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Chapter 1

NATIONAL LEGAL FRAMEWORKS FOR SUSTAINABLE FISHERIES IN TÜRKIYE

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Introduction

Aquatic products are one of the essential elements of healthy nutrition and stand out as a good source of animal protein, especially in the fight against obesity. The aquaculture sector is an important industry that contributes to the economies of countries and was also listed among the sectors with the highest growth in the 2020 report of the United Nations Food and Agriculture Organization (FAO) (FAO 2022, Çöteli 2023). Fishery products are among the most traded food sources worldwide. Figure 1 presents data on global aquaculture production.

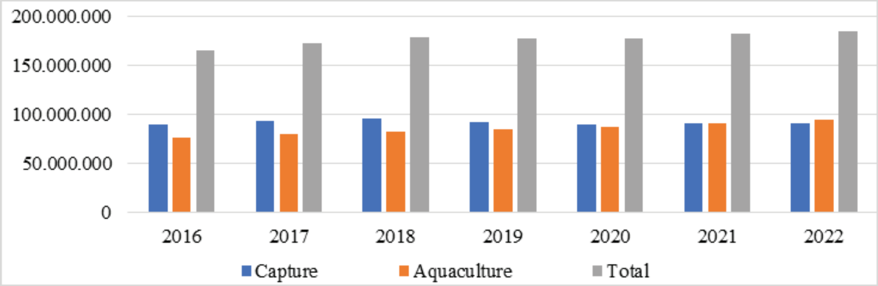

Figure 1. *World fishery production (Tons) (FAO 2024)*

Excessive fisheries, conducted without proper management and foresight due to the high demand for aquatic products, poses a definite threat to the depletion of fishery resources. The long-term sustainability of fishing is also threatened by overfishing, ecosystem changes, and conflicts in management. In this context, legal frameworks are important for the effective management, sustainable use, and conservation of natural resources, including the support of food and agriculture, fisheries and aquaculture. Such laws also play a role in regulating the complex relationships between these elements (FAO 2021).

National legal frameworks related to fisheries and aquaculture are a key enabler of actions towards sustainable development and contribute to this goal. Fisheries legislation encompasses the implementation of processes related to the management, monitoring, and control of fisheries and aquatic products. The legislation also ensures that sanctions are applied in cases where rights are abused, or the relevant authorities fail to fulfill their duties and responsibilities as specified in the law. In this context, legal regulations are also a crucial component for the continued effective and sustainable management of fisheries.

In Türkiye, the Ministry of Agriculture and Forestry is carrying out various efforts under the Fisheries and Aquaculture Legislation to ensure sustainable aquatic product harvesting and reduce fishing pressure on aquatic species. This study focuses on highlighting the sustainable fisheries legislation dimension and includes constraints and recommendations related to the topic.

- Türkiye's Fisheries

The seas surrounding Türkiye form the most critical part of the fisheries sector. The country's total coastline is 8,333 kilometers. The varying temperature and salinity levels of the seas in Türkiye offer diverse opportunities for both fisheries and aquaculture. Among inland waters, there are approximately 200 natural lakes, over 300 dam lakes, around 750 ponds, and 33 major rivers. The mentioned inland waters are also important for aquaculture activities in addition to fisheries. The number of species with economic value in our country is approximately 100 (Anonymous 2017, 2020a). Our country, surrounded by seas on three sides, has significant potential in terms of aquatic product production. According to 2023 data, a total of 1,010,346 tons of aquatic products were produced, with 454,059 tons through fisheries and 556,287 tons through aquaculture (Table 1). Thus, the aquatic products sector has contributed $1.7 billion to the national economy through exports to many countries. Additionally, these developments have had a positive impact on the domestic market, with per capita consumption reaching 7.2 kg in 2023. However, this value remains below the global (20.5 kg) and European (25.1 kg) average per capita consumption levels of 2019 (Anonymous 2024a).

In Türkiye, a significant portion of fisheries production comes from marine products, particularly marine fish. In 2023, a total of 454,059 tons of aquatic products were obtained through fisheries, with 420,527 tons from our seas and 33,532 tons from inland waters (Table 2). In 2023, 92.6% of the total catch was obtained from the seas. While there have been fluctuations in marine capture fisheries over the years, it appears that capture fisheries in inland waters has remained more stable.

Table 1. *Total fishery production (Tons) in Türkiye (TURKSTAT 2024)*

Years	Capture	Aquaculture	Total
2012	432.442	212.410	644.852
2013	374.121	233.394	607.515
2014	302.212	235.133	537.345
2015	431.907	240.334	672.241
2016	335.320	253.395	588.715
2017	354.318	276.502	630.820
2018	314.094	314.537	628.631
2019	463.168	373.356	836.524
2020	364.400	421.411	785.811
2021	328.165	471.686	799.851
2022	335.003	514.805	849.808
2023	454.059	556.287	1.010.346

Table 2. *Total capture production (Tons) in Türkiye (TURKSTAT 2024)*

Capture Production			
Years	**Marine**	**Inland**	**Total**
2012	396.322	36.120	432.442
2013	339.047	35.074	374.121
2014	266.078	36.134	302.212
2015	397.731	34.176	431.907
2016	301.464	33.856	335.320
2017	322.173	32.145	354.318
2018	283.955	30.139	314.094
2019	431.572	31.596	463.168
2020	331.281	33.119	364.400
2021	295.025	33.140	328.165
2022	301.747	33.256	335.003
2023	420.527	33.532	454.059

It is stated that Türkiye ranks first in inland waters and fifth in marine waters among EU countries in terms of fisheries. The number of fishing vessels in the seas is 15,219, while the number of fishing vessels in inland waters is 3,260. Thus, the total number of fishing vessels is reported to be 18,479 (GDFA 2024).

Table 3. *Length distribution of fishing vessels in 2023 (General Directorate of Fisheries and Aquaculture 2024)*

Field of Activity	Length Group (m)							Total
	0-4,9	5-7,9	8-9,9	10-11,9	12-19,9	20-29,9	30+	
Marine	679	8.495	3.488	947	856	460	294	15.219
Inland	416	2.408	356	21	59	0	0	3.260
Total	1.095	10.903	3.844	968	915	460	294	18.479

In the waters of our country, anchovy, sprat, pilchard, horse mackerel& scad, atlantic bonito, and blue fish are the most commonly fished pelagic species. When examining the data for 2023, a total of 273,915 tons of anchovy were caught, which constitutes 60.3% of our total fisheries catch (Table 4).

Whiting, hake-europen hake, striped red, red mullet & goldon banded and turbot are the most commonly caught demersal marine fish species (Table 5).

Table 4. *Production quantities (in tons) of the most caught pelagic marine fish species (TURKSTAT 2024)*

Years	Anchovy	Pilchard	Horse Mackerel & Scad	Atlantic bonito	Blue fish	Sprat
2012	163.982	28.248	30.946	35.764	7.390	12.092
2013	179.615	23.919	28.424	13.158	5.225	9.764
2014	96.440	18.077	16.324	19.032	8.386	41.648
2015	193.492	16.693	16.664	4.573	4.136	76.996
2016	102.595	18.162	11.148	39.460	9.574	50.225
2017	158.094	23.426	12.985	7.578	1.936	33.950
2018	96.452	18.854	20.678	30.920	5.767	20.057
2019	262.544	19.119	19.505	1.578	1.214	38.078
2020	171.253	21.265	12.349	22.743	3.722	26.804
2021	151.598	15.800	24.006	2.595	5.804	28.041
2022	125.980	16.729	14.930	49.892	5.495	11.162
2023	273.915	17.311	14.374	2.083	2.138	45.764

Table 5. *Production quantities (in tons) of the most caught demersal marine fish species (TURKSTAT 2024)*

Years	Whiting	Hake – European hake	Striped red	Red Mullet & Goldon banded	Turbot
2012	7.367	893	3.767	2.453	203
2013	9.397	676	2.333	2.055	209
2014	9.555	642	3.617	1.426	198
2015	13.158	706	3.476	1.255	239
2016	11.541	784	3.047	1.454	221
2017	8.248	1.011	2.074	1.406	167
2018	6.814	1.019	2.915	1.399	139
2019	8.941	1.270	2.342	1.719	272
2020	9.364	1.149	2.775	1.604	412
2021	10.380	839	3.072	1.359	487
2022	7.690	1.084	1.304	1.169	491
2023	9.074	1.108	1.557	1.204	490

In addition, species such as carpet shell & striped venus, sea snails, shrimp & prawn, mussels, and cuttle fish are also fished. carpet shell & striped venus and sea snail are two other important species that are fished in our seas except fish and are exported abroad (Çöteli 2023).

Table 6. *Production quantities (in tons) of the most caught other marine products (TURKSTAT 2024)*

Years	Carpet shell and Striped venus	Sea snail	Shrimp and Prawn	Mediterranean mussel & Bearded horse mussel	Cuttle fish
2012	61.240	9.596	5.038	2.093	1.396
2013	28.113	8.655	4.028	887	1.244
2014	21.836	7.004	4.416	204	697
2015	37.409	8.795	3.995	240	745
2016	20.937	10.354	4.501	78	925
2017	34.941	9.194	4.730	536	986
2018	44.534	9.672	4.536	604	1.042
2019	36.627	11.646	5.137	1.170	940
2020	21.881	8.461	5.204	1.035	961
2021	16.824	7.008	5.494	1.371	837
2022	28.333	7.905	4.585	3.221	714
2023	13.821	9.869	4.715	2.527	697

In the Sea of Marmara, as a result of certain changes in the water (such as increased water temperature and higher nitrogen and phosphorus loads) due to the effects of climate change in 2021, excessive mucilage formation emerged as a significant environmental issue. Due to its structure, mucilage negatively affects fishing activities by clogging fishing nets and also harms the biodiversity of aquatic organisms. As a result of the impact of this issue on fisheries, it has been observed that the fishing catch in the Sea of Marmara decreased compared to the previous year (Anonymous 2022).

In their study, Eyüboğlu and Akmermer (2024) found a positive relationship between long-term fisheries production and economic growth, highlighting that aquaculture production has a significant impact on economic growth in Türkiye. The researchers emphasized that, due to the increasing global demand for seafood, support for new investments should be increased in order to sustainably manage fishery stocks. Hüseyinoğlu and Anagara (2024) highlighted that overfishing is quite prevalent in inland waters today and stressed the need for scientific evaluation of fish catch records, as well as continuous monitoring of invasive species and endangered species.

