Artvin and Rize provinces, prioritizing the sea and nature, and serving the achievement of SDG goals. Within the scope of the study, options and criteria for the production of a new commercially viable marine aquaculture species in the Eastern Black Sea Region will be determined and evaluated. At this point, aquaculture species produced for human consumption will be considered. The solution to this problem will be provided using the t-SF fuzzy multi-criteria decision analysis (MCDA) methodology. Data collected based on the opinions of experts with extensive work experience and knowledge on the subject will be analyzed using the proposed methodology. In this methodology, t-SF-Delphi will be used to define the criteria and options. The importance levels of the criteria will be determined using the t-SF subjective weighting approach. The ranking of the options will be performed using t-SF-CRADIS.

2. Literature

Water covers almost 71% of Earth’s surface. This water possesses characteristics that provide a habitat for a variety of organisms. These organisms include mammals and single-celled organisms. Among all aquatic life, fish are primarily considered a food source for humans. Therefore, countries near bodies of water worldwide are working to utilize these resources as much as possible and to find ways to use them more effectively [14]. While Türkiye has made significant progress in this area, it is necessary to ensure the continuation of innovative solutions and technological advancements through new research.

The variety of aquatic products that can be cultivated in freshwater and marine environments is quite wide. It is estimated that there are around one hundred economically valuable aquatic products that can be cultivated in Türkiye [17]. These products are subjected to processes such as preservation with radioactive irradiation, freezing, salting, smoking, canning, packaging, and crushing, and are offered for sale in the domestic market in supermarkets, markets, fish farms, producer associations, wholesale markets, cooperatives, fishing boats, or fishing harbors [20]. In addition, a significant portion of the aquaculture products produced in Türkiye are shipped to export markets. One of the regions with significant production potential for aquaculture in Türkiye is the Eastern Black Sea. Fishing activities carried out in the Black Sea Region can be divided into two classes: coastal fishing and offshore fishing. Coastal fishing is carried out daily. Offshore fishing, on the other hand, is done according to the movements of fish species and the area in which they are found [19].

Considering the employment figures in the fishing sector in Türkiye, it is understood that nearly half of the workers are employed in the Black Sea Region and a quarter in the Eastern Black Sea [21]. Considering that aquaculture activities differ significantly from fishing, it can be stated that aquaculture has a more sustainable future in terms of trade and employment.

The Eastern Black Sea Region has a favorable structure for aquaculture in both inland waters and the open sea. Cage fish farming is quite popular in production. In this context, the most preferred fish species are rainbow trout, sea bass, carp, and sea bream. In addition to these, the search for new fish and aquatic product species continues [22]. Among the products that can be cultivated, trout, sea bream, sea bass, crustaceans, soft water organisms, sturgeon, eel, crayfish, shrimp, turbot, coral fish, snapper, grouper, black sea bream, minnow, catfish, sea trout, yellowtail, striped seabream, and yellowmouth are primarily listed [9]. In addition, anchovy, bonito, horse mackerel, bluefish, mullet, sprat, garfish, grouper, and scad are also suggested as aquaculture products [23,24]. On the other hand, the Black Sea's water structure is very suitable for mussels, oysters, and mullet, but these products are not preferred in production due to low consumption habits [18]. In Türkiye, sea bass and sea bream are the most produced fish in the seas recently, while trout is produced in freshwater [17].

Although many types of aquaculture products can be cultivated, environmental and social factors create limitations. For example, in the Black Sea, the sea water temperature rises above 20 degrees Celsius in the summer months, necessitating the sale or transportation of fish [18]. In sea cage farming, due to the warming temperatures that begin in June, the air and water warm up, requiring the harvesting and marketing of the farmed fish by October. If the products are not harvested during this period, the decrease in oxygen levels in the water due to the warming will lead to deaths. On the other hand, in freshwater farming, it is known that dramatic changes in water level and content, such as the release of chemical waste, have negative and destructive effects. In such a situation, almost all of the aquaculture products can be lost. To increase production, efficient use of water resources, establishment of a facility suitable for the existing water, and, if possible, a transition to a closed-loop system are necessary [18]. These points should also be considered when selecting the aquaculture products to be farmed.

To protect the future of aquaculture and ensure its sustainability, it is necessary to take measures to prevent pollution and degradation, improve seafood consumption habits, take precautions to prevent diseases caused by intensive production, and take measures that align with expectations of increasing input costs (feed, energy, etc.) (feed stockpiling, etc.). Furthermore, it is recommended to be prepared for the negative consequences that rising prices in China, a major player, will create on a global scale, and to regulate the types and amounts of state support in a way that will prevent exports [17].

At this point, feed emerges as one of the important elements in aquaculture production. It is stated that feed prices increased by 51% in 2022 compared to the previous year. Moreover, feeds vary according to the type of aquaculture, and consequently, costs also differ [17]. Another factor is the varying amounts of state support provided to different types of aquacultures. For example, support is provided at 0.75 TL/kg for trout (1.50 TL/kg for new species, 1.50 TL/kg for closed system production), 0.50 TL/kg for carp, and 0.10 TL/kg for mussels [17].

In the literature, factors considered in determining the type of aquaculture species to be cultivated include the habitat in which the organism can live [6], the structure of suitable water (saltwater, freshwater, brackish water) [25], the temperature at which it can live, its type of feeding [6], and its size [23]. Moreover, aquaculture species' breeding season, the water temperature at which it can reproduce, the water depth at which it can live, the bottom characteristics of the water where it can reproduce (algae, vegetation, gravel, etc.) [6], and its welfare [26] are identified as factors to evaluate options. It has been observed that the following criteria were also taken into consideration: hunting status, taste, economic value [6,23], compatibility with the environment [27], cost [28], feed availability and content [29,30]. Furthermore, market volume or marketability, and business size are other factors [6,7].

The study aims to present these criteria to experts in a comprehensive list and to identify the appropriate ones. In addition, new criteria that are not included in the comprehensive list but that experts deem necessary to consider in their evaluations may also be added to the list. Thus, within the scope of the study, a set of criteria and a set of options will be created, considering current conditions and the regional structure of the Eastern Black Sea region.

