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SUSTAINABLE SURGE IN TURKISH SALMON CULTURE: PRIORITIZING ENVIRONMENTAL RESPONSIBILITY

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Abstract

The Turkish aquaculture sector has rapidly expanded, establishing itself as a leading force in global markets, particularly through the cultivation of Turkish salmon, a large rainbow trout species grown in offshore cages in the Black Sea. This study investigates the environmental sustainability of Turkish salmon farming, focusing on water quality parameters, nutrient levels, and the ecological impact of aquaculture practices in two potential aquaculture areas along the Turkish Black Sea coast. The research applies the Trix Index, a widely used metric for assessing eutrophication risks in coastal waters, to evaluate the suitability of these areas for aquaculture. Results indicate that the studied regions maintain optimal water quality conditions and present no significant risk of eutrophication, supporting the sustainability of aquaculture operations. The findings underscore the importance of strategic planning and environmental monitoring in expanding aquaculture while preserving marine ecosystems.

Keywords: Turkish salmon, Trix index, water quality, sustainable cage aquaculture

Introduction

Turkish aquaculture sector has experienced significant growth over the past few decades, becoming a key player in the global markets. The strategic expansion with focus on sustainability positioned Turkish aquaculture as a leading country in its region as well as Europe. The unique geographical position of the country, combining Europe to Asia, provides access to diverse marine and freshwater resources. Shaped like a large peninsula, the 8,333 kilometers of coastline surrounding the country (excluding the islands) with the Mediterranean Sea, the Aegean Sea, the Black Sea and the Sea of Marmara, as well as rivers and dam lakes (Doğan & Çanak, 2024) are among key drivers for the rapid growth from 79,031 tons in 2000 to 556,287 tons in 2023, that today accounts for 55% of the total fishery production in Türkiye. According to the data provided by the Turkish Statistical Institute (TUIK), total production through fisheries was reported as 454,059 tons, while aquaculture production was 553,862 tons (TUIK, 2024; Yiğit et al, 2024). With the main key species of rainbow trout, seabass, and seabream, Türkiye became the world's top producer, supplying 40% of global demand of seabass and seabream (Thefishsite, 2021). The Turkish aquaculture industry emphasizes sustainability with strict regulations and focus at minimized environmental impacts, ensuring long-term viability. This includes efficient resource use, minimal environmental degradation, and socio-economic benefits for local communities. The aquaculture industry is a significant contributor for the Turkish economy, with a fully integrated production system including hatcheries, grow-out farms, processing and packaging facilities, and aqua-feed factories. Türkiye invests in aquaculture education and research, with various institutions offering specialized courses and collaborating with international organizations to adopt best practices, globally (Yigit et al., 2024). The Turkish salmon, a new driver of the economic trends in the world salmon market, is actually large rainbow trout, grown to a harvest size over 2.5 kg (Yigit et al., 2023a), and often referred to as "Turkish Salmon" or "Turkish Salmon Trout" based on the new marketing strategy support by the Turkish Ministry of Agriculture and Forestry (TMAF, 2020). The rainbow trout is initially grown in freshwater facilities until reaching a size of around 400 g, and thereafter transferred to offshore fish cages operating in the Black Sea for further growth (DOKA 2021; Yigit et al., 2023b). With outstanding production yields, the Turkish salmon ranked as one of the highest exported species in the Turkish aquaculture sector (Daily Sabah, 2022). Over three decades ago, Norwegian entrepreneurs, leveraging Norwegian expertise and technology, attempted to establish Atlantic salmon (*Salmo salar*) farming in the Turkish waters of Black Sea. Smolts weighing around 50 g were transferred from a hatchery based in Bekdemirler Village of Bolu Province and transferred to octagonal-shaped wooden frame cage systems located in the harbor of Kefken Island located in the Western Black Sea region. Due to high temperature conditions in the Black Sea during the summer season, however, these ambitious ventures ultimately failed, as seawater temperature in the Black Sea increases over 25°C (Ginzburg et al 2021), that is higher than the lethal water temperature (23°C) reported for Atlantic salmon (Elson, 1969; Danie et al., 1984; Shepard, 1995). Considering that gravity-cage systems with relatively low net depth (4-5 m) were used those days, high water temperatures during the summer period limited the survival potential of Atlantic salmon in the traditional surface cage constructions, that in terms was a disappointing ending to an unexpected adventure early 1990s. The losses suffered by businesses investing in Atlantic salmon farming in the Black Sea, prevented other investments and caused a long-lasting delay for the initiation of salmon farming in the Black Sea. After a silence for around 30 years, fast forward the farming of "Turkish salmon" (large-sized rainbow trout) has become a success story. This time, local entrepreneurs have managed to take their place among important producers not only locally but also worldwide. Currently, the Turkish aquaculture sector has adopted a new strategy of harvesting large rainbow trout (2.5 kg or more), which are introduced as Turkish salmon to domestic or international markets, with increased profits and economic returns for Turkish cage aquaculture in the Black Sea (Yigit et al., 2023a,b).