- **Legal Regulations on Fisheries**

The General Directorate of Fisheries and Aquaculture, under the Ministry of Agriculture and Forestry, has the authority and responsibility to develop and implement policies for the sustainability of fisheries in Türkiye. Like all countries striving to manage their fisheries responsibly, Türkiye also has a detailed legal framework based on sustainability to manage its fisheries. The regulations define the characteristics of fishing gear, catch limits, species, quotas, spatial and temporal restrictions, and other limitations. While preparing the draft legislation, the views and suggestions of all stakeholders are taken into consideration, and after being discussed and examined in detail, it is implemented. The decisions of the regional fisheries organizations and other international organizations to which Türkiye is a member are also considered in the legislation, taking into account Türkiye ‘s own fisheries dynamics. While adapting these decisions to domestic legislation, they are compared with Türkiye ‘s existing regulations, and the more protective ones are preferred.

The legal regulations regarding aquaculture are organized within the framework of the “Fisheries Law No. 1380” and the regulations and notices prepared under this law. The Fisheries Law No. 1380 grants the Ministry of Agriculture and Forestry the authority and responsibility to make regulations and oversee the control of fisheries in both marine and inland waters, with the aim of ensuring sustainable fishing, the protection and development of stocks, and the promotion of aquaculture (Anonymous 2019).

Under the fisheries legislation, the "Fisheries Regulation" was published in the Official Gazette dated March 10, 1995, with the number 22223. In order to protect fisheries stocks and make the most efficient use of these resources, it includes regulations on fisheries licenses, sport fishing, catching, regulations on fishing areas, use of harmful and explosive substances in fisheries, pollutants and hazardous substances prohibited to be thrown into fishing areas, fishing gear, trawling, bycatch, fisheries health, production of fishery products, marketing, control and inspection (Anonymous 1995).

The regulations related to aquaculture are carried out under the "Regulation on Aquaculture" published in the Official Gazette dated June 29, 2004, with the number 25507. With this regulation, the aim is to ensure the efficient use of the country's water resources, promote sustainability in aquaculture activities, protect the environment, and ensure access to safe food. It also focuses on conducting support and investments in the aquaculture sector within a planned framework, while ensuring the effective execution of supervision activities (Anonymous 2004).

In Türkiye, fishery activities are determined by the "Fisheries Law No. 1380" and the "Fisheries Regulation," based on the "Ministerial Notifications on the Regulation of Commercial and Amateur Fisheries" which are issued for a four-year period at a time. The aforementioned notices are developed through a multi-stakeholder consultation process, where the contributions and suggestions of all relevant parties, including scientific organizations, public institutions, fishermen, and civil society organizations, are gathered. After being evaluated in the "Fisheries and Aquaculture Consultation Board," the "Fisheries and Aquaculture Advisory Board," and the "Fisheries and Aquaculture Scientific and Technical Advisory Board," they are published in the Official Gazette and come into effect for specific periods. In this context, "Ministerial Notification No. 6/1 on the Regulation of Commercial Fisheries" (Notice No: 2024/20) and the "Ministerial Notification No. 6/2 on the Regulation of Amateur Fisheries Fisheries" (Notice No: 2024/21) were published in the Official Gazette dated August 11, 2024, with the number 32629 (Anonymous 2024b; c).

With the "Ministerial Notification No. 6/1 on the Regulation of Commercial Fisheries" (Notice No: 2024/20), which is to be applied in commercial fisheries of aquatic products between September 1, 2024, and August 31, 2028, it aims to regulate the obligations, restrictions, and bans related to fisheries in order to protect aquatic resources and ensure their sustainable management, taking into account scientific, environmental, economic, and social factors. With this Notice, regulations have been introduced regarding species, size, time, location, and fishing gear for aquatic product fisheries in both marine and inland waters (Anonymous 2024b).

With the "Ministerial Notification No. 6/2 on the Regulation of Amateur Fisheries Fisheries" (Notice No: 2024/21), rules and regulations are set for fishing without commercial intent in our seas and inland waters using simple fishing tools such as rods, between September 1, 2024, and August 31, 2028. This Notice includes rules on fishing regulations for Turkish citizens and foreigners, prohibited species, species that can be fished, minimum size and quantity information for these species, as well as time and location restrictions, and other related rules (Anonymous 2024c).

In order to ensure sustainability in fisheries and support production, the "Regulation on the Planning of Agricultural Production" was published in the Official Gazette on September 14, 2023. Under this Regulation, the procedures and principles for planning agricultural production have been established. The regulation aims to cover the processes and procedures for planning production at the level of agricultural basins or enterprises in plant production, animal production, and aquaculture production. The third section of the regulation is dedicated to "Planning Agricultural Production and Issuing Production Permits." Articles 16 and 17 of this section refer to the planning of aquaculture production. In Article 16:

(1) *Aquaculture production planning is carried out by considering development plans, medium-term programs, and the Ministry's strategic plans. It is based on the evaluation of supply and demand balance, production, export, import, exploitable stock status, population projections, scientific studies, environmental variables, socio-economic factors, international obligations, and statistical data.*

(2) *The processes related to determining the products or product groups in the planning of aquaculture production are carried out by the General Directorate of Fisheries and Aquaculture in cooperation with the relevant institutions and organizations.*

(3) *The products or product groups for which production planning will be done are determined based on specific criteria* (Anonymous 2023).

- **Studies Conducted Within the Scope of Fisheries Legislation**

a) Regulations on fish species and sizes

The regulations regarding size and weight have been introduced with the aim of giving each fish a chance to reproduce once during commercial fishing of aquatic products, and to prevent the fishing of small fish. Article 17 of Notification No. 6/1 stipulates the minimum catchable size and weight for aquatic species commercially fished in our country. It is prohibited to fish, keep on vessels, land, transport, or sell individuals smaller than these minimum size and weight limits. Examples of minimum size and weight for species include octopus (0.75 kg), anchovy (9 cm), mackerel (13 cm), turbot (45 cm), whiting (13 cm), bonito (25 cm), pilchard (11 cm), and red mullet (12 cm), among others. (The list of prohibited species can be found in Article 16 of Notification No. 6/1) (Anonymous 2024b). When compared with Notification No. 5/1, Notification No. 6/1 introduces minimum catchable size limits for certain aquatic species, while the size limits for some species have been revised. The table below presents the new regulations included in Notification No. 6/1.

Table 7. *New regulations in Notification No. 6/1*

Species	**Scientific Name**	**Notification No. 5/1 Minimum Lenght (cm)**	**Notification No. 6/1 Minimum Lenght (cm)**
Red mullet	*Mullus barbatus*	13 cm	12 cm
Giant red shrimp Blue and red shrimp	*Aristaeomorpha foliacea* *Aristeus antennatus*	-	2.5 cm
Swordfish	*Xiphias gladius*	125 cm	110 cm
Dolphinfish	*Coryphaena hippurus*	-	50 cm
Striped red mullet	*Mullus* surmuletus	11 cm	12 m

In order to ensure the sustainable management of aquatic species stocks, while commercial species are allowed to be fished, the fishing of endangered and endemic species is prohibited to protect their biodiversity. In this context, Article 16 of Notification No. 6/1 prohibits the fishing, collection, possession on vessels, landing, transport, and sale of the species listed in all of our waters. Examples of these species include the Mediterranean monk seal, sea turtles, sturgeons, grouper, sharks, seagrasses, dolphins, whales, and others. In addition, Article 16 of the aforementioned Notification also includes the leopard barbel (*Luciobarbus supquincunciatus*) and the Batman River loach (*Paraschistura chrysicristinae*), both of which are endangered species found in our country's waters (Anonymous 2024b).

b) Regulations on seasonal bans

The Ministry introduces seasonal bans for commercial fishing of aquatic products as part of fisheries management (Table 8). These seasonal bans are determined based on the breeding periods of aquatic species and scientific studies.

Table 8. *Example seasonal bans in Notification No. 6/1*

Species	Regulations
-	15 April - 31 August / General Fishing Ban
Atlantic Bonito and Skipjack Tuna	Forbidden between 15th of April and 15st of August
Turbot	Forbidden between 15th of April and 15th of June
Sole and Plaice Fishing	Forbidden between 1st of January and 15th of February
Bluefin Tuna	Forbidden between 1st of July and 14th of May
Leerfish and Amberjack	Forbidden between 15th of April and 15th of May
Swordfish ve Longfin Tuna	Forbidden between 15th of February - 15th of March and 1st October – 30th November
Dusky Grouper	Forbidden between 1st of June and 31st of August
Octopus	Forbidden between 15th of April and 31st of October

c) Regulations on spatial bans

To ensure sustainable fishing of aquatic species, the Ministry of Agriculture and Forestry imposes spatial bans. These restricted areas are determined based on scientific research, as well as the opinions of institutions, organizations, and civil society groups. In the spatial bans outlined in Notification No. 6/1, fishing may be restricted partially, completely, or through the prohibition of certain fishing gear. These areas, in addition to being important breeding and conservation zones, may also fall within areas of strategic importance, such as oil, natural gas, military, and transportation zones. In this context, spatial bans in Notification No. 6/1 are presented under the headings of the Mediterranean, Aegean, Marmara, Black Sea, and other spatial bans, and are illustrated with maps. Also, in this Notification, fishing with any type of fishing gear, except for handlines, rods, and drift lines, is prohibited in areas designated as artificial reef zones on maritime navigation charts.

The management of fisheries and the regulation of fishing gear used in fisheries are being implemented to ensure sustainable fishing practices. When the 6/1 Notification is examined, it includes sections related to bottom trawling, midwater trawling, purse seines, light fishing, longlining, drift nets, and other fishing gear and methods. In this Notification, the coordinates and maps of the prohibited areas for fishing gear are shown (Figure 2).

Figure 2. *Regarding bottom trawling in the Mediterranean (Anonymous 2024b).*

In addition, the 6/1 Notification also includes regulations regarding commercial fishing for aquatic species in our inland waters. The places where catching is completely or partially prohibited have been determined. As in the seas, the minimum length or weight of the species to be fished in inland waters has also been determined. Regulations have been established regarding carp, catfish, trout, freshwater perch, pike, bass, eel, crayfish, frog, land snail, leech, and aquatic plants. Ministerial Notification No. 6/2 on the Regulation of Amateur Fisheries Fisheries (Notice No: 2024/21) introduces regulations for recreational fishing, which will be conducted within specific rules without being commercialized, between **September 1, 2024, and August 31, 2028.** These regulations cover aspects such as species, quantity, size or weight, length, time, location, and fishing gear (Anonymous 2024c).

d) Regulations regarding the quota system in fishing

When planning aquatic production, development plans, medium-term programs, institutional strategies, supply, demand, production, export, import stocks, scientific studies, environmental factors, socio-economic variables, and statistical data have been taken into account. Using this information, the aim is to plan production in the fields of aquaculture and fisheries (Anonymous 2023).

