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PROF. DR. KORAY ÖZRENK

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Chapter 1

THE ROLE OF THE GENDARMERIE IN COMBATING FOREST FIRES OF TÜRKIYE

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Introduction

Forests are among the most vital ecosystems on Earth, providing essential ecological, economic, and social benefits. They act as carbon sinks, regulate water cycles, support biodiversity, and serve as a source of livelihood for millions of people. However, forest fires pose a significant threat to these ecosystems, leading to devastating environmental and socio-economic consequences (Türkeş, 2021). In Türkiye, a country characterized by its Mediterranean climate, the risk of forest fires is particularly high, with approximately 60% of forested areas located in fire-prone regions (OGM, 2019).

Türkiye's diverse landscapes, ranging from Mediterranean forests to arid steppe regions, are highly susceptible to forest fires. Recent decades have witnessed a rise in the frequency, scale, and intensity of these fires, driven largely by climate change, urban encroachment, and socio-economic dynamics. Addressing this growing crisis requires a multidisciplinary approach that integrates forest ecology, climate science, and governance frameworks. Among Türkiye's key actors, the Gendarmerie occupies a pivotal position in coordinating forest fire response, enforcing regulations, and supporting disaster management. This chapter critically examines the Gendarmerie's role, drawing on scientific studies to contextualize their contributions within Türkiye's broader forest fire management systems.

One of the key institutions involved in combating forest fires in Türkiye is the Jandarma Genel Komutanlığı (JGK). The gendarmerie, which functions as a paramilitary law enforcement agency, has a significant role in fire prevention, rapid response, law enforcement, and post-fire recovery efforts. However, despite its importance, the effectiveness of the gendarmerie in forest fire management has been underexplored in academic literature. This chapter seeks to fill that gap by providing a comprehensive analysis of the gendarmerie's role in combating forest fires, drawing on empirical data collected from personnel operating in high-risk regions.

Literature Review

Forest fires can be classified into different types based on their spread and impact:

Surface Fires: These are the most common, burning grass, shrubs, and fallen leaves, often causing limited damage if contained early (Bilgili, 2024). Surface fires, also known as low-intensity fires, are the most common type of forest fire. These fires burn the forest floor, consuming litter, grass, herbs, low shrubs, fallen branches, and other ground-level biomass (Pyne et al., 1996). Typically, surface fires do not reach the canopy, although under specific environmental conditions—such as high wind speeds or sloped terrain—they can contribute to vertical fire propagation.

Surface fires play a crucial role in the maintenance of fire-adapted ecosystems. They can enhance biodiversity, reduce fuel loads, and limit the likelihood of more severe fire events (Bond and Keeley, 2005). In pine-dominated ecosystems (e.g., Pinus palustris), frequent surface fires are essential for regeneration and maintaining open-canopy structures (Mitchell et al., 2009).

According to Rothermel's fire spread model (1972), surface fire behavior is influenced primarily by fuel load, fuel moisture, wind speed, and slope. Fireline intensity, rate of spread, and flame length are key variables used to characterize surface fire dynamics.

Crown Fires: These fires spread through tree canopies and are particularly destructive, leading to complete forest stand loss (Çanakçıoğlu, 1993). Crown fires, or canopy fires, occur when flames move into the upper strata of the forest—the canopy layer—and propagate through the foliage and branches of trees. These are high-intensity fires, often resulting in complete stand replacement and significant ecological disturbance (Van Wagner, 1977).

Crown fires can be further divided into:

Passive crown fires: where individual tree crowns ignite but do not sustain fire spread through the canopy.

Active crown fires: where the fire moves continuously through the canopy.

Independent crown fires: which spread through the canopy without support from the surface fire—though rare and typically short-lived.

The transition from surface to crown fire is contingent upon the vertical fuel continuity, particularly the presence of ladder fuels. Canopy bulk density and foliar moisture content are crucial thresholds, as described in Van Wagner's (1977) crown fire initiation model. When the heat flux from the surface fire exceeds the ignition threshold of the canopy fuels, crowning is initiated.