In the October-November period when the sea water temperature is below 20°C, Turkish Salmon candidate rainbow trout with an average weight of 500 g are transported from dam lake net cages or freshwater pond farms to sea net cage facilities, and harvest is carried out in the May-June period when the sea water temperature rises to 18-20°C (Yiğit et al., 2023b; Çakmak et al., 2024). Ensuring effective environmental management in marine aquaculture is paramount for sustainable aquatic production, efficient yet controlled use of water resources, and the preservation of a clean environment for future generations. Consequently, close monitoring of water quality parameters alongside production quantities is essential. The strategic placement of new facilities should prioritize environmental conditions and adhere to scientific principles. In this context, the identification of suitable marine areas for cage aquaculture and the evaluation of the ecological quality of marine environments, particularly in coastal regions, play a critical role in curbing the rise of marine pollution. This process also involves determining the trophic status of the marine environment through assessment and monitoring studies. The Turkish Ministry of Environment, Urbanization, and Climate Change issued the 'Regulation on the Environmental Management of Fish Farms Operating in the Seas' in October 2020. According to this regulation, areas for aquaculture in the seas have been designated for the determination of eutrophication risk.

Considering that fish farms in Türkiye follow these strict environmental procedures, the ecosystem-based production cycle of cage facilities have been evaluated for the sustainable future of the aquaculture industry in the Black Sea.

Materials and Methods

In this case study conducted within this framework, the Trophic Index values of two potential aquaculture areas to be operating in the Black Sea were assessed to determine their trophic status and to evaluate their potential effects on the marine environment (Figure 1, 2).

Figure 1. General view of potential Aquaculture Production Area 1.

Figure 2. General view of potential Aquaculture Production Area 2.

Water quality variables such as temperature, salinity, pH, and dissolved oxygen levels (percent saturation and mg/L) were measured *in situ* at the sampled stations using a YSI 600QS model multiprobe system. In both potential aquaculture areas, two separate sampling points were selected as Farm and Reference station (Ref).

Nutrients

Seawater samples were taken from designated stations and depths to determine the amounts of nutrient elements such as Nitrite (NO^-_2), Nitrate (NO^-_3), Ammonium (NH_4), Total Nitrogen (TN), and Total Phosphorus (TP). The samples were brought to Lakton Environmental Laboratory Inc., which holds an International Accreditation Certificate within the scope of the TS EN ISO / IEC 17025 standard by the Turkish Accreditation Agency (TÜRKAK) and has Competency Certificates from the Ministry of Environment, Urbanization, and Climate Change, the Ministry of Labor and Social Security, and the Ministry of Health. The analyses were carried out according to ISO, EPA, TS, and EN standards, in accordance with the Ministry of Environment and Urbanization (2015) guidelines.