Seven species (anchovy, bluefin tuna, sea cucumber, striped venus, eel, medicinal leech, and tarek) have been included in the production planning for our country's waters, and the total catchable harvest amounts have been determined (Anonymous 2024d). Among these species, anchovy, which constitutes 70% of our country's fisheries production, has been allocated a catch quota of 400,000 tons for the period between **September 1, 2024, and April 14, 2025**. Only fishing vessels with a valid fishing permit for **gillnets, midwater trawling, and seine nets** will be able to benefit from this quota. The quota amount (400,000 tons) was divided by the total sum obtained after multiplying the full length of fishing vessels, which have a valid fishing permit, by the corresponding coefficients for each size group. This calculation determined the quota amount per meter of vessel length. The quota amount per meter of vessel length was multiplied by the full length of each vessel and the size group/fishing gear coefficient, and the resulting amount was allocated as the quota for each vessel (Anonymous 2024e).

Bluefin tuna fishing is regulated according to the rules set by the **International Commission for the Conservation of Atlantic Tunas (ICCAT),** to which 52 member countries, including Türkiye, are signatories. In this context, ICCAT has allocated a quota of **2,600 tons per year** for the years **2023, 2024, and 2025.** The bluefin tuna fishing quota allocated to Türkiye is being utilized by Turkish fishing vessels with a full length of **30 meters or more.** Bluefin tuna fishing is carried out by fishing vessels, determined through a lottery held in the presence of a notary, in the **Eastern Mediterranean** and **off the coast of Malta** between **May 15 and July 1.** The vessels permitted for fishing are monitored via satellite, and the data is transmitted to ICCAT.

e) Limitation of the fishing fleet

In order to ensure sustainable fishing of aquatic species and reduce fishing pressure on aquatic resources, the Ministry of Agriculture and Forestry has carried out a number of initiatives. In this context, a buyback program was launched to reduce the fishing fleet, and between 2012 and 2018, 1,264 fishing vessels were removed from the fleet under this program (Anonymous 2019).

f) New regulations regarding reef areas

In addition to the Ministry of Agriculture and Forestry, various institutions and organizations are creating artificial reef areas in designated suitable locations by constructing structures that are harmful to nature in different sizes and forms. Thanks to these underwater structures, **77 artificial reef areas** have been created with the aim of enhancing, conserving, and increasing aquatic biodiversity, boosting production, providing artificial nesting and breeding grounds, combating illegal fishing, promoting diving tourism and recreational fishing, and restoring degraded aquatic ecosystems. Thanks to these areas, positive developments have been observed in terms of aquatic biodiversity, fish species, quantity, weight, fish eggs, and larvae. Additionally, a provision not included in previous regulations has been introduced in Article 8, paragraph (e) of the "Ministerial Notification No. 6/1 on the Regulation of Commercial Fisheries" (Notice No: 2024/20). It states that *the areas designated on nautical navigation charts as artificial reef zones, fishing for marine products is prohibited using all types of fishing gear, except fishing rods, trotlines, and longlines.*

g) Regulations and efforts regarding the management of invasive species

In Türkiye, to prevent the introduction, settlement, and spread of foreign invasive species, the unauthorized live transport of aquatic species and stocking activities have been prohibited; the use of these species as live bait has also been banned. Additionally, various legal regulations and incentives have been provided to create fishing pressure on established invasive species, and awareness and education campaigns are being carried out. However, considering the changing environmental conditions due to climate change and the high adaptability of invasive species, more comprehensive legal regulations and additional measures are needed.

Invasive species primarily reach the Mediterranean through the Suez Canal and the Black Sea via ballast water from ships. For example, the pufferfish population, which began to be observed in the Mediterranean since 2020, is causing harm to the marine ecosystem and fishing activities.

The General Directorate of Fisheries and Aquaculture in our country is carrying out various studies on invasive species. Among these activities, the "Regulation on Supporting the Fishing of Pufferfish" issued in 2020 (Anonymous 2020b) includes the use of pufferfish in industries such as leather and pharmaceuticals; training on the safe capture and cleaning of lionfish; fishing for sea snails with export potential; and Pacific oyster farming. The aim of these activities is to exert fishing pressure on the species and contribute to the economy. Planning and supporting the fishing of species such as poisonous sea urchins and lionfish is of great importance. The Ministry of Agriculture and Forestry has set a target to catch a total of 16.5 million pufferfish between 2021 and 2023. With the recent sightings of pufferfish in the Aegean, Marmara, and Black Seas, it has become increasingly important to increase support for fishing activities.

h) Fisheries vessel monitoring systems

Fisheries vessel monitoring systems aim to track the identification, location, time, speed, direction, and fishing activity data of fishing vessels through GSM, satellite, and other communication tools. This information is collected and recorded digitally, allowing for analysis, detection of rule violations, and monitoring of compliance. For this purpose, the Fisheries Vessel Monitoring System and the Electronic Logbook, which enable the digital recording and monitoring of fishing data, are used to ensure tracking and documentation. These systems and applications facilitate the collection and monitoring of fishing-related information.

- Sustainable Fishing - Restrictions and Possible Approaches Regarding Regulatory Practices

While fishing management strategies in Türkiye aim to promote the sustainable use of marine and freshwater resources, there are various challenges and limitations that hinder their effectiveness and contribute to ongoing ecological impacts (Table 9). In this context, it provides explanations of the challenges and limitations encountered in sustainable fishing and suggests possible approaches to address them.

Table 9. *Key challenges and solution suggestions in fisheries legislation and fishing practices*

Subject	**Problem**	**Suggestion**
Scientific studies	There are complexities in the assessment of fish stocks, the prediction of population dynamics, and the consideration of environmental variability and ecosystem interactions	- Due to the lack of long-term data and studies that would allow for the assessment of aquatic species stocks, it is necessary to conduct long-term monitoring studies on our stocks - Development of data collection and monitoring techniques. - Utilizing new technological applications
Implementation and Control Activities	Limited resources, stakeholder discord, and the number of control activities	- Allocation of sufficient resources for implementation. - Increasing stakeholder participation and collaboration - Further increasing control activities.. - Increase in penalty amounts and incentive practices.
Climate change and environmental stress	Changes in sea water temperatures, acidification, currents, and nutrient patterns could affect fish stocks and render current strategies ineffective.	- Developing adaptive management strategies. - Encouraging research on the impacts of climate change. - Increasing efforts for habitat conservation and restoration.
R&D studies	Inadequate allocation of resources and time for R&D studies	Allocating the necessary budget for R&D studies, considering the importance and potential of the sector.

Table 9. *Key challenges and solution suggestions in fisheries legislation and fishing practices (continued)*

Technological Developments.	Delays in adapting to technological developments worldwide.	Monitoring rapid global advancements in science and technology, aligning education and R&D infrastructure with these developments, and supporting budgetary resources
Projects and Strategies.	Development of long-term strategy and policy, the insufficiency of projects.	Inter-institutional collaborations are needed to carry out long-term planning that requires large budgets and extended periods of work, as well as projects such as developing strategies to combat climate change and global warming.
Support	Problems in the sector due to rising input costs.	Increasing the support amounts. Support policies should be redefined, taking into account the ecosystem, biodiversity, climate change, economic conditions, supply-demand balance, current requirements, and the status of the sector.

Result

Since the harvestable stock size has been reached in our country, there is no possibility of increasing production through hunting. In this context, the fishing fleet's fishing capacity should be aimed at reducing the fishing pressure on the stocks. For this purpose, despite various limiting factors such as personnel and legal regulation deficiencies in the field, fleet size, and the extent of aquaculture areas, effective supervision and control mechanisms are needed. In addition to Table 9, specific suggestions regarding sustainable fisheries can be listed as follows, in line with the relevant legal regulations:

- Continuing stock assessment activities for aquatic ecosystems such as the Black Sea, Sea of Marmara, and Keban Dam Lake,

- Conducting monitoring studies on current gillnet and trawl fishing and grounding these data on a scientific basis,

- Conducting comprehensive studies on the population and biological characteristics of commercial species,

- Increasing efforts to identify the genetic resources in our marine and inland waters,

- Ensuring the continuity of oceanographic and limnological monitoring studies, starting with carrying capacity assessment studies in terms of the sustainability of water resources,

- Regulating fishery policies by forecasting the pollution risk of marine and inland water ecosystems,

- Implementing more comprehensive legal regulations for aquatic invasive alien species used in aquaculture and research & development R&D studies, and conducting risk analyses for species to be introduced for the first time into the country,

- Continuing the controlled farming of species that have entered the ecosystem to prevent their spread, and keeping regular fishing data for those that have been proven to form populations,

- Given that declines in harvestable fish stocks may occur because of climate change, to combat this, the scope of the quota system applied to certain species in our country's fisheries should be expanded to include other species as well,

- Encouraging the use of low-carbon emission tools and equipment, as well as alternative and renewable energy sources, in fishery.

In this context, the successful implementation of legal strategies, considering the suggestions mentioned above, will help ensure the long-term functionality of fishery and water resources. Indeed, with the right scientifically based framework and the cooperation of key stakeholders, healthier fish stocks and sustainable fisheries will be possible.

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Chapter 2

USE OF GENOMIC TOOLS FOR DISEASE MANAGEMENT IN AQUACULTURE

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1. Introduction

Aquaculture has become a very important sector within the global seafood production, supplying over 50% of fish consumption worldwide. However, as the sector grows, the challenges associated with fish health and disease become worth considering for academicians as well. Pathogens, including bacteria, viruses, parasites, and fungi, pose significant risks to aquaculture populations, leading to significant economic losses, reducing productivity, and in some cases, environmental damage due to uncontrolled disease transmission (Calcagnile et al., 2024).

Common disease management in aquaculture relies on antibiotics, chemical treatments, and vaccines. However, overuse of antibiotics contributes to antimicrobial resistance (AMR), posing risks to both aquatic ecosystems and human health (Singh, 2024). Vaccination, although effective for some diseases, presents challenges such as high costs, labor-intensive application, and limited efficiency pathogens (Marnis and Syahputra, 2025).

Recent advances in genomic technologies have opened new avenues for disease prevention and control. These tools facilitate early pathogen detection, selective breeding for disease resistance, and targeted genetic modifications to enhance fish immunity (Bolaños et al., 2024). Genomic selection has become useful for increasing disease resistance lately. This section also discusses the economic and ecological impacts of major diseases encountered in aquaculture and the important stages in the role of genomic technologies in aquaculture health management.