Crown fires result in significant mortality of overstory vegetation, alteration of microclimates, and profound shifts in species composition and successional trajectories (Turner et al., 1994). In some boreal and subalpine forests, however, crown fires are part of a natural fire regime and play a role in stand rejuvenation.

Ground Fires: These fires burn organic matter beneath the forest floor, smoldering for long periods and being difficult to detect (Kılıç, 2012). Ground fires are the least visible but often the most destructive type of wildfire. These fires burn organic matter beneath the surface layer, including peat, duff, and humus, often with smoldering combustion (Rein, 2013). Unlike surface fires, ground fires are sustained by below-ground biomass, which can smolder for extended periods—even months.

Ground fires are typified by low temperatures and slow spread, yet they can be extremely persistent and difficult to suppress, especially in peatland ecosystems. They often occur during prolonged droughts, when subsurface organic layers become dry enough to ignite.

One of the most significant concerns associated with ground fires is their carbon emissions. Peat fires, in particular, release large quantities of CO_2, CH_4, and particulate matter, contributing disproportionately to global greenhouse gas emissions (Page et al., 2002). These fires also have severe ecological impacts, including long-term soil degradation, hydrological disruption, and loss of biodiversity.

Regions such as Indonesia, Russia, and Canada are frequently affected by ground fires due to extensive peatlands. The 1997–1998 Southeast Asian fires are a notable example, where ground fires released an estimated 0.81–2.57 Gt of carbon, impacting regional air quality and public health (Page et al., 2002).

The primary causes of forest fires in Türkiye include:

Human Activities: Negligence (campfires, discarded cigarette butts), land clearing, arson, and energy infrastructure failures are among the leading causes (Turan, 2019; OGM, 2022). It is estimated that approximately 90 per cent of forest fires in Türkiye are of anthropogenic origin. The underlying cause of nearly half (48 per cent) of human-caused forest fires remains unknown (OGM, 2022).

Human-induced ignitions represent the leading cause of forest fires in Türkiye, accounting for over 90% of fire incidents, according to data from the General Directorate of Forestry (OGM, 2022). These fires result from both intentional and unintentional activities, including:

- Agricultural burning (e.g., stubble burning, land clearing)
- Recreational negligence (e.g., unattended campfires, discarded cigarettes)
- Infrastructure development (e.g., power lines, machinery sparks)

- Arson and land speculation

Research by Kuter et al. (2022) highlights that fire occurrence in southwestern Türkiye is spatially correlated with population density, road networks, and tourism activity. Moreover, urban expansion into wildland areas (the wildland-urban interface, or WUI) has increased both ignition risk and fire suppression complexity.

Unregulated land use, limited public awareness, and deficiencies in enforcement of fire safety regulations contribute to the frequency of human-caused fires. Additionally, in some rural regions, fire is still used as a traditional land management tool, often without adequate safety measures.

Anthropogenic pressure, combined with weak land-use planning and enforcement, amplifies the vulnerability of Turkish forests to ignition and degradation (Kuter et al., 2022).

Natural Factors: Lightning strikes account for a smaller percentage of fires but can lead to uncontrollable wildfires, particularly during dry seasons (Gorriz-Mifsud et al., 2019). In contrast to anthropogenic causes, naturally ignited wildfires are rare in Türkiye but can occur under specific meteorological and ecological conditions. Lightning strikes, particularly in mountainous areas of the Eastern Black Sea and Taurus Mountains, have been documented as ignition sources, albeit infrequently (Çanakçıoğlu, 1993).

Natural topographical variables such as elevation, slope, and aspect also modulate fire behavior and frequency. Steep slopes accelerate fire spread due to preheating of upslope fuels, while south-facing aspects (in the Northern Hemisphere) are more fire-prone due to increased solar radiation and desiccation of fuels (Bilgili and Sağlam, 2003).