Chlorophyll-a

To determine the concentration of chlorophyll-a, an indicator of primary production, water samples were taken from specified depths using a 5 L Nansen bottle. Spectrophotometric determination of chlorophyll-a concentration was conducted after extraction with a 90% acetone solution (APHA, 1995).

$$Chlorophyll\text{-}a = 11.64(OD665) - 2.16(OD645) - 0.10(OD630) \quad (1)$$

$$Chlorophyll\text{-}a\ (mg/l) = (Chlorophyll\text{-}a \times acetone\ volume)/Volume\ of\ filtered\ water\ sample \quad (2)$$

The evaluation focused on offshore cage culture sites, utilizing Trix Index calculations based on factors such as chlorophyll-a concentration, total inorganic nitrogen, total phosphorus, and deviation values from % saturated oxygen.

In the calculation of the TRIKS Index, the formula specified in the "Environmental Management Regulation for Fish Farms Operating in Marine Areas" published by the Ministry of Environment, Urbanization, and Climate Change in the Official Gazette dated October 28, 2020, and numbered 31288, have been used.

$$TRIKS\ Index = (Log\ (Chlorophyll\text{-}a \times \%O2 \times TIN \times TP) + 1.5) \times 0.833 \quad (3)$$

The values in the formula are defined as follows:

Chlorophyll-a : The concentration of chlorophyll-a in water (µg/L)
$\%O_2$: The absolute percentage deviation from the saturation level of oxygen $= |\%DO - 100|$
TIN : Total dissolved inorganic nitrogen, N-(NO^{-}_{3}+NO^{-}_{2}+NH_4), (µg/L)
TP : Total phosphorus (µg/L)

The comparative evaluation of the TRIKS Index results was conducted according to the table below (Table 1).

Table 1. "Eutrophication Risk Scale Table" from the "Environmental Management Regulation for Fish Farms Operating in Marine Areas"

TRIKS Index (TI)	Eutrophication Status	Explanation
< 4*	No Eutrophication Risk	Aquaculture is permitted.
4 - 5*	Low Eutrophication Risk	Aquaculture is allowed for existing facilities, but no new facilities are permitted.
5 - 6*	Eutrophication Risk Present	No new aquaculture facilities are allowed; restrictions are imposed on existing facilities.
> 6*	High Eutrophication Risk	Aquaculture is not permitted, and existing facilities must cease operations.

*For the Black Sea, an additional +1 is applied.

Results

It has been determined that the environmental water quality parameters, including salinity, temperature, pH, and dissolved oxygen levels, align with seasonal averages and within the optimal values in Potential Aquaculture Area 1 and Potential Aquaculture Area 2 (Table 2 and 3).

Table 2. Temperature, Salinity, Dissolved Oxygen, % Dissolved Oxygen Saturation, and pH in Potential Aquaculture Area No. 1 (September 2019)