2. Major Fish Diseases in Aquaculture

Fish diseases in aquaculture arise from bacteria, viruses, parasites, and fungi, each causing some economic and ecological consequences. Disease outbreaks can lead to mass fish mortality, reduced growth rates, increased treatment costs, and restrictions on fish trade (Bolaños et al., 2024). Climate change, intensification of aquaculture, and the overuse of antibiotics have further complicated disease management (Calcagnile et al., 2024).

2.1 Bacterial Diseases

Bacterial infections are among the most common and severe threats in aquaculture, often linked to poor water quality, high stocking densities, and environmental stress. Some bacteria are opportunistic pathogens, meaning they only cause disease when fish are stressed or immunocompromised, while others are highly virulent and capable of causing rapid mortality even in healthy fish.

2.1.1 Vibriosis (Vibrio spp.): Vibrio is responsible for vibriosis, a major disease in marine fish, causing tissue necrosis, hemorrhaging, and high mortality.

- Causative Agent: *Vibrio anguillarum*, *Vibrio harveyi*, *Vibrio vulnificus*, and other *Vibrio* species.

- Affected Species: Salmon, shrimp, seabass, tilapia, and shellfish.

- Symptoms: Hemorrhagic septicemia, skin ulcers, fin erosion, lethargy, and eye damage (exophthalmia).

- Transmission: Contaminated water, ingestion of infected material, and direct fish-to-fish contact.

- Economic Impact: Major cause of mortalities in marine aquaculture; outbreaks can lead to 70–100% stock loss (Islam and Taweethavonsawat, 2025).

Prevention & Control:

- Vaccination: Commercial vaccines like AquaVac Vibrio reduce mortality.

- Probiotics & Immunostimulants: *Bacillus spp.* and *Lactobacillus spp.* can outcompete *Vibrio* species.

- Genomic Surveillance: PCR-based kits for *Vibrio anguillarum* can be used to test fish for pathogen, which can help for application of antibiotics or other treatments on time. In addition, studies on the genomic epidemiology of vibrio infections have monitored the genomic diversity of vibrio species, especially *Vibrio anguillarum*, and the spread of infections in marine fish farms, and researchers have been able to observe the source and spread of infection by sequencing the genomes of bacterial isolates. This study has helped identify high-risk areas and transmission routes, allowing for better targeted biosecurity measures. Apart from these studies, research has also been conducted to detect antibiotic-resistant Vibrio strains using next-generation sequencing (NGS) technology (Calcagnile et al., 2024). CRISPR-based gene knockout studies are being developed to disable genes associated with antibiotic resistance in Vibrio spp., restoring antibiotic effectiveness (Marnis and Syahputra, 2025).

2.1.2 Aeromonas: Gram-negative, rod-shaped bacteria called Aeromonas species are frequently found in aquatic settings (Pessoa et al. 2019). They have multiple virulence factors, such as adhesins and exotoxins, and are opportunistic pathogens (Tomás, 2012). Fish with the infection can exhibit a variety of symptoms, including eye abnormalities, fin erosion, skin lesions, and hemorrhages. High death rates are possible, especially in groups that are overcrowded or under stress.(Hamid et al. 2016).

•Causative Agent: *Aeromonas hydrophila, Aeromonas salmonicida* and other.

•Affected Species: Salmonids, carp, seabream, catfish, shrimp, lobster and crab.

•Symptoms: Deep skin lesions, hemorrhaging, swollen kidneys, and high mortality rates in intensive aquaculture systems.

•Economic Impact: Furunculosis has been responsible for catastrophic losses in Atlantic salmon farms, particularly in Europe and North America (Singh, 2024).

Control Measures:

• Antibiotics & Vaccines: Resistance to antibiotics is increasing, making genomic tracking of antimicrobial-resistant strains crucial (Bolaños et al., 2024)

•Selective Breeding: Genetic markers for furunculosis resistance are currently being used in genomic selection programs (Yuan et al., 2025).

•NGS (Next Generation Sequencing) *Aeromonas hydrophila* is identified using NGS technology, allowing scientists to track specific strains and determine virulence factors, antibiotic resistance patterns, and epidemiological characteristic

•CRISPR-Cas9 technology: In tilapia farming, CRISPR/Cas9 has been discovered to edit immune-related genes, improving the fish's ability to resist *Aeromonas hydrophila* infections. Edited tilapia demonstrated enhanced immune responses and better survival rates after exposure to *A. hydrophila*

Researchers are also investigating bacteriophage genomes to develop phage-based therapies that specifically target Aeromonas strains and provide a sensitive alternative to antibiotics.

2.1.3 Columnaris Disease (Flavobacterium columnare): According to Declercq et al. (2013), Flavobacterium columnare is a destructive fish pathogen that causes columnaris disease in both wild and cultivated fish populations worldwide. High mortality rates are typical in aquaculture and lead to substantial financial losses because of fish death, decreased feeding activity during epizootics, and higher treatment costs. (Morris, J. M.et al.,2006; Faisal, M.,2017).

•Causative Agent: *Flavobacterium columnare.*

• Affected Species: Catfish, tilapia, and carp.

• Symptoms: Yellowish mucus patches on the skin, gill necrosis, frayed fins, and rapid mortality in warm waters (>25°C).

• Transmission: Direct contact and waterborne spread.

Prevention and Control:

•CRISPR Gene Editing: Researchers are investigating gene editing to enhance fish immunity against *Flavobacterium* infections (Marnis and Syahputra, 2025).

•Biofloc Technology: Biofloc systems enhance water microbiomes, reducing *Flavobacterium* growth.

2.1.4 Tenacibaculum spp.(Tenacibaculum maritimum): Tenacibaculosis occurs due to the marine bacterial pathogen *Tenacibaculum maritimum.* This ulcerative disease causes high mortalities for various mari-culture fish species worldwide (Mabrok, M.et al.,2023).

•Affected Species: European sea bass, atlantic salmon, rainbow trout, sea bream, chinook salmon

•Symptoms: Gross body lesions include tail rot, ragged fins, an eroded or hemorrhagic mouth, and ulcerative and/or necrotic skin lesions.

Prevention and Control: For *T. maritimum*, the only vaccination that is currently on the market is for turbot, especially strain LPV1.7 serotype O2. The effectiveness of using antibiotics to treat tenacibaculosis varies. When it comes to pure cultures and early identification through infectious indications in farmed fish, the bacterium's taxonomic status is clear and sensitive diagnostic methods (PCR, molecular probes in PCR-ELISA, RT-PCR-EHA and MALDI-TOF assays, etc.) are available. The development of useful techniques for *T. maritimum* genetic (MLSA) and serotype (mPCR) tracking has been aided by advancements in genome sequencing.

2.2 Viral Diseases

Viruses are highly contagious, difficult to treat, and often result in rapid disease spread across entire fish populations. Viral diseases have been responsible for some of the most devastating outbreaks in aquaculture (Bolaños et al., 2024).

2.2.1 Infectious Hematopoietic Necrosis Virus (IHNV): Infectious hematopoietic necrosis virus (IHNV) is the causative agent for infectious hematopoietic necrosis in salmonid fishes such as salmon and trout, which represent some of the most important species in aquaculture.

• Affected Species: Salmonids (rainbow trout, Pacific salmon, Chinook salmon, Coho salmon).

• Symptoms: Lethargy, darkened body coloration, anemia, hemorrhaging in the eyes and internal organs, leading to mass mortality in juveniles.

• Economic Impact: IHNV outbreaks cost millions annually in lost fish production.

Control Measures:

Scientists are using CRISPR-Cas9 to knock out genes encoding viral receptors on fish cells, preventing IHNV from attaching and entering cells (Bolaños et al., 2024). Inspired by COVID-19 vaccine technology, mRNA vaccines are being tested for IHNV. These vaccines trigger a stronger and more specific immune response compared to traditional vaccines.

- Genomic Tracking: Whole-genome sequencing is useful in tracking IHNV mutations and outbreaks.

2.2.2 Koi Herpesvirus (KHV): Common carp and koi carp variants are susceptible to the extremely contagious viral infection known as Koi herpesvirus (KHV), also called Cyprinid herpesvirus 3 (CyHV3) or carp interstitial nephritis gill necrosis virus. The virulence of the virus strain, the age of the fish (younger fish are more impacted than older fish), and the water temperature are some of the factors that determine mortality rates.

- Affected Species: Koi carp and common carp.
- Symptoms: Gill necrosis, lethargy, sunken eyes, erratic swimming.
- Mortality Rate: Up to 90% mortality within days of infection.

Prevention and Control:

• Genome-Wide Association Studies (GWAS): GWAS studies in koi carp have identified major genetic loci linked to KHV resistance, allowing farmers to breed resistant fish for disease (Singh, 2024).

• PCR-based diagnostic tests: Early detection using PCR-based diagnostic tests has helped farmers mitigate the spread of the virus. PCR assays targeting KHV DNA have enabled rapid detection in asymptomatic carriers, preventing widespread outbreaks.

• CRISPR-based Immunity Research: Ongoing research is exploring genetic modifications to create KHV-resistant strains (Marnis & Syahputra, 2025).

2.2.3 Infectious Salmon Anaemia (ISA): In farmed Atlantic salmon (Salmo salar), the infectious salmon anemia virus (ISAV) can have disastrous effects, leading to high mortality rates and significant financial losses (Johansen, L. H., 2011). According to the Office International des Epizooties, ISAV is the fourth of the ten aquatic animal diseases that need to be reported.

• Species Affected: Coho salmon, rainbow trout, and Atlantic salmon.

• Symptoms: Lethargy, severe anemia, ascites, petechiae in the swim bladder's and peritoneal cavity's adipose tissue, and hemorrhagic liver necrosis are among the symptoms.

• Mortality rates: It is extremely important to note that mortality rates might range from 30% to 90%. Given these mortality rates, there is a very high chance that a viral outbreak will have a negative economic impact.

Detection, Prevention and Control:

•Reverse Transcription PCR (RT-PCR) is commonly used for viral pathogens like ISA , as it allows for the detection of RNA viruses by converting RNA into complementary DNA (cDNA) for analysis.

•Whole Genome Sequencing (WGS): Whole genome sequencing of viruses such as Infectious Salmon Anemia (ISA) increases diagnostic accuracy by providing information on mutation patterns and helps develop molecular assays for early diagnosis.

•SNPs: A study by Gonen et al. (2015) identified genetic resistance to ISA by analyzing single nucleotide polymorphisms (SNPs) in the salmon genome. By performing genomic selection, salmon with higher resistance to ISA were good candidates for breeding programs.

•Genomic sequencing: Researchers identified genetic markers associated with resistance to ISA through genomic sequencing. By selecting broodstock that carry these resistance markers, farms have been able to breed more disease-resistant salmon.