Studies in the literature mainly focus on the development and current state of aquaculture in Türkiye or worldwide. However, for the increasing demand for aquatic products and the developing Turkish aquaculture sector, one aspect of development should be sought in the production of new products. In this context, the study will contribute to the literature with a decision model proposal for determining new marine product species that can be cultivated. Within this model, the criteria to be considered in the selection of new products for aquaculture will be determined, and the processes of evaluating new product types will be carried out.

For the contribution of aquaculture to prevent the depletion of world fish stocks and meet the nutritional needs of the growing population, to increase and be sustainable, state and private organizations need to act with a common vision. At this point, production methods and species that do not harm the environment, and natural species can be supported [29]. It is believed that the study will contribute to sustainable development and environmental protection by identifying the criteria to be considered in regionally appropriate species selection and evaluating candidate species.

Aquaculture not only provides a sustainable food source but also makes significant contributions to employment. It is estimated that around 200 million people are employed in this sector worldwide [4]. For Türkiye, the aquaculture sector plays an important role. The sector has shown approximately 11% annual growth since 1984 [1]. In particular, the aquaculture sector has the potential to play a significant role in closing the gap between the Eastern Black Sea region, which is relatively underdeveloped industrially and where creating new jobs is difficult, and other developed regions of Türkiye. The study's significant contributions to businesses' decisions regarding new product types will support increased employment and economic development.

Considering sustainability and ecosystem protection in identifying new marine products that can be cultivated will support the goals of sustainable development and environmental protection. The ranking results that the study will provide in the identification and evaluation of new marine product species will increase the effectiveness of investments by businesses making new investments. Thus, it will lead to outcomes that will increase the economic development and employment opportunities of the relatively underdeveloped provinces of Artvin and Rize, and the Eastern Black Sea Region, particularly in agriculture and rural development. Contributions to the development of Artvin and Rize provinces will also positively impact the reduction of inter-regional inequalities. Furthermore, the successful production and marketing of the product types identified within the scope of the study can increase Türkiye's competitiveness in aquaculture and its share in the international market.

The study focuses on aquaculture, directly contributing to the protection and sustainable use of aquatic ecosystems. Thus, it will offer implications for supporting the sustainable management of marine and coastal ecosystems. Moreover, the production of new seafood species will support food production, positively impacting the achievement of the SDGs "ending hunger" and "responsible consumption and production". Identifying alternative seafood species in the Artvin and Rize regions can create new job opportunities and contribute to regional economic growth. Such a contribution, particularly towards increased employment and revitalizing the local economy, will support the achievement of the SDGs "decent work and economic growth", "industry, innovation and infrastructure", and "reducing inequalities." In this context, it can be stated that the study supports the main objectives and related sub-objectives and targets specified in the SDGs.

The study will guide the sector in the future to solve a problem that is intuitively approached in the current conditions on a scientific basis. The decision model proposed by the study will allow the opinions of experts with experience in the sector to be transferred to a scientific framework. In the future, researchers will be able to carry out solutions for different problems by using the framework provided by the study.

The research questions of this study, which focuses on developing a decision model for determining a new product type for aquaculture in the Eastern Black Sea, have been determined as follows:

i. What are the potential marine species that can be cultivated in seawater in the Eastern Black Sea region?
ii. What criteria should be considered when determining which species can be grown in seawater in the Eastern Black Sea region?
iii. What is the importance level of the criteria considered when determining which species can be grown in seawater in the Eastern Black Sea region?
iv. How would the species that can be grown in seawater in the Eastern Black Sea region be ranked in terms of preference and expected performance?

3. Methodology

t-spherical fuzzy sets (t-SFSs) are an advanced extension of classical and generalized fuzzy set approaches, developed to model uncertainty, instability, and missing information more flexibly and comprehensively. While classical fuzzy sets, heuristic fuzzy sets, and Pythagorean fuzzy sets have strict mathematical constraints on membership and non-membership degrees, t-SFSs define membership, instability, and non-membership degrees such that the sum of their t-th powers is less than or equal to one. This allows t-SFSs to represent a wider range of uncertainty and offers a more general and flexible structure encompassing spherical, Pythagorean, and picture fuzzy sets. This feature provides more realistic and powerful modeling possibilities, especially in MCDA problems [31,32].

t-SFSs have been used in a wide variety of decision-making problems, including pattern recognition [33], alternative fuel selection [34], H2 refueling site selection [35], assessing green strategy for logistics companies [36], enhancing learning environments with IoT [37], evaluating solar thermal energy technologies [38], and music composition evaluation [39]. These examples demonstrate that t-SFSs are an effective tool for solving problems in various fields involving uncertainty. This study will also utilize these effective features of t-SFSs in handling uncertainty.

The Delphi technique is a qualitative decision-making tool that aims to systematically achieve consensus on uncertain and complex problems based on expert opinions. In this technique, evaluations are obtained from experts in multiple rounds. The feedback obtained in each round is summarized and shared with the participants. The process is completed when consensus is reached on the expert opinions. Extensions of the Delphi technique have been developed under various fuzzy sets that effectively handle uncertainty. These include classic fuzzy-Delphi [40], Pythagorean fuzzy Delphi [41], q-rung-orthopair fuzzy Delphi [42], and Fermatean Fuzzy Delphi [43]. In this study, a new extension of the Delphi technique, t-SF-Delphi, will be proposed. This extension is expected to play a significant role in defining criteria and options, which are crucial components of an unstructured problem.

The compromise ranking of alternatives from distance to ideal solution (CRADIS) method is an integrated ranking approach that aims to determine the best option in MCDA problems by considering the distances of alternatives from ideal and anti-ideal solutions [44]. The method provides a compromise ranking by simultaneously considering the relative positions of alternatives to both the best and worst solutions. Furthermore, the simplicity and interpretability of the calculation steps make the CRADIS method effective and applicable to various decision-making problems [44,45]. Problems to which the CRADIS method is applied include sustainable suppliers in agribusiness [46], optimizing radioactive waste reduction [47], supply chain risk management [48], decoding green university rankings [49], evaluating Turkish non-life insurers [50], assessing international marketing entry strategies [51], and digital innovation performance evaluation [52]. In this study, a new CRADIS extension will be proposed for the evaluation of cultivated marine species.