Station*	Temperature (°C)			Salinity (‰)			% O_2			Dissolved O_2 (mg/L)			pH		
	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom
K1	25.3	24.6	22.7	17.9	17.6	17.5	98.6	96.1	99.0	8.15	8.07	8.01	8.56	8.46	8.29
K1Ref	25.3	24.1	23.7	17.8	17.6	17.7	100.2	99.8	97.8	8.2	8.11	8.03	8.5	8.43	8.39
K2	25.2	24.7	22.9	17.8	17.7	17.7	100.3	98.5	98.1	8.23	8.12	8.0	8.5	8.41	8.34
K2Ref	25.1	24.1	23.5	17.8	17.7	17.6	100.3	99.7	97.5	8.3	8.18	8.04	8.47	8.4	8.31
K3	25.0	24.6	23.0	17.8	17.7	17.7	100.1	99.5	97.5	8.3	8.17	8.01	8.45	8.34	8.23
K3Ref	25.1	24.6	23.3	17.8	17.7	17.7	99.7	99.6	97.3	8.26	8.13	8.05	8.45	8.35	8.25
M1	24.5	23.1	22.0	17.8	17.7	17.6	100.1	98.7	97.5	8.25	8.16	8.06	8.48	8.34	8.22
M1Ref	24.7	23.3	22.0	17.8	17.7	17.7	100.1	98.7	97.4	8.29	8.15	8.05	8.49	8.31	8.23
M2	24.9	23.7	22.1	17.8	17.7	17.6	100.1	99.8	97.4	8.27	8.17	8.07	8.47	8.36	8.25
M2Ref	24.8	23.4	22.4	17.8	17.6	17.6	100.2	98.7	97.4	8.29	8.16	8.05	8.48	8.36	8.25
M3	24.7	23.5	22.3	17.7	17.7	17.6	100.2	98.9	98.0	8.28	8.2	8.07	8.46	8.36	8.25
M3Ref	24.6	23.2	22.1	17.8	17.7	17.6	100.1	99.5	97.3	8.27	8.17	8.04	8.49	8.35	8.27
A1	23.9	22.9	22.4	17.1	17.2	17.0	99.8	98.5	97.4	8.25	8.15	8.02	8.37	8.32	8.21
A1 Ref	24.1	23.5	22.8	17.4	17.5	17.5	100.1	98.6	97.2	8.28	8.19	8.05	8.42	8.3	8.21
A2	24.1	23.0	22.2	17.6	17.7	17.7	98.4	98.3	98.1	8.42	8.12	8.01	8.42	8.31	8.23
A2Ref	23.9	23.6	22.9	17.7	17.7	17.8	99.8	98.3	97.8	8.3	8.21	8.09	8.4	8.33	8.25

*Station abbreviations: Kemal 1-K1; Kemal 1 Reference-K 1Ref; Kemal 2-K2; Kemal 2 Reference-K2Ref; Kemal 3-K3; Kemal 3 Reference-K3Ref; Marines 1-M1; Marines 1 Reference-M1Ref; Marines 2-M2; Marines 2 Reference-M2Ref; Marines 3-M3; Marines 3 Reference-M3Ref; Aqua 1-A1; Aqua 1 Reference-A1Ref; Aqua 2-A2; Aqua 2 Reference-A2Ref

Table 3. Temperature, Salinity, Dissolved Oxygen, % Dissolved Oxygen Saturation, and pH in Potential Aquaculture Area No. 2 (September 2019)

Station	Temperature (°C)			Salinity (‰)			% O_2			Dissolved O_2 (mg/L)			pH		
	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom	Surface	Mid	Bottom
S5	24.9	23.7	22.1	17.8	17.8	17.7	100.1	98.7	97.3	8.3	8.17	8.1	8.43	8.35	8.23
S5Ref	25.0	24.0	22.9	17.8	17.7	17.7	99.7	98.6	97.6	8.28	8.16	8.09	8.42	8.34	8.25
S4	24.6	23.9	22.4	17.8	17.7	17.7	100.1	99.0	97.8	8.28	8.17	8.08	8.46	8.36	8.27
S4Ref	24.7	23.5	22.4	17.8	17.7	17.7	100.1	99.7	98.6	8.27	8.19	8.07	8.44	8.35	8.26
S3	24.9	23.7	22.1	17.8	17.8	17.7	100.0	98.7	97.3	8.3	8.17	8.1	8.43	8.35	8.23
S3Ref	25.0	24.0	22.9	17.8	17.7	17.7	100.1	98.5	97.4	8.28	8.16	8.09	8.42	8.34	8.25

*Station abbreviations: Sagun 5-S5; Sagun 5 Reference-S5Ref; Sagun 4-S4; Sagun 4 Reference-S4Ref; Sagun 3-S3; Sagun 3 Reference-S3Ref

This case study was conducted by evaluating the two potential aquaculture areas to be operating in the Black Sea using Trix Index values in accordance with the regulations. In both Potential Area 1 and Potential Area 2, Chlorophyll-a, TIN and TP values did not exceed 1 µg/L, 33 µg/L and 10 µg/L, respectively. The percentage of dissolved oxygen levels at the stations and depths where the study was conducted ranged between 96.1 % and 100.3% for Potential Area 1 and 97.3-100.1 for Potential Area 2. These levels exceeded 90% saturation, and they are within the general quality criteria for seawater as specified in the WPLC (2004). The study on the examination, comparison, and evaluation of Trix Index values in the Black Sea regions concluded that there is "*No Eutrophication Risk*" in the studied regions wherein the Eutrophication Scale values for the Black Sea as "4+1" (Table 4, 5; Figure 3, 4).