•CRISPR/Cas9 has been used to modify the genetic makeup of salmon to improve their resistance to viral diseases such as Infectious Salmon Anaemia (ISA).

2.2.4 Viral Nervous Necrosis (VNN): VNN as a worldwide and disastrous disease classified as one of the most important diseases in marine fish, which occurred often in fry and juvenile fishes with high economic losses. The virus is a Betanodavirus within the family Nodaviridae.

•Affected Species: Striped jack, tiger puffer, Atlantic halibut, Atlantic cod, flounder, Asian sea bass, European sea bass, groupers and turbot.

•Symptoms: loss of appetite, erratic swimming patterns such as whirling, spiral, looping swimming, and belly up, loss of equilibrium, minimized nervous coordination, uncoordinated swimming, and alterations in pigmentations.

Prevention and Control:

•Recombinant DNA technology: The genome of betanodavirus was sequenced to identify viral proteins involved in immune evasion and infection. Recombinant DNA technology was used to create a vaccination strategy involving recombinant viral proteins. Reverse Transcription PCR (RT-PCR) is commonly used to identify viral pathogens like VNN, as it allows for the detection of RNA viruses by converting RNA into complementary DNA (cDNA) for analysis.

2.3 Parasitic Diseases

Various parasites, including protozoans, helminths (worms), and crustaceans cause parasitic diseases in fish. These parasites can affect fish health, leading to weight loss, skin lesions, organ damage, and even death if left untreated.

2.3.1 Ichthyophthiriasis ("Ich"): This disease is a major problem to freshwater aquarists and commercial fish producers worldwide. All species of freshwater fish are considered susceptible, and the parasite has been found in all areas of the world in both cultured and wild fish.

- Causative Agent: *Ichthyophthirius multifiliis.*

•Symptoms: The classic sign of an Ich infection is the presence of small white spots on the skin or fins. Prior to the appearance of white spots, fish may have shown signs of irritation, flashing, increased mucus, weakness, loss of appetite, and decreased activity.

- Transmission: Highly contagious in closed aquaculture systems.

Prevention and Control:

•DNA vaccine: β-tubulin is a conserved protein present in all eukaryotes and responsible for participating in cell motility and microtubule polymerization. In a study, in order to investigate its effectiveness in preventing Ich infestation in grass carp, Ich β-tubulin gene was cloned and Ich β-tubulin DNA vaccine was prepared.

•RNA Interference (RNAi): RNAi-based treatments disrupt parasite gene expression (Yuan et al., 2025).

•Metagenomic sequencing of water samples can detect Ich DNA before clinical symptoms appear, allowing for early intervention strategies (Bolaños et al., 2024).

2.3.2 Sea Lice Infestations: The sea lice, Lepeophtheirus salmonis and various Caligus species, are ecto-parasites of marine finfish (Copepoda: Caligidae). They have a major impact on salmonid aquaculture worldwide.

- Causative Agents: *Lepeophtheirus salmonis*, *Caligus spp.*
- Impact: Infestations lead to weight loss, skin lesions, and secondary infections.

Prevention and control:

•Marker-Assisted Selection (MAS): Breeding salmon with higher genetic resistance to sea lice.

•CRISPR Knockout Studies: Targeting key genes involved in lice attachment (Ramos-Vivas and Acosta, 2024).

•RNAi technology is another molecular tool to silence genes that are crucial for sea lice attachment to fish, reducing their ability to infest salmon (Marnis & Syahputra, 2025).

2.4 Fungal Infections

Fungal diseases often follow bacterial or viral infections, making fungus secondary opportunistic pathogens.

2.4.1 Saprolegniosis (Saprolegnia spp.): Saprolegnia sp. is classified within Oomycetes, a group of pathogens similar to fungi but which are more closely related to golden-brown algae and are part of the Chromista or chromoalveolates and therefore are not “true fungi”.

- Affected Species: Tilapia, catfish, salmon.
- Symptoms: Cotton-like fungal growth on the skin, gills, and eyes, leading to necrosis.

Prevention and Control:

- Genomic Prediction of Susceptibility: Selective breeding efforts have identified genetic markers for resistance to *Saprolegnia* infections (Yuan et al., 2025).

•GWAS studies have identified genetic variants linked to increased resistance to Saprolegnia infections.

•CRISPR gene-editing techniques are being explored to enhance fish immune responses by modifying genes involved in antifungal defense mechanisms.

3. Genomic Tools in Fish Disease Prevention

Genomic technologies have revolutionized the understanding and management of fish diseases in aquaculture. These tools enable early detection, more accurate diagnostics, prevention, and the development of new therapeutic strategies. Here are some key genomic tools applied in fish disease prevention in order to be useful for aquaculture practices.

3.1. Genomic Sequencing for Pathogen Detection

Next-Generation Sequencing (NGS) and Whole Genome Sequencing (WGS) allow for the rapid identification and characterization of pathogens, even those with unknown genetic profiles. This tool is essential in identifying new or emerging diseases. For example, *Aeromonas hydrophila* has been identified using NGS technology, which allows scientists to track specific strains and determine their virulence factors, antibiotic resistance patterns, and epidemiological characteristics. Additionally, whole genome sequencing of viral diseases such as Infectious Salmon Anemia (ISA) and Koi Herpes Virus (KHV) has increased diagnostic accuracy by providing insights into mutation patterns and helped develop molecular assays for early diagnosis.

3.2. Molecular Diagnostics

Polymerase Chain Reaction (PCR) and Quantitative PCR (qPCR) are molecular tools that enable rapid detection of pathogens in fish farms. PCR can detect even low levels of bacterial or viral DNA and provide early warning signs of infections before clinical symptoms appear. For example, PCR-based kits for *Vibrio anguillarum* are useful tools to test for the presence of the bacteria in fish, helping to encourage administration of antibiotics or other treatments on time. Therefore, Reverse Transcription PCR (RT-PCR) is also commonly used for viral pathogens such as ISA or VNN, as it converts RNA into complementary DNA (cDNA) for analysis, allowing the detection of RNA viruses.

3.3. Genetic Selection for Disease Resistance

Genetic breeding programs using genomic tools are quite effective to develop fish strains with increased disease resistance. Fish farms can apply selective breeding programs in order to obtain fish that are less susceptible to common diseases by identifying genetic markers associated with immune responses and disease resistance. For instance, Atlantic salmon has developed resistance for the ISA virus using genomic selection techniques in selective breeding programs, reducing the impact of ISA outbreaks. In the Genomic Selection procedure applied to tilapia farming, markers associated with resistance to *Aeromonas hydrophila* have been identified, allowing farmers to select fish that are genetically less susceptible to bacterial infections.

3.4. Metagenomics for Monitoring Fish Health

Metagenomics refers to the use of genomic sequencing to analyze microbial communities in water, fish skin, gills, and digestive tracts. This tool helps monitor the microbiome of fish and provides insights into how environmental stressors, farming practices, and pathogens interact. For example, metagenomic profiling has been used to study the gut microbiome of farmed salmon. A healthy microbiome helps protect fish from infections, while an imbalance (dysbiosis) can increase susceptibility to diseases such as vibriosis or tenascibaculosis. Metagenomics has also been used to track the presence of antibiotic resistance genes in fish pathogens, which is critical for managing the risks associated with antibiotic overuse.

3.5. CRISPR/Cas9 and Gene Editing

CRISPR/Cas9 gene editing technology holds promise for developing disease-resistant fish. By directly modifying specific genes involved in immune responses or pathogen recognition, scientists can create fish that are less susceptible to disease. For example, researchers are investigating CRISPR-based editing in salmon to increase resistance to viral infections such as Infectious Pancreatic Necrosis (IPN). Gene editing also has the potential to improve fish health traits, such as better skin integrity, which could make fish less susceptible to fungal or bacterial infections.

3.6. Bioinformatics for Disease Prediction

Advanced bioinformatics tools analyze genomic data to predict potential disease outbreaks in aquaculture systems. By integrating environmental data, genomic sequences, and farm management practices, predictive models help to predict disease risks and recommend preventive measures. For example, predictive modeling for sea lice infestations in salmon farms can help predict high-risk periods and inform management strategies such as adjusting stocking densities or implementing targeted treatments (Ramos-Vivas and J.,Acosta, F.,2024).

3.7. Ethical and Environmental Considerations

While genomic technologies offer powerful solutions, challenges remain regarding public acceptance, regulatory approval, and long-term ecological impacts. Common concerns include genetically modified organisms (GMOs) and their release into wild fish populations, and the potential for CRISPR-edited disease-resistant fish to disrupt natural ecosystems.

4. **Conclusion**

Bacterial, viral, parasitic, and fungal diseases cause significant risks to aquaculture, and outbreaks result billions of dollars in losses globally. Genomic technologies, selective breeding, CRISPR, and probiotics are transformative measures for how to prevent and manage these diseases. With further advances in genomics-based interventions, the need for antibiotics and chemical treatments could be eliminated, making aquaculture more sustainable and resilient.

The integration of genomic tools into aquaculture represents a major shift in disease prevention, enabling a shift from traditional antibiotic-based treatments to precision breeding, gene editing, and microbiome management. Advances in genomic selection, CRISPR, metagenomics, and RNAi-based treatments offer promising solutions to long-standing disease challenges in aquaculture. However, adoption of genomic-based disease management strategies requires investment in infrastructure to access the tools, clear regulatory frameworks to ensure ethical and safe implementation, and farmer education and training to integrate genomic tools into daily aquaculture practices. With sufficient time and quality to sustain these concepts, it is an undeniable fact that genomic technologies have the potential to revolutionize fish health management and ensure sustainable and disease-free aquaculture in the future.

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Chapter 3

HEAVY METAL POLLUTION IN INLAND SURFACE WATERS IN TERMS OF HUMAN HEALTH RISKS

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Introduction

The heavy metal pollution in water resources has become a significant environmental issue worldwide, posing a threat to aquatic ecosystems and human health. Toxic and potentially carcinogenic metals (HMs) are considered major pollutants in freshwater habitats (lakes, rivers, ponds, etc.) due to their durability, lethal aggregation, and ability to support biological growth in renewable cycles (Wang et al. 2019, Saravanan et al. 2024). Today, the term "heavy metal" is used to describe metallic chemical elements and metalloids that are toxic to the environment and humans. Heavy metals with a density greater than 5 g/cm³ are classified according to their toxicity levels, as shown in Table 1.