A literature review has been conducted to pre-determine aquaculture options and the criteria that can be used in their evaluation. On the other hand, the ecological, economic, and social structure of the Eastern Black Sea Region, as well as current developments in national and international markets, necessitate addressing the problem within the context of expert evaluation. In this framework, the problem of determining a new aquaculture product will be considered as a group decision problem. To solve the problem, interviews will be conducted with at least seven experts who have in-depth knowledge and experience on the subject. The methodological approach to be used in solving the problem is the MCDA approach defined under t-spherical fuzzy (t-SF) sets. In this approach, the Delphi technique defined under t-SFS will be used to finalize the criteria and option sets, the t-SF-subjective weighting approach will be used to determine the weight values of the criteria, and the t-SF-CRADIS method will be used to rank and grade the options. In this context, the details of the methodological approach proposed in the study are as follows.

3.1 t-Spherical Fuzzy Sets

t-SF sets are generalized forms of q-rung orthopair fuzzy sets, picture fuzzy sets, spherical fuzzy sets, and classic fuzzy sets [31]. Let X be a universal set. Then, a t-SFS B on X is defined as $B = \{\langle x, s_B(x), a_B(x), d_B(x) | x \in X \rangle\}$, where $s_B(x): X \rightarrow [0,1], a_B(x): X \rightarrow [0,1]$, $d_B(x): X \rightarrow [0,1]$, $0 \leq s_B^t(x) + a_B^t(x) + d_B^t(x) \leq 1, t \geq 1, \forall x \in X$. Here, $s_B(x)$ depicts the membership degree, $a_B(x)$ denotes the neutral membership degree, and $d_B(x)$ represents the non-membership degree. Moreover $ϟ_B = \sqrt[t]{1 - s_B^t(x) - a_B^t(x) - d_B^t(x)}$ is the refusal membership degree [32,36].

For convenience, a triplet (s, a, d) is used to depict the t-SF numbers (t-SFNs). Assume that $b_1 = (s_1, a_1, d_1)$ and $b_2 = (s_2, a_2, d_2)$ are two t-SFNs. The fundamental operations, the score function, the accuracy function, and the Minkowski distance measure for these t-SFNs are provided in Eq.s (1)-(7), where $\lambda > 0$ [36,53].

$$\lambda * b_1 = \langle \begin{matrix} \left(1-(1-s_1^t)^{\lambda}\right)^{\frac{1}{t}}, \left((1-s_1^t)^{\lambda}-(1-s_1^t-a_1^t)^{\lambda}\right)^{\frac{1}{t}}, \\ \left((1-s_1^t-a_1^t)^{\lambda}-(1-s_1^t-a_1^t-d_1^t)^{\lambda}\right)^{\frac{1}{t}} \end{matrix} \rangle, \tag{1}$$

$$b_1{}^{\lambda} = \langle \begin{matrix} \left((1-d_1^t-a_1^t)^{\lambda}-(1-d_1^t-a_1^t-s_1^t)^{\lambda}\right)^{1/t}, \left((1-d_1^t)^{\lambda}-(1-d_1^t-a_1^t)^{\lambda}\right)^{1/t}, \\ \left(1-(1-d_1^t)^{\lambda}\right)^{1/t} \end{matrix} \rangle, \tag{2}$$

$$b_1 \oplus b_2 = \langle \begin{matrix} \left(1-(1-s_1^t)(1-s_2^t)\right)^{1/t}, \left((1-s_1^t)(1-s_2^t)-(1-s_1^t-a_1^t)(1-s_2^t-a_2^t)\right)^{1/t}, \\ \left((1-s_1^t-a_1^t)(1-s_2^t-a_2^t)-(1-s_1^t-a_1^t-d_1^t)(1-s_2^t-a_2^t-d_2^t)\right)^{1/t} \end{matrix} \rangle, \tag{3}$$

$$b_1 \otimes b_2 = \langle \begin{matrix} \left((1-d_1^t-a_1^t)(1-d_2^t-a_2^t)-(1-d_1^t-a_1^t-s_1^t)(1-d_2^t-a_2^t-s_2^t)\right)^{1/t}, \\ \left((1-d_1^t)(1-d_2^t)-(1-d_1^t-a_1^t)(1-d_2^t-a_2^t)\right)^{1/t}, \left(1-(1-d_1^t)(1-d_2^t)\right)^{1/t} \end{matrix} \rangle, \tag{4}$$

$$\mathcal{S}(b) = (1+s^t-a^t-d^t)/2, \tag{5}$$

$$\mathcal{A}(b) = s^t+a^t+d^t, \tag{6}$$

$$b_1{}^{com} = (d_1, a_1, s_1), \tag{7}$$

$$\mathrm{M_p}(\mathbf{b_1}, \mathbf{b_2}) = \left(\left|\mathrm{s}_1^t-\mathrm{s}_2^t\right|^{\mathrm{p}}+\left|\mathrm{a}_1^t-\mathrm{a}_2^t\right|^{\mathrm{p}}+\left|\mathrm{d}_1^t-\mathrm{d}_2^t\right|^{\mathrm{p}}\right)^{1/\mathrm{p}}. \tag{8}$$

The t-SF weighted arithmetic aggregation operator $\mathrm{T-SWAI}_w$ and the weighted geometric aggregation operator $\mathrm{T-SWGI}_w$ are given in Eq. (9) and Eq. (10), respectively [32,53]:

$$\mathbf{T-SWAI}_w(b_1, b_2, \ldots, b_n) = \langle \begin{matrix} \left(1-\prod_{j=1}^{n}(1-s_j^t)^{w_j}\right)^{\frac{1}{t}}, \left(\prod_{j=1}^{n}(1-s_j^t)^{w_j}-\prod_{j=1}^{n}(1-s_j^t-a_j^t)^{w_j}\right)^{\frac{1}{t}}, \\ \left(\prod_{j=1}^{n}(1-s_j^t-a_j^t)^{w_j}-\prod_{j=1}^{n}(1-s_j^t-a_j^t-d_j^t)^{w_j}\right)^{\frac{1}{t}} \end{matrix} \rangle. \tag{9}$$

$$\mathbf{T-SWAI}_w(b_1, b_2, \ldots, b_n) = \langle \begin{matrix} \left(\prod_{j=1}^{n}(1-d_j^t-a_j^t)^{w_j}-\prod_{j=1}^{n}(1-d_j^t-a_j^t-s_j^t)^{w_j}\right)^{1/t}, \\ \left(\prod_{j=1}^{n}(1-d_j^t)^{w_j}-\prod_{j=1}^{n}(1-d_j^t-a_j^t)^{w_j}\right)^{1/t}, \left(1-\prod_{j=1}^{n}(1-d_j^t)^{w_j}\right)^{1/t} \end{matrix} \rangle, \tag{10}$$

here $b_j = \langle s_j, i_j, d_j \rangle$ $(j = 1, \ldots, n)$, $w = (w_1, w_2, \ldots, w_n)$, and $\sum_{j=1}^{n} w_i = 1$.