Table 4. Calculated TRIX Index values at the stations and depths studied in Potential Aquaculture Area No. 1 (September 2019)

Stations* / Trix Index	Surface	Mid Layer	Bottom	Limit
K1	3.47	3.84	3.35	5
K1Ref	2.77	2.77	3.63	5
K2	2.91	3.49	3.58	5
K2Ref	2.91	2.91	3.68	5
K3	2.51	3.1	3.68	5
K3Ref	2.91	3.02	3.71	5
M1	2.51	3.44	3.68	5
M1Ref	2.51	3.44	3.69	5
M2	2.51	2.77	3.69	5
M2Ref	2.77	3.44	3.69	5
M3	2.77	3.38	3.6	5
M3Ref	2.51	3.1	3.71	5
A 1	2.51	3.47	3.72	5
A 2	3.52	3.54	3.58	5
A 2Ref	2.77	3.54	3.63	5

*Station abbreviations: Kemal 1-K1; Kemal 1 Reference-K 1Ref; Kemal 2-K2; Kemal 2 Reference-K2Ref; Kemal 3-K3; Kemal 3 Reference-K3Ref; Marines 1-M1; Marines 1 Reference-M1Ref; Marines 2-M2; Marines 2 Reference-M2Ref; Marines 3-M3; Marines 3 Reference-M3Ref; Aqua 1-A1; Aqua 1 Reference-A1Ref; Aqua 2-A2; Aqua 2 Reference-A2Ref

Table 5. Calculated TRIX Index values at the stations and depths studied in Potential Aquaculture Area No. 2 (September 2019)

Stations / Trix Index	Surface	Mid Layer	Bottom	Limit
S5	2.51	3.44	3.71	5
S5Ref	2.91	3.47	3.66	5
S4	2.51	3.35	3.63	5
S4Ref	2.51	2.91	3.47	5
S3	2.51	3.44	3.71	5
S3Ref	2.51	3.49	3.69	5

*Station abbreviations: Sagun 5-S5; Sagun 5 Reference-S5Ref; Sagun 4-S4; Sagun 4 Reference-S4Ref; Sagun 3-S3; Sagun 3 Reference-S3Ref