Table 1. Classification of heavy metal based on toxicity (Patel et al. 2021)

Highly Toxic Metals	Moderately Toxic Metals	Low Toxic Metals	Non-toxic Metals
Uranium	Antimony	Tin	Sodium
Zinc	Boron	Gold	Lithium
Vanadium	Actinium	Erbium	Bismuth
Zirconium	Beryllium	Gallium	Iron
Silver	Cadmium	Holmium	Calcium
Polonium	Chromium	Neodymium	Magnesium
Titanium	Lead	Thulium	Manganese
Radium	Mercury	Terbium	Strontium
Tungsten	Nickel	Ytterbium	Rubidium
Rutbenium	Platinum	Samarium	Molybdenu m
Thorium	Palladium	Barium	Aluminum
Thallium	Indium	Scandium	Potassium
	Copper	Germanium	
	Hafnium		

Heavy metals reach recipient environments through two pathways: natural (resulting from the erosion and weathering of rocks and ores containing naturally occurring heavy metals in the Earth's crust) and anthropogenic (due to human activities such as vehicle exhaust, inadequate waste disposal, fossil fuel combustion, fertilizer and pesticide application, untreated wastewater irrigation, mining, smelting processes, agriculture, etc.). This situation can affect vegetation, the food chain, and water quality, thereby impacting human health (Mohammadi et al. 2019). In other words, depending on the quality of water used for crop irrigation or household purposes, the likelihood of human exposure to heavy metals increases due to pollutants reaching the soil, plants, and surface or groundwater (Castresana et al. 2019). Therefore, even if people do not directly consume water contaminated with heavy metals, they are often exposed to high levels of heavy metals through plant and aquatic food sources grown in polluted waters.

In terms of the sustainability of water resources, determining and monitoring water quality characteristics is of great importance. Continuous monitoring contributes to the provision of real-time data related to water quality, helping to protect public health and ensure the safe use of water resources. Under the 'Surface Water Quality Management Regulation' currently in force in Turkey, the quality of aquatic environments is determined based on various parameters. In light of these parameters, water quality is classified, and the monitoring results of specific pollutants and priority substances are evaluated, taking into account the water body. Within the scope of the regulation, priority substances and environmental quality standards have been determined for surface water resources. In this context, when evaluating water quality monitoring results for specific pollutants and priority substances, including heavy metals, the arithmetic average of the annual monitoring results is compared with the annual average environmental quality standard (Mean-EQS) for the relevant water body category (rivers/lakes, coastal and transitional waters). For any specific pollutant and/or priority substance, individual monitoring data is compared with the maximum allowable environmental quality standard (Max. EQS). As a result of the evaluation, if the monitoring data are lower than both Max.-EQS and Mean-EQS values, the receiving environment environmental quality standard values are met (TSWQR 2016).

Table 2 presents the sources of certain heavy metals and the permissible limits according to WHO, USEPA, and TSWQR (2016).

Health risk refers to the likelihood of encountering a hazardous substance that could potentially cause disease in humans, and the process of assessing health risk consists of four steps: hazard identification, exposure assessment, concentration determination, and using a mathematical model based on exposure and dose-response evaluations to assess human health risk (HHR) (Babuji et al. 2023).

Table 2. Sources (Jyothi 2020, Patel et al. 2021, Sharma et al. 2023, Saravanan et al. 2024) and permissible limits of some heavy metal

Heavy metals	**Sources**	**Permissible limit**			
		WHO	**USEPA**	**TSWQR**	
				Mean-EQS*	**Max.-EQS****
Lead(Pb)	-Batteries -Coal combustion -Paint industry -Pecticide -Automobile	0.01 mg/L	0.010 mg/L	1.2 µg/L	14 µg/L
Cadmium (Cd)	-Plastic -Fertilizers -Pesticides -Welding -Electroplating -Cd-Ni batteries	0.003 mg/L	0.005 mg/L	< 0.08 (Class I) 0.08 (Class II) 0.09 (Class III) 0.15 (Class IV) 0.25 (Class V)	< 0.45 (Class I) 0.45 (Class II) 0.6 (Class III) 0.9 (Class IV) 1.5 (Class V)
Arsenic (As)	-Atmospheric deposition -Mining -Pesticides -Fungicides - Metal smelters	0.01 mg/L	0.010 mg/L	53 µg/L	53 µg/L
Mercury (Hg)	-Coal combustion -Fish -Mining -Paint industry -Paper industry -Volcanic eruption -Cement production -Chlor-alkali production	0.006 mg/L	0.002 mg/L	-	0.07 µg/L
Chromium (Cr)	-Steel fabrication -Electroplating -Textile -Leather industries -Dyeing industries	0.05 mg/L	0.1 mg/L	1.6 µg/L	142 µg/L
Copper (Cu)	-Copper polishing -Plating -Printing -Mining industries -Metallurgy	2 mg/L	1.3 mg/L	1.6 µg/L	3.1 µg/L

Cobalt (Co)	-Hip alloy replacement case -Ferromagnetic	-	-	0.3 µg/L	2.6 µg/L
Zinc (Zn)	-Oil Refining -Plumbing -Brass manufacturing	-	-	5.9 µg/L	231 µg/L
Iron (Fe)	-High intake of iron supplements & oral consumption	-	-		

*Mean-EQS: Annual average environmental quality standard

** Maximum -EQS: Maximum allowable environmental quality standard

Xiao et al. (2019) reported that high metal levels in freshwater ecosystems could pose significant health risks for both humans and aquatic organisms. Therefore, monitoring metal levels and assessing health risks are critical for protecting aquatic ecosystems and human health. In this context, current research has focused on both the local and seasonal variations of heavy metals in surface waters, as well as the human health risk assessment associated with heavy metals, due to their significant impact on public welfare (Qu et al. 2018, Saleem et al. 2019).

This study focuses on: a) The potential effects of heavy metals on human health, b) Risk assessment methods, c) Methods for removing heavy metals from aquatic ecosystems, d) Summarizing studies related to the topic conducted in inland waters of our country.

Possible Effects of Heavy Metals on Human Health

Toxicity is defined as the characteristic property of a chemical substance that can affect an organism's survival, proper growth, and regular reproductive processes. Some heavy metals, depending on the dose and duration of exposure, exhibit carcinogenic, mutagenic, and teratogenic effects. It has been proven that heavy metal toxicity poses a significant threat, and metal toxicity depends on the absorbed dose, exposure route, and duration of exposure, i.e., whether it is acute or chronic. This can lead to various disorders, as well as excessive damage due to oxidative stress caused by the formation of free radicals. In Figure 1, the toxicities caused by heavy metals are presented, while Table 3 outlines the routes of entry of heavy metals into humans and their possible effects on human health.

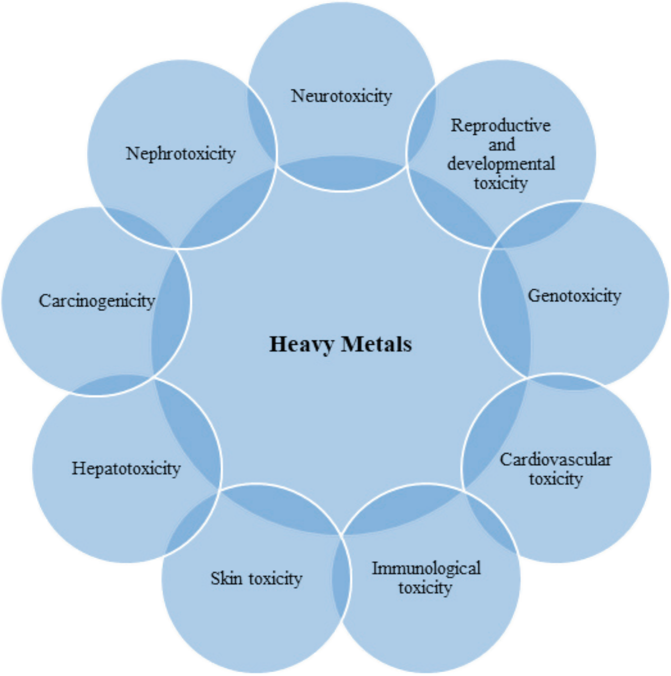

Figure *1. Toxicities caused by heavy metals (Mitra et al. 2022)*

Table 3. Routes of entry of some heavy metals into humans and their effects on human health (Jyothi 2020, Patel et al. 2021, Saravanan et al. 2024)

Heavy metal	Entry route	Health effects
Chromium (Cr)	Inhalation, ingestion and absorption through skin	-Lung disorders (bronchitis, cancer), -Renal and reproductive system -Stomach cancer,
Lead (Pb)	Inhalation and ingestion	-Serious effect on mental health (Alzheimer's disesase), -Nervous system -Liver, kidney damage, -Mental retardation in children
Arsenic (As)	Inhalation and ingestion	-Highly effects dermal region (Cancer, Dermatitis), -Brain & Cardiac problems -Bronchitis
Cadmium (Cd)	Inhalation and ingestion	-Osteo related problems, -Cancer -Lung diseases -Renal issues -Gastrointestinal disorder,
Mercury (Hg)	Inhalation, ingestion and absorption through the skin	-Brain damage -Sclerosis -Blindness -Minamata disease -Deafness -Gastric problems -Renal disorders -Skin rashes and dermatitis
Copper (Cu)		-Abdominal disorders (vomiting and diarrhea), -Metabolic activity abnormalities, -Kidney problem,
Cobalt (Co)		-Haemotological -Cardiovascular -Hepatic -Endocrine -Skin, respiratory and kidney
Zinc (Zn)		-Gastrointestinal disorders, -Kidney &Liver abnormal functioning
Iron (Fe)		-Vomiting -Diarrhea -Abdominal pain -Dehydration & lethargy

Heavy metals can enter the human body through four routes: a) Consumption of contaminated food, b) Inhalation from the atmosphere, c) Drinking contaminated water, d) Skin contact from agricultural, pharmaceutical, manufacturing, residential, and industrial areas. Exposure to heavy metals in surface waters occurs through oral ingestion of surface water as drinking water by adults and children, and dermal contact while taking a shower/bath. Reactive exposure routes include oral ingestion and dermal contact with surface water while swimming (Briffa et al. 2020).

Ingestion exposure can occur through the consumption of contaminated food, water, and other liquids. Edible products may contain chemical residues, which reach humans through pesticide use, atmospheric pollutants, and/or biotic uptake and accumulation from contaminated soil or water. Ingestion exposure can also occur through the deliberate or accidental consumption of soil, dust, or chemical residues from surfaces or objects that come into contact with the hands or objects during hand-to-mouth or object-to-mouth activities, especially by children, outside of their regular diet. When a contaminant is ingested, the amount that enters the body in a biologically available form is referred to as the dose. There are several different ways to measure the dose (Figure 2).