3.2 Proposed Methodology

The research will be carried out in four stages. The first stage of problem solving involves defining criteria and options using t-SF-Delphi [45,54]. The second stage involves determining the weights of the criteria using the t-SF (subjective weighting) approach. The third stage involves determining the ranking of the options using t-SF-CRADIS [45,51]. The last stage is the evaluation and comparison of the problem solutions. The processes to be followed and the methods to be used in each stage are explained in the following section.

Stage 1 – *Preliminary process and application of the t-SF-Delphi technique*.

In multi-criteria group decision problems, consulting the opinions of experts is a frequently adopted approach for solving them. However, the number of experts to be consulted is a controversial issue on which there is no consensus. In the literature, some studies emphasize the structural differences of the problems and state that it is not correct to give a definite number of experts. On the other hand, studies that specifically examine the number of experts state that this number should be between four and 20. In these evaluations, it is understood that the number of experts will approach twenty as the education, experience, and knowledge diversity of the experts increase. Otherwise, it is recommended that the number should not be unnecessarily increased to ensure efficiency in terms of material, time, and abstract aspects [55,56]. Another important issue is determining the number of members (experts) in the Delphi technique. At this point, it is stated that there should be at least seven experts for research involving the use of the Delphi technique [57]. Within this framework, the opinions of at least seven experts will be sought out as part of the research.

In selecting experts, the following criteria will be considered:

i. having at least three years of work experience in the field of aquaculture;
ii. having at least a bachelor's degree;
iii. having conducted research related to aquaculture or high knowledge about the sector.

Based on the open-ended and/or verbal opinions that the experts will provide regarding the broad lists, arrangements will be completed, and the evaluation process, which is the second step of the t-SF-Delphi technique, will begin. The t-SF-Delphi technique will enable the systematic and scientific definition of the problem. The t-SF-Delphi technique is applied in the following manner [54,57]:

Round 1: Based on scientific studies in the literature and reports prepared by various organizations, the criteria and options are determined in draft form. Following this process, a committee consisting of at least seven experienced experts is consulted to evaluate the elements in the two broad lists, combine those that are the same or similar, and add those that should be included but were not. The problem and its components are explained to the members of the expert committee. The expectations of the experts regarding the t-SF-Delphi implementation process will be explained. A draft list of criteria and options is presented to the experts.

Round 2: Expert panel members are asked to review the criteria and option lists and identify elements that are the same or similar. Then, they are asked for their open-ended opinions on the lists and whether there are any elements they believe should be added outside the list. The answers received from the experts are noted.

Round 3: Based on the opinions received from the previous round, the lists containing the criteria and option sets are updated. Then, expert panel members are asked to evaluate the meaningfulness of the criteria in terms of their impact or contribution to solving the problem using the linguistic expressions in Table 1 [36]. A similar process is performed for the option set.

Round 4: Linguistic evaluations received from experts are converted into t-SF numerical equivalents and integrated through an aggregate process. Then, using a scoring function, significant values are created for each element, measuring its consideration in the problem. The highest significance values are determined in the criteria set and the options set, and the value of each element is proportioned by these highest values. As a result, the normalized significance score of each element is determined. Criteria with relative significance values below the arithmetic mean of the normalized significance scores are classified as "non-critical", those above the third quartile are classified as "critical", and those between these two values are classified as "moderately critical".

Table 1
Linguistic expressions for t-SF-Delphi

Criteria and options	Expert evaluations	Corresponding t-SFN		
		s	*a*	*d*
Very important (VI)	Very high (VH)	0.90	0.10	0.10
Important (IM)	High (H)	0.70	0.30	0.30
Moderately important (MI)	Moderate (M)	0.50	0.50	0.50
Low important (LI)	Low (L)	0.30	0.30	0.70
Unimportant (UI)	Very low (VL)	0.10	0.10	0.90

Round 5: The linguistic evaluations, the normalized significance scores, and criticality statuses are noted in separate columns in lists and presented to the experts. Consensus is sought among the experts for the criteria and option lists. If there is no consensus among the experts, the evaluations are repeated until consensus is reached. In this way, the criteria and option sets are finalized.

Stage 2 – *Obtaining the experts' evaluations of the criteria and options*.

Following the first step, the experts' evaluations are obtained through the linguistic expressions in Table 2, considering the importance level of the criteria and the benefit or performance that the options will provide. If there are no significant differences in the knowledge and experience of the experts, it is planned to give equal weights to the experts. Otherwise, the t-SF numerical equivalents of the experts' evaluations are determined using the linguistic expressions in Table 1 and defuzzied via Eq. (5). The defuzzied importance values are subjected to the summation-based normalization process, and the expert weights are determined.