The accumulation of fine fuels, such as pine needles and dry leaf litter, particularly in Pinus brutia (Turkish red pine) forests, enhances flammability. These forests—common in the Aegean and Mediterranean regions—are highly adapted to fire and possess volatile resins that exacerbate fire intensity (Uzun et al., 2015).

Climate Change: Rising temperatures and prolonged droughts have exacerbated fire risks, increasing both frequency and intensity (Özden et al., 2012). Climate change acts as a fire regime modifier, altering both the frequency and severity of forest fires. In recent decades, Türkiye has experienced increasing temperatures, decreasing precipitation, and more frequent drought events, particularly in its southern and western regions.

A study by Turco et al. (2018) demonstrates a statistically significant increase in fire-prone weather conditions across the Mediterranean basin, including Türkiye, linked to anthropogenic climate forcing. Key climate-induced fire risk factors include:

- Increased evapotranspiration leading to fuel desiccation
- Extended fire seasons (now starting earlier and ending later)
- Extreme fire weather events marked by low relative humidity and high wind speeds

Climate-induced aridity is exacerbating fuel dryness and making ecosystems more fire-conducive, even in historically less fire-prone regions of Türkiye (Lestienne et al., 2022).

The catastrophic fires of summer 2021 in southwestern Türkiye provide a salient example of the climate-fire nexus. These fires, affecting provinces such as Antalya, Muğla, and Aydın, were fueled by a confluence of record-breaking heatwaves, prolonged drought, and strong winds, consistent with climate change projections (Karakaş et al., 2022). Over 139,000 hectares of forest were burned, making it the largest fire season in Türkiye's recorded history.

Forest fire management is a complex field involving prevention, detection, suppression, and post-disaster recovery. González et al. (2020) emphasize the integration of remote sensing technologies, while studies by Bowman et al. (2013) underline the ecological consequences of fire suppression. Türkiye-specific research, such as that by Küçük and Bilgili (2007), evaluates fire behavior under Mediterranean conditions, highlighting the interplay of topography, vegetation, and climatic variables.

Forest fire management in Türkiye involves multiple institutions:

- **General Directorate of Forestry (OGM)**: The primary agency responsible for fire prevention, firefighting, and post-fire rehabilitation.
- **Jandarma Genel Komutanlığı (JGK)**: Plays a crucial role in security, surveillance, law enforcement, and public safety in fire-prone regions.
- **Local Fire Departments**: Provide immediate fire suppression services.
- **AFAD (Disaster and Emergency Management Authority)**: Assists in large-scale fire incidents and disaster response coordination.

Effective forest fire management requires seamless inter-agency coordination, yet challenges such as bureaucratic inefficiencies and resource limitations persist (Çelik et al., 2024).

From a governance perspective, Boin et al. (2016) propose frameworks for disaster management that emphasize coordination among multiple stakeholders, including military and law enforcement agencies. Aydin et al. (2022) explore the legal frameworks governing forest protection in Türkiye, identifying gaps in enforcement mechanisms. Studies on law enforcement's role in environmental management (e.g., Dwyer, 2019) highlight the importance of interdisciplinary training and community engagement, offering valuable insights into the operational context of the Gendarmerie.

Forest Fires in Türkiye

Türkiye's geographic and climatic diversity renders it susceptible to a range of natural hazards, among which forest fires have emerged as increasingly destructive phenomena, particularly in the 21st century. The Mediterranean, Aegean, and Marmara regions, characterized by hot, dry summers and dense forest cover, are particularly vulnerable. Historically perceived as localized disasters, forest fires in Türkiye now exhibit patterns indicative of broader environmental transformations, necessitating a multidisciplinary analytical approach.