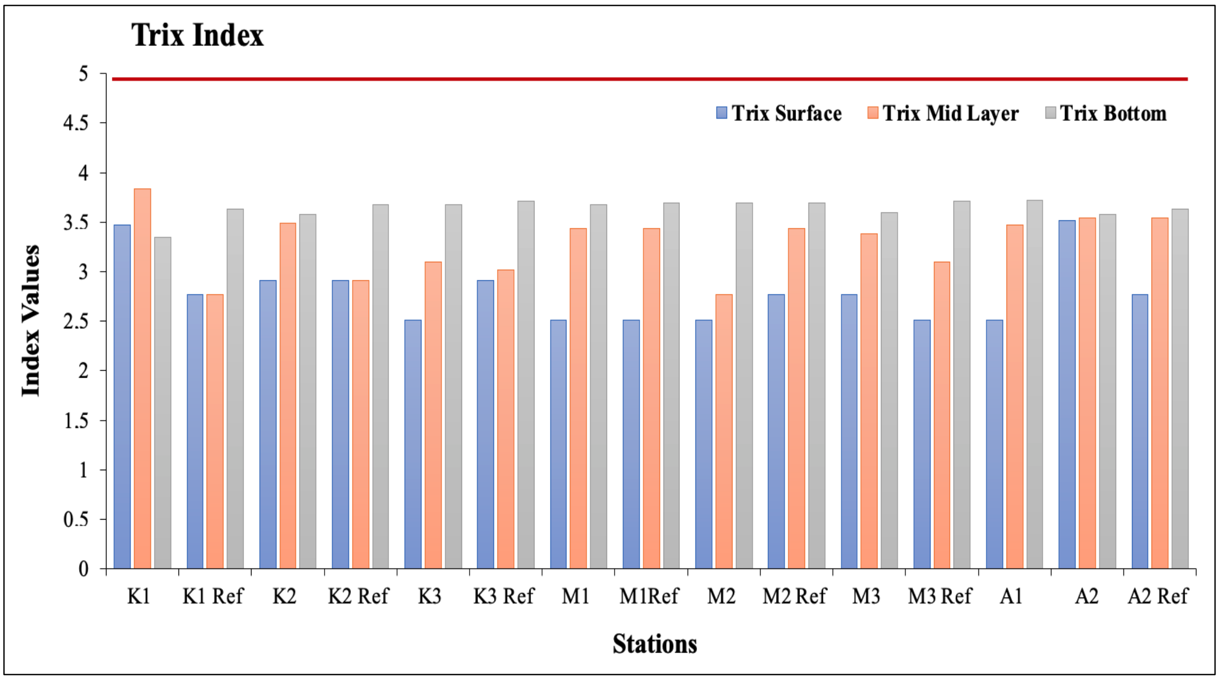

Figure 3. Trix Index values at the stations and depths where studies were conducted in Potential Aquaculture Area No. 1 (*Station abbreviations: Kemal 1-K1; Kemal 1 Reference-K 1Ref; Kemal 2-K2; Kemal 2 Reference-K2Ref; Kemal 3-K3; Kemal 3 Reference-K3Ref; Marines 1-M1; Marines 1 Reference-M1Ref; Marines 2-M2; Marines 2 Reference-M2Ref; Marines 3-M3; Marines 3 Reference-M3Ref; Aqua 1-A1; Aqua 1 Reference-A1Ref; Aqua 2-A2; Aqua 2 Reference-A2Ref)