Table 2
Linguistic expert evaluation expressions

Expert evaluations	Corresponding t-SFN		
	s	*a*	*d*
Very high (VE)	0.99	0.01	0.01
High (HI)	0.8	0.2	0.2
Moderately high (MH)	0.7	0.3	0.3
Moderate (MO)	0.6	0.4	0.4
Moderately low (ML)	0.4	0.4	0.6
Low (LO)	0.99	0.01	0.01
Very low (VL)	0.8	0.2	0.2

After obtaining the experts' evaluations regarding the criteria and options, the data is compiled. In this context, the linguistic evaluations of the experts will be converted into t-SF numerical equivalents. The criteria, which are components of the problem, will be symbolized by $C = \{C_1, \dots, C_n\}$, the options by $O = \{O_1, \dots, O_m\}$, and the experts by $U = \{U_1, \dots, U_r\}$, where k=1,…,r; For i=1,…,m and j=1,…,n. Accordingly, the k-th expert's evaluation of the importance level of criterion j will be depicted by $\iota_j^{(k)} = \langle s_j^{(k)}, a_j^{(k)}, d_j^{(k)} \rangle$ and their evaluation of the preferability of alternative i in criterion j will be denoted by $\eta_{ij}^{(k)} = \langle s_{ij}^{(k)}, a_{ij}^{(k)}, d_{ij}^{(k)} \rangle$. The weighting of the evaluations of the experts whose opinions will be sought will be symbolized by λ_k, and weights will be assigned to the experts.

Stage 3 – *Analyses*.

In determining the weight values of the criteria considered in solving the problem, the t-SF subjective weighting approach will be used. In this framework, the evaluations of the experts are integrated through the aggregation operator to obtain the t-SF criterion importance value vector. Then, defuzzied importance values for the criteria are created using the score function. Criterion weight values are obtained by subjecting these values to a summation-based normalization. Criterion weight values reveal the extent to which each criterion is important compared to others.

The T-SF-CRADIS method will be used to evaluate and rank the options. In the application process of T-SF-CRADIS, the individual evaluations of the experts are aggregated to create the t-SF decision matrix using Eq. (9) [44,51]. Unidimensional structure is achieved by performing a normalization process that considers the minimization and maximization aspects of the criteria. For this purpose, Eq. (7) is employed. Then, the weight values of the criteria are reflected in the solution to the problem to create ideal and anti-ideal solution vectors via Eq. (1). Deviation from the ideal solution (S_{i+}) and deviation from the anti-ideal solution (S_{i-}) values are calculated to obtain the degrees of deviation for the options. For this purpose, Eq. (8) is employed. In the final step, the utility function values of the options (K_{i+} and K_{i-}) and their associated overall utility value (OU_i) are calculated. The options are ranked from largest to smallest according to their overall utility values, and the solution to the problem is completed [44,45].

4. Results

The research involves solving a group decision-making problem based on expert opinions. Information regarding the experts is presented in Table 3.

Table 3
Information regarding experts

Experts	Experience (in years)	Age	Position	Graduate
U1	10	34	Quality manager	Fisheries engineer
U2	4	26	Fisheries engineer	Fisheries engineer
U3	6	29	Fisheries engineer	Fisheries engineer
U4	13	35	Fisheries engineer	Fisheries engineer
U5	9	28	Fisheries engineer	Fisheries engineer
U6	5	36	Vice president	Maritime transportation and operations
U7	15	48	Company owner	Teaching

To determine the weighting coefficients for the experts' evaluations, an assessment was conducted based on criteria such as experience, education, and position. These evaluations were conducted using the linguistic expressions in Table 1. The weights assigned to the experts are presented in Table 4.

Table 4
Weighting coefficients of the experts

Experts	Experience	Position	Graduation	Integrated significance	Weight
U1	M	H	VH	0.7033	0.1524
U2	L	M	VH	0.6144	0.1332
U3	L	M	VH	0.6144	0.1332
U4	H	M	VH	0.7033	0.1524
U5	M	M	VH	0.6354	0.1377
U6	L	H	H	0.5464	0.1184
U7	VH	VH	M	0.7964	0.1726

In the first step of the t-SF-Delphi technique, a broad list of criteria (Table 5) and a wide set of options (Table 6) were defined.

Table 5
Comprehensive list of criteria

Code	Criterion	Code	Criterion	Code	Criterion
G1	Habitat suitability	G10	Welfare level	G19	Marketability
G2	Temperature tolerance	G11	Predatory behavior	G20	Energy requirement
G3	Feeding type	G12	Meat quality	G21	Sustainability of production
G4	Body size	G13	Economic value	G22	Ecosystem impact
G5	Reproductive period	G14	Environmental compatibility	G23	Disease susceptibility
G6	Optimal water temperature	G15	Production cost	G24	Government support
G7	Suitable water depth	G16	Feed availability	G25	Reproductive efficiency
G8	Bottom substrate suitability	G17	Feed composition	G26	Meat yield
G9	Spawning season	G18	Market size	G27	Euryhaline capability

The lists of the criteria and options, shaped by expert opinions, are given in Tables 5-6.

Table 6
Comprehensive list of options

Code	Options	Code	Options
S1	European seabass	S19	Brown meager
S2	Seabream	S20	Mullet
S3	Shrimp	S21	Sprat
S4	Crab	S22	Garfish
S5	Mussel	S23	Annular seabream
S6	Lobster	S24	Striped seabream
S7	Octopus	S25	Shi drum
S8	Squid	S26	Anchovy
S9	Sturgeon	S27	Bonito
S10	Eel	S28	Horse mackerel
S11	Crayfish	S29	Grouper
S12	Turbot	S30	Twaite shad
S13	Common pandora	S31	Rainbow trout
S14	Common dentex	S32	Brown trout
S15	White grouper	S33	Atlantic salmon
S16	Black sea bream	S34	Wreckfish
S17	Meagre	S35	Black sea salmon/ trout
S18	Catfish	S36	Yellowtail amberjack

The t-SF-Delphi result for the criteria is presented in Table 7. Table 7 shows the threshold values considered in assigning criteria to classes, determined through normalized scores. These values are 0.8532 for the distinction between non-critical and moderately critical classes, and 0.9536 for the distinction between moderately critical and critical classes.