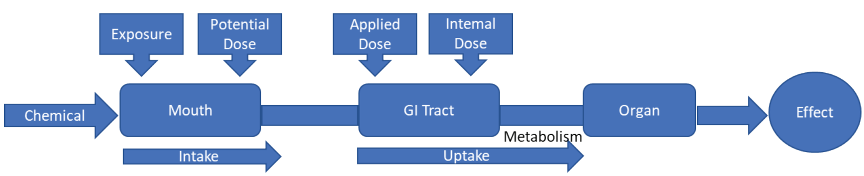

Figure 2. *Illustration of ingestion route (Anonymous 2023a, 2023b)*

Health risk assessment

The EPA uses risk assessment to characterize the nature and magnitude of health risks for various populations, such as residents, recreational visitors, and both children and adults. The following risk assessments present commonly used formulas for drinking water ingestion, swimming or showering/bathing, and dermal contact with water. Health risk calculations are performed to estimate total exposure to heavy metals, either in a carcinogenic or non-carcinogenic manner.

Non-carcinogenic health risk

$ADD_{ingestion} = C_{water}$ x IR x EF x ED / BW x AT

$ADD_{ingestion}$: The Average Daily Doses (μg/ kg-day) through ingestion exposure (mg/ kg/day)
C_{water} : Measured metal concentration (μg/ L)
IR : Ingestion rate (L/day) 2.2 L/day (adults), 1.8 L/day (children)*
EF : Exposure frequency 350 days/year** 365 days/year***
ED: Exposure duration 70 years (adults), 6 years (children)**, ***
BW: Body weight of humans: 70 kg (adults), 15 kg (children)**, ***
AT = Average time: 365 days/year x ED**, ***

* Li and Zhang (2010), Naveedullah et al. (2014)
** USEPA (2004), Saleem et al. (2019)
*** USDOE (2011), USEPA (2011)

ADD_{dermal} : C_{water} x SA x K_p x ET x EF x ED x CF / BW x AT

ADD_{dermal} : The Average Daily Doses (μg/ kg-day) through dermal exposure
SA : Skin surface area; 18000 cm^2 (adults), 6600 cm^2 (children)*
K_p : Dermal permeability coefficient (cm/h) in water; Fe, Cd, As, Cu : 0.001; Pb: 0.0001; Ni:0.0002;
Zn: 0.0006; Cr:0.002; Hg:0.001*
ET : Exposure time: 0.58 h/day (adults), 1 h/day (children)**
CF : Conversion factor (0.001 L/cm^3)

* USEPA (2004), Li and Zhang (2010), Naveedullah et al. (2014), Saleem et al. (2019)
** USEPA (2004), Wang et al. 2017, Saleem et al. (2019)

$$\mathbf{HQ_{ingestion} = ADD_{ingestion} / RfD_{ingestion}}$$

$HQ_{ingestion}$: The non-carcinogenic health quotient (HQ) of heavy metals through ingestion
$ADD_{ingestion}$: The Average Daily Doses (µg/ kg-day) through ingestion exposure (mg/kg/day)
$RfD_{ingestion}$: 0.02, 0.0035, 0.001, 0.003, and 0.07 mg/kg for Ni, Pb, Cd, Cr, and Fe respectively*

*: USEPA (2004), Li and Zhang (2010), Naveedullah et al. (2014), Qu et al. (2018)

$$\mathbf{HQ_{dermal} = ADD_{dermal} / RfD_{dermal}}$$

HQ_{dermal} : The non-carcinogenic health quotient (HQ) of heavy metals through dermal adsorption
ADD_{dermal} : The Average Daily Doses (µg/ kg-day) through dermal exposure
RfD_{dermal} : 0.00042, 0.000025, 0.0054, 0.000075, and 0.14 mg/kg for Pb, Cd, Ni, Cr, and Fe respectively*

*: USEPA (2004), Li and Zhang (2010), Naveedullah et al. (2014), Kumar et al. (2019)

$$\mathbf{HI_{ingestion/dermal} = \sum HQ_{ingestion/dermal}}$$

$HI_{ingestion/dermal}$: Hazard Index

$$\mathbf{THI = HI_{ingestion} + HI_{dermal}}$$

THI : Total Hazard Index

If the values of HI and THI > 1, indicates that there may be a potential for adverse non-carcinogenic health effects to occur, while HI and THI values < 1 indicates that non-carcinogenic health effects are not expected (USEPA 2004)

$CR_{ingestion} = ADD_{ingestion}$ x CSF
$CR_{ingestion}$: Carcinogenic health risk
$ADD_{ingestion}$: The Average Daily Doses (µg/ kg-day) through ingestion exposure (mg/kg/day)
CSF : Cancer slope factor (µg/ kg-day), Cr: 0.0005; Ni: 0.0017; As: 0.0015*

$CR_{dermal} = ADD_{dermal}$ x CSF
CR_{dermal}: Carcinogenic health risk
ADD_{dermal}: The Average Daily Doses (µg/ kg-day) through dermal exposure
CSF : Cancer slope factor (µg/ kg-day), Cr: 0.0005; Ni: 0.0017; As: 0.0015*

$TCR = CR_{ingestion} + CR_{dermal}$

A value of $CR > 1.0\times10^{-4}$ is considered unacceptable; $1.0\times10^{-4} < CR < 1.0\times10^{-6}$ is considered an acceptable range depending on the exposure conditions; $CR<1.0\times10^{-6}$ is considered not to have significant health effects**

* Kumar et al. (2019), Mohammadi et al. (2019)
** Mohammadi et al. (2019), Custodio et al. (2020)

Carcinogenic health risk

Remediation Strategies

Remediation strategies play an important role in reducing and mitigating the harmful effects of pollutants on the environment and human health. Traditional cleanup methods generally focus on removing or limiting pollutants from the environment. The conventional physical and chemical methods used to remove heavy metals from aquatic habitats are often expensive, slow, not environmentally friendly, and somewhat ineffective. t is stated that selecting the most suitable heavy metal removal technique is a challenging process, especially due to the non-uniform and complex structure of lakes. While physical remediation techniques are a good option for removing heavy metals from lakes, they have limitations such as high operational costs, the need for significant capital investment and engineering equipment, and the risk of exposing heavy metals to the environment. Chemicals used in chemical remediation techniques are non-biodegradable and produce secondary toxic by-products; they have significant disadvantages such as high cost, applicability issues, changes in water quality, and potential harm to aquatic flora and fauna. On the other hand, biological remediation techniques emerge as the most effective, simple, environmentally friendly, and low-cost method for removing heavy metals from lakes (Giripunje et al. 2015). The classification of lake water remediation techniques is shown in Figure 3.

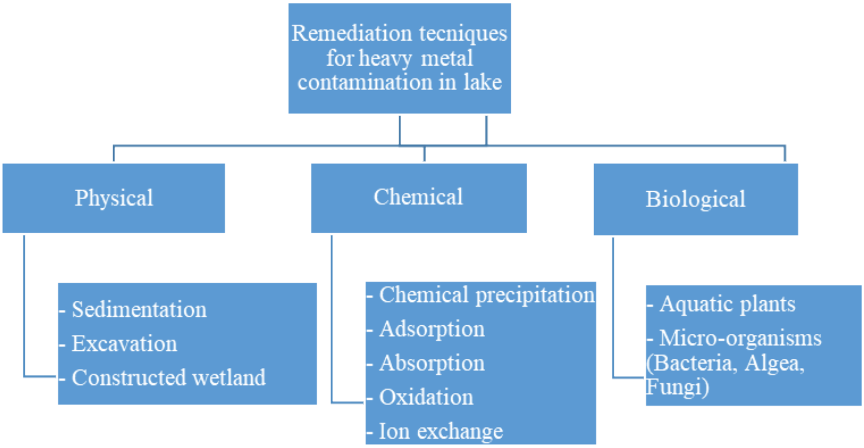

Figure 3. *Classification of lake water remediation techniques (Giripunje et al. 2015)*

Methods such as phytoremediation and microbe-assisted remediation technologies have gained significant interest in recent years and have provided better solutions to the problem. In this context, innovative, eco-friendly, and more effective approaches have emerged today, not only aiming to remove pollutants but also to reduce toxicity levels and restore ecosystems to their natural states. Some of the innovative remediation strategies mentioned below are discussed.

1. Phytoremediation: It is a sustainable and eco-friendly remediation approach that uses plants to remove, break down, or stabilize pollutants in soil, water, and air. Plants have the ability to absorb and accumulate pollutants in their tissues through processes such as phytoextraction, phytodegradation, and phytostabilization. By planting hyperaccumulating plants in contaminated areas, phytoremediation has been reported to effectively reduce the toxicity levels of heavy metals, organic pollutants, and other contaminants. This method, which has been reported to help improve ecosystem health, has been successfully applied in contaminated areas such as abandoned industrial sites, mining fields, and landfills (Haldar and Ghosh 2020, Madhuppriya et al. 2020, Babuji et al. 2023, Dhilleswara et al. 2024, Yadav et al. 2024). In this method, it has been emphasized that some organisms used may cause diseases in humans, the disposal methods could lead to additional costs, and safety procedures are extremely important (Rai 2019, Shen et al. 2022).

3. Nanoremediation: Nanoremediation is an advanced remediation technology that uses nanomaterials to treat and remove pollutants from the environment. Zero-valent iron, carbon nanotubes, and nanoscale metal oxides, such as nanoparticles, have unique properties that enable them to effectively adsorb, catalyze, or immobilize pollutants in soil and water. Nanoremediation offers an extremely effective and targeted approach, especially in complex and challenging environmental conditions, to reduce the toxicity levels of pollutants. It has also been reported that this method has been successfully applied in the treatment of contaminated groundwater, soil, and wastewater, playing a role in reducing toxicity levels in polluted areas (Abubakar et al. 2024, Dhilleswara et al. 2024). It is believed that graphene (an antibacterial nanoparticle) and similar chemicals used in nanoremediation could harm the ecosystem, and further studies are needed on the behavior of nanoparticles in nature (Thangavelu and Veeraragavan 2022, Ali et al. 2023).

4. Electrokinetic remediation: Electrokinetic remediation is an innovative technology that uses electric currents to transport and remove pollutants from soil and groundwater. By applying direct current to electrodes placed in the soil, pollutants are mobilized and directed towards the electrodes, where they can be captured and removed. Electrokinetic remediation is effective in the treatment of soils contaminated with heavy metals, radionuclides, and organic pollutants, and it helps reduce the toxicity levels in polluted areas. It has been stated that this method is effective in cleaning contaminated soils and groundwater, providing a sustainable solution to reduce toxicity levels and restore environmental quality (Madhuppriya et al. 2020, Abubakar et al. 2024, Dhilleswara et al. 2024). Although it can be used in wastewater treatment, it has been noted that there could be issues with its use in large water bodies due to electrical conductivity, and further studies are needed due to potential effects on living organisms in both freshwater and saline environments (Cherifi et al. 2009).