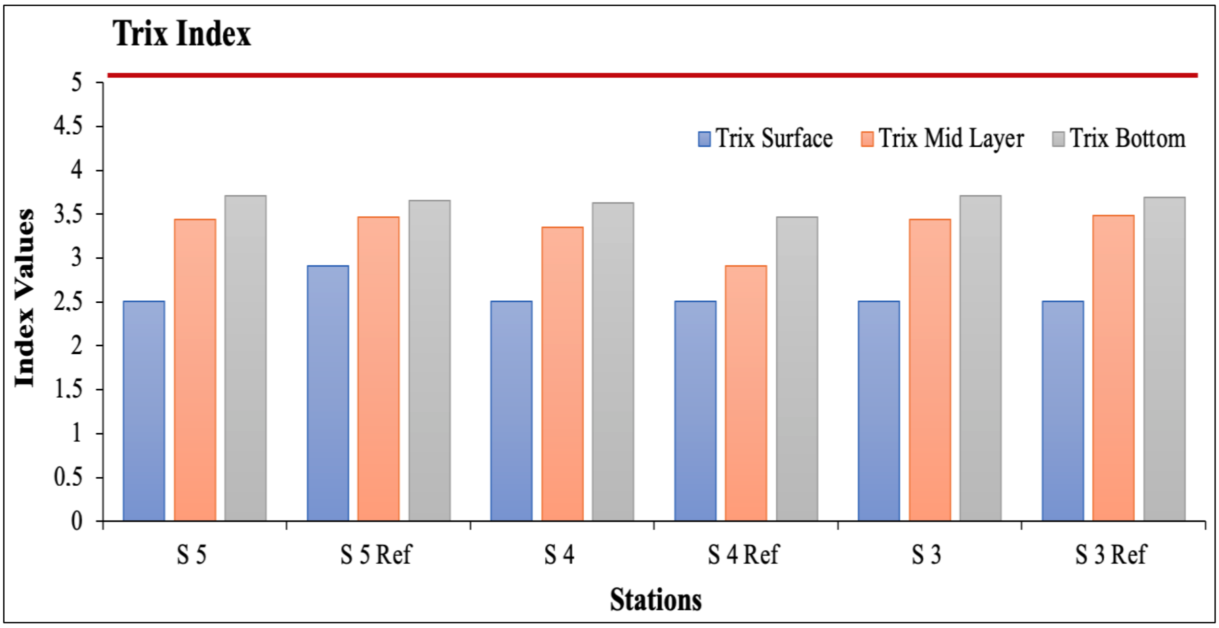

Figure 4. Trix Index values at the stations and depths where studies were conducted in Potential Aquaculture Area No. 2 (*Station abbreviations: Sagun 5-S5; Sagun 5 Reference-S5Ref; Sagun 4-S4; Sagun 4 Reference-S4Ref; Sagun 3-S3; Sagun 3 Reference-S3Ref)

Discussion

The production of Turkish salmon in the Black Sea is being practiced between October and June, when the surface water temperatures are below the upper tolerance limits of 23°C (Elson 1969; Danie et al. 1984; Shepard 1995). Between June and October, however, the cage facilities usually remain empty without fish, until the new production season. It has been reported that some facilities introduce warm water species such as Gilthead seabream (*Sparus aurata*) and the European seabass (*Dicentrarchus labrax*) during the summer period (Yigit et al., 2023b), In most cases however, fish farming activities in the Black Sea is being practiced only during the winter season, that in turns provide a resting period which allows the marine ecosystem to regenerate. With this production cycle, Turkish salmon production in the Black Sea is an important example of an environmentally friendly method of fish production.

Considering measurements of water temperature, salinity, % dissolved oxygen saturation, dissolved oxygen levels, and pH, it can be noted that these are within the specified water quality parameters and threshold values for marine fish farming in both Potential Aquaculture Area 1 and Potential Aquaculture Area 2 to be operating in the Black Sea.

The Trix Index, also known as Trophic Index, is commonly used in coastal area studies to assess the levels of eutrophication in seawater masses and to classify the trophic status of marine and coastal areas. For a sustainable environment, production in marine areas must be carried out under strict control. Efficient use of resources, the use of innovative technologies, environmentally friendly production, and production using domestic and national technology will also play a significant role in enhancing food safety. The case study examining, comparing, and evaluating Trix Index values in two Potential Aquaculture sites of the Black Sea concluded that there is "*No Eutrophication Risk*" in the areas analyzed. When comparing the data from the Reference stations and the rest, it is observed that the Trix values are similar. The data obtained from the analyses of water samples taken from both the surface, mid layer and the bottom in the studied Trix area show that farm activities do not lead to a significant nutrient load in the water column.

As new facilities are considered, it is essential to prioritize environmental factors and follow scientific guidelines. Identifying appropriate marine areas for cage aquaculture, coupled with assessing the ecological health of these environments -particularly in coastal zones- are key steps in mitigating the risk of escalating marine pollution.

Conclusion

This study demonstrates that the Turkish salmon farming practices in the Black Sea, conducted under strict environmental monitoring and management, present no significant risk to the marine ecosystem, as evidenced by the favorable Trix Index values. The absence of eutrophication risks and the adherence to optimal water quality parameters affirm the sustainability of current aquaculture applications in the studied regions. As Turkish salmon production continues to grow, these findings highlight the necessity for ongoing environmental assessments and the adoption of best aquaculture practice to ensure the long-term viability of fish farming in the Black Sea. The results emphasize that environmentally responsible aquaculture can coexist with economic growth, provided that strategic site selection and rigorous environmental monitoring are prioritized.

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Ethical approval

Ethical review and approval were waived for this study.

Informed consent
Not available

Data availability statement
The authors declare that data can be provided by corresponding author upon reasonable request.

Conflicts of interest
There is no conflict of interests for publishing this study.

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All authors have read and agreed to the published version of the manuscript.

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