Table 7
t-SF-Delphi result for the criteria

Criterion	Score	Norm. score	Class	New code	Criterion	Score	Norm. score	Class	New code
G1	0.8950	1.0	Influential	C1	G15	0.8755	0.9782	Influential	C6
G2	0.8950	1.0	Influential	C2	G16	0.8761	0.9789	Influential	C7
G3	0.7229	0.8077	Not critical		G17	0.8249	0.9217	Moderate	C8
G4	0.3854	0.4306	Not critical		G18	0.7974	0.8909	Moderate	C9
G5	0.8376	0.9358	Moderate	C3	G19	0.8535	0.9536	Influential	C10
G6	0.8047	0.8991	Moderate	C4	G20	0.6012	0.6717	Not critical	
G7	0.7326	0.8185	Not critical		G21	0.8950	1.0	Influential	C11
G8	0.6171	0.6895	Not critical		G22	0.7925	0.8855	Moderate	C12
G9	0.6703	0.7489	Not critical		G23	0.8761	0.9789	Influential	C13
G10	0.6585	0.7357	Not critical		G24	0.5317	0.5941	Not critical	
G11	0.7633	0.8529	Not critical		G25	0.7891	0.8816	Moderate	C14
G12	0.7283	0.8138	Not critical		G26	0.7891	0.8816	Moderate	C15
G13	0.8535	0.9536	Influential	C5	G27	0.7891	0.8816	Moderate	C16
G14	0.7630	0.8525	Not critical						

Table 8 contains the t-SF-Delphi results for the options. Table 8 shows the threshold values considered in assigning the options to classes, determined through normalized scores. These values are 0.4772 for the distinction between non-critical and moderately critical classes, and 0.8746 for the distinction between moderately critical and critical classes. The t-SF-Delphi process was completed when the experts did not change their opinions in this round and found them sufficient. The experts' evaluations were sought based on the finalized criteria and options.

Table 8
t-SF-Delphi result for the option

Option	Score	Norm. score	Class	New code	Option	Score	Norm. score	Class	New code
S1	0.8123	0.9547	Influential	A1	S19	0.1956	0.2298	Not critical	
S2	0.7410	0.8709	Moderate	A2	S20	0.2788	0.3277	Not critical	
S3	0.2440	0.2868	Not critical		S21	0.2588	0.3042	Not critical	
S4	0.2461	0.2893	Not critical		S22	0.2588	0.3042	Not critical	
S5	0.3338	0.3923	Not critical		S23	0.1956	0.2298	Not critical	
S6	0.1550	0.1821	Not critical		S24	0.1956	0.2298	Not critical	
S7	0.1984	0.2331	Not critical		S25	0.1550	0.1821	Not critical	
S8	0.3474	0.4083	Not critical		S26	0.4311	0.5067	Moderate	A6
S9	0.8229	0.9671	Influential	A3	S27	0.4703	0.5527	Moderate	A7
S10	0.4529	0.5323	Moderate	A4	S28	0.4727	0.5556	Moderate	A8
S11	0.1746	0.2052	Not critical		S29	0.1550	0.1821	Not critical	
S12	0.8508	1.0000	Influential	A5	S30	0.2013	0.2366	Not critical	
S13	0.2184	0.2566	Not critical		S31	0.7901	0.9286	Influential	A9
S14	0.1550	0.1821	Not critical		S32	0.7901	0.9286	Influential	A10
S15	0.1550	0.1821	Not critical		S33	0.7901	0.9286	Influential	A11
S16	0.2409	0.2831	Not critical		S34	0.7534	0.8855	Influential	A12
S17	0.2409	0.2831	Not critical		S35	0.7534	0.8855	Influential	A13
S18	0.3291	0.3868	Not critical		S36	0.7534	0.8855	Influential	A14

All criteria are benefit-oriented (maximizing). The weighting coefficients of the criteria were calculated using the t-SF subjective weighting approach. These values are presented in Table 9. The results in Table 9 show that the most important criterion is "euryhaline capability (ability to live in both marine and freshwater)" (C16). "Ecosystem impact" (C12) is ranked second. Two third-ranked criteria are "habitat suitability (habitat in which it can live)" (C1) and "temperature tolerance (temperature in which it can live)" (C2).

Table 9
Results of the criteria weighting

	C1	C2	C3	C4	C5	C6	C7	C8
Score	0.5897	0.5897	0.8207	0.6377	0.7339	0.7194	0.6317	0.5947
Weight	0.0543	0.0543	0.0755	0.0587	0.0675	0.0662	0.0581	0.0547
Rank	3	3	14	7	12	11	6	5
	C9	C10	C11	C12	C13	C14	C15	C16
Score	0.7033	0.8275	0.8851	0.5836	0.7629	0.6811	0.6860	0.4215
Weight	0.0647	0.0761	0.0814	0.0537	0.0702	0.0627	0.0631	0.0388
Rank	10	15	16	2	13	8	9	1

The euryhaline capability is the most important criterion in marine species cultivation, which is consistent with studies in the literature [23,58]. In nature, some fish species can live in both freshwater and marine environments. These species are defined as migratory (anadromous or catadromous) fish and play an extremely important role in the ecosystem. Salmon is one of the best-known examples of this. Migratory fish contribute to the flow of matter and energy in nature by moving between different ecosystems throughout their life cycles and play a critical role in maintaining ecological balance.

The reproductive strategies of these species have evolved to increase reproductive efficiency. Eggs are usually laid in freshwater environments, which are safer for the offspring. After completing their development, the offspring migrated to marine environments to access richer food sources. This cycle continues for generations and ensures the continuity of the population. Furthermore, in the face of adverse conditions such as climate change, water pollution, food scarcity, natural disasters, or potential environmental crises, the ability of these species migrate to different habitats increases their chances of survival. Therefore, the risk of extinction for these species is relatively low, and their survival success is higher. Migratory fish have both economic value for humanity and contribute to the preservation of the balance of the natural environment.

Not every species can survive in every environment. Therefore, habitat suitability and temperature tolerance are fundamental criteria for the growth, survival, and efficient reproduction of fish. Fish generally live in three main habitats: freshwater, saltwater, and brackish water. Each of these habitats has different environmental characteristics such as temperature, dissolved oxygen levels, nutrient content, protein sources, and current conditions. In particular, current speed and direction directly affect the suitability of the habitat for many fish species. A fish species that is not compatible with the habitat characteristics cannot adapt to the environmental conditions and survive.