Forest ecosystems in Türkiye are predominantly located in fire-prone regions, such as the Mediterranean Basin, which accounts for approximately 60% of the country's forested area. Research by Ürgenç et al. (1992) categorizes fire causes into natural (lightning) and anthropogenic (agricultural burns, illegal logging) factors, with the latter contributing to over 90% of incidents. Studies such as that by Bilgili et al. (2011) provide detailed fire modeling, offering predictive tools essential for preemptive measures.

The ecological impact of forest fires extends beyond immediate biomass loss to long-term soil degradation, altered hydrological cycles, and biodiversity decline. For instance, Yıldırım et al. (2021) quantify post-fire soil erosion rates in southwestern Türkiye, illustrating the broader environmental ramifications. Addressing these challenges necessitates not only technical solutions but also robust institutional frameworks.

Forest fires in Türkiye are not a novel phenomenon; Ottoman archival records indicate frequent wildfire events, particularly in the coastal provinces. However, the frequency, intensity, and spatial distribution of fires have markedly increased over recent decades. According to General Directorate of Forestry (OGM) data, between 1990 and 2020, Türkiye experienced an average of 2,000–2,500 forest fires annually, affecting approximately 10,000–15,000 hectares of forestland each year (OGM, 2022).

Climatological analyses attribute much of this escalation to rising temperatures, prolonged drought periods, and extreme weather events—consistent with broader global patterns of climate change. In particular, the anomalously severe fire season of 2021, during which approximately 140,000 hectares were burned, has been linked to unprecedented heatwaves and low humidity levels.

Gendarmerie in Türkiye

The Gendarmerie has historically been one of Türkiye's primary internal security actors. Throughout its development from the Ottoman Empire to the modern Republic, the Gendarmerie has assumed different roles, functioning both as a military entity and a civil law enforcement body in response to evolving societal needs.

The Gendarmerie's roots date back to 1839, during the Tanzimat reforms of the Ottoman Empire, when rural security units were formalized. Under Sultan Mahmud II, significant reforms replaced the timariot cavalry system with organized police units known as zaptiye (Sönmez, 2006). In 1845, the establishment of the Zaptiye Müşiriyeti centralized the administration of public security under a single authority, aiming to resolve the fragmented security structure of the provinces (Sönmez, 2006). By 1879, inspired by the French model, the term "gendarmerie" replaced "zaptiye," indicating a move towards a more professionalized policing force (Sönmez, 2006). The modern Gendarmerie, established in 1923, has evolved to meet the demands of a rapidly urbanizing society. Historical analyses, such as that by Çolak (2017), trace the Gendarmerie's transformation from a traditional rural police force to a multi-dimensional organization capable of addressing complex challenges, including environmental disasters.

The Gendarmerie General Command is a unique hybrid of military and civilian law enforcement, tasked with rural security across approximately 92% of Türkiye's land area. Its dual structure enables it to address a wide range of issues, from criminal investigations to disaster response. Scholars such as Demirci and Yıldız (2018) argue that the Gendarmerie's extensive rural presence and hierarchical organization make it a critical actor in managing emergencies, including forest fires.

Role of Gendarmerie in Disasters

The Gendarmerie's disaster management capabilities are well-documented, particularly in responding to earthquakes, floods, and forest fires. Studies by Kaya et al. (2020) highlight the Gendarmerie's contributions to search and rescue operations, logistical support, and public safety enforcement during emergencies.

The gendarmerie's involvement in forest fire management extends beyond traditional law enforcement. The key responsibilities of Gendarmerie can be summarized below:

1. Fire Prevention

o Conducting regular patrols in high-risk areas.

o Implementing public awareness campaigns to educate communities on fire hazards.

o Monitoring illegal land use and enforcing forestry regulations (Uygun et al., 2023).

2. Emergency Response

o Assisting in evacuations and securing affected areas.

o Supporting firefighting teams by providing logistical and security assistance.

o Coordinating rescue operations in case of civilian casualties (OGM, 2022).