5. Advanced Oxidation Processes: Due to the high oxidation capabilities of heavy metals, significant developments have been observed in advanced oxidation processes (AOP) in recent years, including Fenton oxidation, electrochemical oxidation, photocatalytic oxidation, and ozonation oxidation. Advanced oxidation processes are innovative treatment technologies that involve the production of highly reactive hydroxyl and other radicals to break down and detoxify pollutants in water and air. Additionally, complex-forming substances (CAs) can be oxidized into lower-toxic or non-toxic products such as carbon dioxide, water, and inorganic salts. AOPs can not only destroy heavy metal complexes but also facilitate the recovery of metals. It has been reported that AOPs have been successfully applied in the treatment of polluted water bodies, improving water quality and biodiversity while reducing the toxicity levels of pollutants. However, most AOPs are operated under acidic conditions, which require large amounts of acid supplementation, leading to increased operating costs. It has been reported that combining different AOPs may yield unexpected results that need to be considered (Du et al. 2020, Dhilleswara et al. 2024).

6. Photocatalysis: Photocatalysis is an emerging method based on catalytic oxidation technology, where light energy is used as the sole energy source. The method works on the principle of accelerating chemical reactions on a catalyst surface using light energy. Light excites electrons on the catalyst's surface, thereby generating free radicals. These radicals react with organic pollutants in wastewater, converting them into less harmful substances or completely mineralizing them. This process, as an environmentally friendly and effective method, creates a natural reaction while purifying water without the use of chemical additives. Since photocatalysis does not require additional energy input other than light, the generated active species have good redox capabilities and do not produce extra pollution. It is highly suitable for use in redox reactions in water treatment. However, issues such as low efficiency, catalyst regeneration, separation, etc., have been reported as areas that need improvement in this technique (Gao and Meng 2021, Pang et al. 2024).

Studies conducted in Türkiye on this topic

Similar to the rest of the world, studies on health risk assessment related to different surface waters in Turkey have gained momentum in recent years.

Varol (2019) assessed non-carcinogenic and carcinogenic risks through ingestion and dermal contact exposure routes in the Keban Dam Reservoir, which is of international importance due to its location on the Euphrates River, a significant transboundary river. While the Hazard Index (HI) and total HI values were found to be below 1, the carcinogenic risk (CR) values for As and Cr for each exposure route, as well as the total CR values, were found to be within the acceptable range of 10^4 and 10^6. Based on the findings, the researcher stated that the Keban Dam Reservoir is safe for human health regarding both residential and recreational uses. Canpolat et al. (2020), on the other hand, determined the levels of 17 trace elements (Pb, Hg, Cd, As, Cr, Ni, Co, Mn, Cu, Fe, Al, Sr, U, V, Zn, Zr, and Ba) in surface and deep water samples from the same reservoir and assessed the health risks of these metals for residential and recreational users. The findings indicated that the HI values for children were higher than for adults, suggesting that children's health is at greater risk than that of adults. For water ingestion, As, and for dermal contact, U, V, and

Cr were identified as the primary contributors to the total risk (HI). The carcinogenic risk values for As and Cr in surface and deep waters were found to be below the target risk value of 1×10^{-4}. Similar to Varol (2019)'s findings, the results revealed that the trace elements in both surface and deep waters of the reservoir do not pose a health risk for residential and recreational users.

Tokatlı and Ustaoğlu (2020) assessed the toxic element concentrations in the waters of the Meriç River Delta Wetland (Thrace Region) ecosystem using health risk assessment methods such as Hazard Index (HI), Hazard Quotient (HQ), and Carcinogenic Risk (CR), evaluating the public health risks. According to the HQ and CR results, arsenic (As) was found to be the most hazardous toxic substance among the elements studied, and the most affected delta components were Gala Lake and the Ergene River. The Hazard Quotient (HQ) and Hazard Index (HI) values for the trace elements in Turnasuyu Stream (Eastern Black Sea Basin) showed that the water of the river is not within dangerous limits in terms of public health risk (Ustaoğlu et al. 2020).

The results of the health risk assessment study conducted on 10 different lakes used as irrigation and drinking water sources north of the Saros Bay (Turkey) showed that neither individual nor combined metals in the water samples pose non-carcinogenic risks for adults and children. It was also determined that Cr and As do not pose a carcinogenic risk for the local residents (Tokatlı and Varol 2021).

Monthly water samples taken from 8 stations along the Karasu River, the main tributary of the Euphrates River, the longest river in Southwest Asia, showed that the Hazard Quotient (HQ) risk level for both water ingestion and dermal contact pathways for the residents was below the risk threshold for the heavy metals considered. However, for children, the Hazard Index (the sum of HQs of all heavy metals) for water ingestion indicated that the ingestion of the ten heavy metals considered could pose non-carcinogenic health risks. The carcinogenic risk results for As and Cr, both for water ingestion and dermal absorption, were found to be within or below the acceptable carcinogenic risk range (Varol et al. 2021). Ustaoğlu et al. (2021) calculated all Hazard Quotient (HQ) and Hazard Index (HI) values for the Terme River (Black Sea Region), which is under anthropogenic pressure and serves as the region's primary source of drinking and irrigation water, to be below the risk threshold (<1). The researchers noted that the total HI values for children were higher than for adults, indicating that children's health is at greater risk than that of adults.

Yüksel et al. (2021) conducted a study on water quality due to a waste disposal facility built near Çavuşlu Stream (Giresun), the primary drinking water source for the local population. The results indicated that the facility reduced the water quality of the stream and pointed out that it is responsible for potential lifetime cancer risk to human health, especially at Station I, and is significant for both adults and children.

According to a study conducted by Fural et al. (2022) at Doğancı Dam (Bursa), the health risk index values indicated that there is no non-carcinogenic health risk in the dam.

Baran et al. (2023) reported that the waters of İnci and Maden streams, located in two major mining sites in the Eastern Anatolia Region of Turkey, are contaminated with heavy metals. The study, within the scope of human health risk assessment, showed that the Hazard Index values from ingestion and dermal exposure did not indicate any non-carcinogenic risk.

Kutlu and Sarıgül (2023) conducted a study to determine the non-carcinogenic/carcinogenic health risk levels of heavy metals in surface water samples taken from the Munzur River area (Ramsar Site) for both children and adults. Among the metals examined, Pb (lead) had the highest HQ and HI values in both adults and children. However, all HQ and HI values for both adults and children were found to be below 1. It has been reported that the Munzur River area is safe for residential use from a public health perspective. A study was conducted in the Central Black Sea Region in Samsun, where six rivers exposed to significant agricultural and industrial discharges were selected. Among the rivers, the one most heavily polluted was the Kızılırmak River, with an As value (1.3E-04) and a CR exceeding the predicted standard limit value (Odabaşı and Ceylan 2023).

Heavy metal (Hg, As, Cd, Cr, Pb, Ni, Cu, Zn) analyses were conducted on the waters of four streams (Sukesen Creek, Başpınar Creek, Yavrucak Creek, Gölcük Creek) in the Mogan Lake Basin, which is under anthropogenic pressure. The HQingestion values were found to be higher than the HQdermal values for both adults and children, due to As. According to the HI non-carcinogenic health values, Sukesen, Başpınar, and Gölcük Streams show high non-carcinogenic health risk levels for heavy metals, which vary by month and age group. However, for Yavrucak Stream, no non-carcinogenic health risk was found for either adults or children. The CR values calculated for chromium, nickel, and arsenic indicate that exposure via ingestion is riskier than dermal exposure, and they express the likelihood of cancer development in both adults and children (Pulatsü and Latifi 2023).

Human health risk assessments for Uluabat Lake, one of the important Ramsar sites in our country, conducted by Şener et al. (2023), have shown that the consumption of lake water can lead to both carcinogenic and non-carcinogenic health issues. The same researchers have reported that the water of Lake İznik, one of Turkey's important lakes, also carries both carcinogenic and non-carcinogenic health risks, and is not suitable for use as drinking water. They emphasized that even using the lake water for irrigation in agricultural activities could indirectly affect human health (Şener et al. 2025).

Tokatlı and Islam (2023), in their study aimed at determining the spatiotemporal distributions of organic pollution parameters in the Meriç-Ergene Basin, which is exposed to intense agricultural and industrial pressure, reported that the non-carcinogenic health risk conditions based on regional food pollutants in the Meriç-Ergene Basin varied across stations during the wet season.

Varol and Tokatlı (2023), in their study on the water quality and health risk assessment of the highly polluted Çorlu Stream, selected three sampling stations. The health risk assessment results indicate the presence of non-carcinogenic heavy metals due to the ingestion of combined metals in the first station, located in the middle and lower regions of the stream, where water from industrial, domestic wastewater, and agricultural activities is discharged. In the first station, the risk is identified for children, while in the second station, the risk is identified for both children and adults. Additionally, it is predicted that Cr (chromium) in both pathways during both seasons, and As (arsenic) via water ingestion during the rainy season, could cause carcinogenic health risks for local residents at the station located in the lower section of the stream.

Result

The effects of water pollution on health are numerous and varied. Heavy metals, one of the elements causing water pollution, are considered systemic toxic substances that, in addition to teratogenic and carcinogenic effects, can lead to damage in multiple organs. Heavy metals in water can cause significant harm to the ecological environment and, consequently, to human health due to their toxicity, poor biodegradability, and bioaccumulation characteristics. As mentioned above, exposure to polluted water can lead to acute or chronic health effects depending on the specific pollutants, the duration, and the level of exposure. Prolonged exposure to heavy metals can result in organ damage, developmental issues, reproductive problems, and an increased risk of cancer. In this context, studies on the effects of polluted surface water and/or groundwater masses on human health have emerged as an active area of research in recent years.

Regular monitoring of water sources and food for heavy metals, along with the implementation of mitigation measures, is crucial to prevent adverse health outcomes in the human population. Innovative remediation strategies such as phytoremediation, bioremediation, nanoremediation, electrokinetic remediation, and advanced oxidation processes play a significant role in reducing the toxicity levels of environmental pollutants. These technologies provide sustainable, cost-effective, and efficient solutions to clean contaminated sites, restore ecosystem health, and protect human health.

In most studies conducted on inland waters in Turkey, non-carcinogenic and carcinogenic health risks have been found to be at threatening levels due to anthropogenic pressure, with children's health being at much higher risk compared to adults. In this context, the application of innovative remediation approaches to Turkey's inland water ecosystems could lead to a healthier and more sustainable environment for future generations.

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