Water temperature is another vital criterion for fish. Water temperatures are known to have a significant impact on fish farming. This research has confirmed that finding [59]. Since fish are cold-blooded creatures, their body temperature is directly dependent on the temperature of the water they live in. Therefore, an ideal and balanced water temperature directly affects all vital activities of fish. Even small changes in water temperature can significantly alter metabolic rate, mobility, oxygen consumption, and reproductive processes. Each fish species has a specific temperature range in which it can survive. For example, cold-water fish (like trout) generally live in the 10–15 °C range, while warm-water fish (like carp) prefer the 18–25 °C range. Tropical fish, on the other hand, survive at higher temperatures such as 24–30 °C.

An increase in water temperature causes a decrease in the amount of dissolved oxygen in the water. This leads to fish needing more oxygen and can result in mass fish deaths, especially in warm water conditions. In addition, temperature changes have significant effects on the ecosystem. Unsuitable temperature conditions can lead to serious consequences such as a decrease in fish populations, reproductive failure, increased disease risks, and, in the long term, the threat of species extinction.

Habitat suitability, temperature tolerance, and the ability to live in both freshwater and saltwater are complementary but not entirely the same criteria. Habitat encompasses the general characteristics of the environment in which the fish live, the type of water (freshwater, saltwater, or brackish water), depth, current conditions, oxygen levels, food sources, vegetation, and hiding places are evaluated within this scope. Temperature is a component of habitat and a fundamental factor determining the fish's metabolism, mobility, breeding timing, and oxygen requirements. The ability to live in both freshwater and saltwater refers to the capacity of some species to adapt to different salinity levels. The common point of these three criteria is that they aim to increase the healthy development, reproductive success, and survival rate of the fish. However, from a business perspective, each carries different strategic meanings. Habitat characteristics are generally unchangeable and dependent on regional conditions. Temperature can be controlled to a certain extent with technological applications, but this requires careful and sensitive management.

The fact that the ecological impacts of marine species cultivation stand out as a significant criterion is an important indicator that businesses are aware of their environmental responsibilities. Furthermore, this finding is consistent with the literature [60,61]. The fact that the ecosystem impact criterion stands out as the second most important criterion clearly demonstrates how critical environmental sustainability has become in aquaculture. The potential impacts of aquaculture activities on water quality, benthic structure, natural species diversity, and the food chain can have not only environmental but also economic and legal consequences. Choosing species or production methods that are incompatible with the ecosystem can lead to environmental degradation, production losses, and decreased public acceptance in the long term. Therefore, preferring species that have a low impact on the ecosystem, protect environmental balance, and are compatible with natural systems ensures both the continuity of production and contributes to the development of aquaculture as an environmentally friendly sector.

The ability to live in both freshwater and saltwater, while not a mandatory criterion, is a preferable characteristic that provides flexibility to businesses and offers advantages during times of crisis. In conclusion, the correct evaluation of these criteria enables businesses to select species suitable for their region, ensure sustainable production, and increase efficiency and profitability. It also forms the basis of an environmentally and legally compliant, long-term, and sustainable aquaculture operation.

The evaluations regarding the options were analyzed using the t-SF-CRADIS method. Table 10 presents the t-SF CRADIS results. As can be seen from Table 10, among the options, rainbow trout (A9) ranks first, Black Sea salmon (A13) ranks second, red-spotted trout (A10) ranks third, European sea bass (A1) ranks fourth, and sea bream (A2) ranks fifth. In addition, anchovy (A6) is sixth, and sturgeon (A3) is seventh. Rainbow trout farming has a relatively long history in Türkiye. This has led to an increase in experience and knowledge regarding this species. Therefore, its ranking among the most suitable species is consistent with the literature [60,61]. Moreover, Black Sea salmon is a species with high consumer preference and economic value. Therefore, its high ranking in the evaluation of options is consistent with the literature [60,61].

Table 10
Results of t-SF-CRADIS

	S_{i+}	S_{i-}	K_{i+}	K_{i-}	OU_i	Rank
A1	0.0322	0.0344	0.4739	0.6958	0.5849	4
A2	0.0342	0.0329	0.4459	0.6645	0.5552	5
A3	0.0398	0.0343	0.3831	0.6936	0.5384	7
A4	0.0587	0.0191	0.2598	0.3863	0.3230	13
A5	0.0417	0.0326	0.3663	0.6589	0.5126	8
A6	0.0399	0.0353	0.3820	0.7130	0.5475	6
A7	0.0575	0.0206	0.2653	0.4167	0.3410	11
A8	0.0554	0.0203	0.2757	0.4104	0.3431	10
A9	0.0153	0.0495	1.0	1.0	1.0	1
A10	0.0264	0.0427	0.5791	0.8635	0.7213	3
A11	0.0450	0.0284	0.3388	0.5739	0.4564	9
A12	0.0638	0.0174	0.2394	0.3512	0.2953	14
A13	0.0188	0.0462	0.8130	0.9340	0.8735	2
A14	0.0652	0.0206	0.2341	0.4164	0.3253	12

An examination of the ranking results reveals that expert opinions based on professional experience particularly highlight alternatives coded A9, A13, A1, A2, and A3. This indicates that these species are currently among the most preferred and possess the greatest potential for sustainable production. It is known that a large portion of existing aquaculture businesses focus their production activities especially on trout and salmon species. Indeed, it is observed that aquaculture businesses operating in Rize and Artvin provinces predominantly focus on these species. The high-income potential of these species plays a decisive role in their prominence. In addition, suitable habitat characteristics, water temperature, and high reproductive efficiency in terms of regional conditions have been effective in shaping this ranking. The evaluations show that species rankings are shaped especially on the basis of environmental adaptation, biological suitability, and operational conditions. According to the research results, rainbow trout ranks first due to its low production risk, rapid growth performance, and ease of cultivation. Black Sea salmon ranked second due to its high adaptability to the regional ecosystem and significant economic value. In contrast, red-spotted trout was ranked lower due to technical challenges in the aquaculture process and limited production capacity. Sea bass and sea bream were ranked in the middle due to limited regional production opportunities and relatively more challenging aquaculture conditions. Anchovy, while not suitable for aquaculture, is also low in the ranking, but has high economic value and a large market share in terms of natural fishing. Sturgeon was ranked last due to its long production period, high investment costs, and slow payback period. Although various studies and research studies are being conducted on sturgeon farming in the region, definitive and widespread production success has not yet been achieved in this area. Overall, the ranking clearly shows that aquaculture businesses prioritize low-risk, quickly profitable, and economically sustainable species. This indicates that the sector follows a rational and risk-averse production strategy under current conditions.

4. Conclusions

Regions with high potential in terms of natural structures, coastlines, and abundant water resources are of strategic importance for aquaculture. These regions offer highly favorable areas for aquaculture activities thanks to their environmental conditions. The region, especially encompassing the provinces of Rize and Artvin, creates a suitable ecosystem for many aquaculture activities, primarily cage fish farming, with its strong water currents, high dissolved oxygen levels, and cool water temperatures. The numerous streams and rivers in the region provide a clean and continuous water source, significantly contributing to the healthy cultivation of fish. The aquaculture sector is not only a production activity but also a significant source of employment and income for the regional economy. A large part of the economic activities in Rize and Artvin are shaped by seafood farming, which increases regional economic vitality. Opening the cultivated seafood to international markets increases export volume and adds value to the national economy. Fish farming also offers a reliable and nutritious food source for human health. High protein content and fresh production possibilities make seafood an important element of balanced nutrition. Regular and planned production ensures a stable supply of products, contributing to a balanced price formation in the market. If aquaculture businesses conduct their production processes based on scientific principles, using planned and correct methods, significant gains in terms of sustainable development can be achieved. This approach ensures the protection of the natural environment while guaranteeing the continuity of economic gains in the long term, increasing the production performance of the region, and paving the way for the development of sectors related to aquaculture. In conclusion, effectively utilizing regional potential offers significant opportunities in terms of both environmental sustainability and socio-economic development.

All the criteria determined within the scope of this study, while important in themselves, form a holistic decision-making structure that complements each other. Species selection in aquaculture businesses is shaped by these criteria in line with the environmental characteristics of the region where the business is located, its production capacity, and its sustainability goals. Correct species selection plays a critical role in the long-term success of the business and forms the basis of decision-making processes. The suitability of a fish species for aquaculture primarily depends on the compatibility of its habitat conditions with the region where the facility will be established. In case of habitat incompatibility, even if the fish survive for a short time, reproductive success decreases, and premature deaths occur due to high stress, oxygen deficiency, and increased disease risk. Similarly, the water temperature must be suitable for the biological structure and physiological tolerances of the fish. Since fish are cold-blooded animals, imbalances in water temperature directly and negatively affect their metabolism, growth, and reproduction processes. The breeding season is largely dependent on water temperature, and the correct management of this process is important for the sustainability of reproductive efficiency. From an economic perspective, supply and demand balance, market expectations, and price formation are the determining factors in species selection. The marketability of the cultivated species is essential for the business to cover its costs and maintain profitability. As the scale of production increases, costs such as raw materials, labor, and energy also increase. Therefore, choosing high-yielding and relatively low-cost species contributes to the longevity of the business.

In terms of nutrition, feed availability and feed content directly affect production speed and product quality. High-protein, high-quality, and environmentally friendly feeds support the healthy development of fish, improve meat quality, and increase the market value of the final product. In addition, the market volume and marketability of the selected species are of great importance for the business's income continuity.

Environmental sustainability is also a fundamental element that should not be overlooked in species selection. Choosing species that cause minimal harm to the ecosystem, have high environmental compatibility, and are resistant to diseases ensures both the reduction of environmental impacts and the minimization of legal and economic risks. Furthermore, high reproductive efficiency and meat yield increase production capacity, reduce the business's dependence on external sources, and support profitability. Finally, species capable of surviving in both freshwater and saltwater offer significant strategic advantages to businesses by providing resilience to environmental changes. In general, conscious and scientific species selection based on these criteria forms the basis for aquaculture businesses to achieve a sustainable, efficient, and economically successful production structure.

While all criteria considered in aquaculture are important, some criteria stand out strategically for businesses. These include water temperature, economic value, and cost. Water temperature is a fundamental environmental factor determining which species can be cultivated in the region where the facility will be located. Incompatibility between the temperature tolerance of the chosen species and regional water temperatures increases production risks and prevents the business from achieving its goals. Therefore, species selection should primarily be based on suitability to the region's water temperature. For economic sustainability, the chosen species should have high market value and demand. Choosing a species with insufficient market demand reduces profitability and jeopardizes the long-term sustainability of the business. Furthermore, production costs are also a determining factor in species selection. Cost items such as energy, feed, equipment, and production infrastructure vary depending on the species; species that provide high yields at low cost offer a more advantageous structure for businesses in the long term. Among the species that have gained prominence in the region in recent years are Black Sea salmon and rainbow trout. In addition, sea bass and sea bream are also cultivated. These species demonstrate suitability in terms of regional environmental conditions and specified criteria. However, increasing competition is leading businesses to seek new and alternative species. In this context, species that can be cultivated in both marine and freshwater environments constitute a strategic alternative for businesses. For example, sturgeon has high caviar potential but requires high investment, while turbot, despite its high market value, requires advanced technical knowledge and professional management. This research serves as a guide for individuals and businesses interested in aquaculture, helping them in decision-making processes, reducing risks, and supporting strategy development. The established criteria will contribute to reducing production risks and costs for new investors entering the sector and increasing efficiency and sustainability. It also provides an important guide in terms of job creation, supporting regional development, and the development of the aquaculture sector. In future studies, research into new cultivable species should not be limited to the Black Sea Region but should also be conducted in the Aegean, Mediterranean, and other water resources, contributing to the sector's innovative and sustainable structure.

One of the significant limitations of the research is that it was conducted specifically within the region encompassing Rize and Artvin provinces. Furthermore, the difficulty in accessing a larger number of more qualified experts is another limitation. However, the methodology used in the study made it possible to model a problem that had not been systematically addressed before. The transfer of the intuitive knowledge of highly knowledgeable and experienced experts into a scientific framework is one of the study's important contributions. Aquaculture businesses can use the proposed methodology to solve various problems. Moreover, similar problems in different fields can also be solved using the proposed methodology. The approach of determining criteria and option sets based on expert opinions, subjective weighting, and consensus resolution has contributed to the flexibility of the study's decision-making process, integrating different perspectives and producing more realistic results for implementation.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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