3. Post-Fire Law Enforcement

o Investigating the causes of fires and identifying perpetrators.

o Prosecuting arsonists and negligent offenders.

o Assisting in rehabilitation efforts to prevent future occurrences (Bilgili, 2020).

Discussion and Evaluation

The Gendarmerie's effectiveness in combating forest fires can be assessed through several dimensions:

- **Operational Strengths:** Their rural presence ensures rapid deployment to remote areas, while their hierarchical structure facilitates efficient decision-making.

- **Challenges:** Limited access to specialized firefighting training and equipment, as well as insufficient inter-agency coordination, remain significant barriers. Studies by Özkaya et al. (2023) identify communication gaps between the Gendarmerie and forestry officials, leading to delays in response times.

- **Comparative Perspectives:** Analyzing international examples, such as the role of the California National Guard in wildfire management, can offer valuable lessons for enhancing the Gendarmerie's capabilities.

Conclusion and Recommendations

Forest fires in Türkiye represent a complex interplay of natural, anthropogenic, and systemic factors, amplified by the exigencies of climate change. A paradigm shift from reactive to proactive management, emphasizing resilience-building, community involvement, and ecosystem-based approaches, is imperative. Future research should prioritize longitudinal studies to monitor ecological recovery and evaluate policy efficacy, ensuring that Türkiye's rich forest ecosystems are preserved for future generations.

The Gendarmerie plays a vital role in Türkiye's forest fire management system, leveraging its extensive rural presence and operational capacity. However, maximizing its impact requires addressing several critical areas:

- **Training and Capacity Building:** Incorporate advanced firefighting techniques and environmental science into Gendarmerie training programs.

- **Technology Integration:** Expand the use of drones, GIS-based mapping, and remote sensing tools for fire detection and monitoring.

- **Policy Harmonization:** Strengthen legislative frameworks to facilitate seamless coordination between the Gendarmerie and other stakeholders.

- **Community Engagement:** Develop participatory approaches that involve local populations in fire prevention and awareness campaigns.

- **International Collaboration:** Establish partnerships with global agencies to share knowledge, technology, and best practices.

By adopting these strategies, the Gendarmerie can significantly enhance its contributions to forest fire management, aligning its efforts with Türkiye's broader environmental and disaster resilience goals.

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Chapter 2

CARBON-NEGATIVE AGRICULTURE: THEORETICAL FRAMEWORK AND PRACTICAL APPLICATIONS FOR CLIMATE MITIGATION

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1. Introduction

Carbon-negative agriculture represents a promising solution to address climate change by reducing greenhouse gas emissions while actively capturing atmospheric carbon. Traditional agricultural practices contribute significantly to climate change through deforestation, excessive fertilizer use, and soil degradation, leading to the release of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). However, innovative approaches such as biochar incorporation, soil carbon sequestration, agroforestry, and bioenergy with carbon capture and storage (BECCS) are gaining traction as viable strategies for achieving carbon negativity in agriculture (Fawzy et al., 2020; Jeswani et al., 2022).

Theoretical models of carbon-negative agriculture emphasize the integration of multiple negative emissions technologies within farming systems. Biochar application enhances soil fertility while stabilizing carbon for centuries (Jeswani et al., 2022). Conservation agriculture, no-till farming, and cover cropping improve soil organic carbon storage, contributing to sustainable land management (Northrup et al., 2021). Agroforestry integrates trees into agricultural landscapes, enhancing biomass carbon storage and biodiversity (Gaboury et al., 2009). BECCS combines bioenergy production with carbon capture and storage, preventing CO_2 from re-entering the atmosphere (Full et al., 2021). Additionally, enhanced weathering involves the application of silicate minerals to agricultural soils, accelerating CO_2 absorption and long-term sequestration (Beerling et al., 2018).

Several studies highlight the effectiveness of these approaches in mitigating climate change. Research indicates that biochar application can sequester significant amounts of CO_2, while BECCS has the potential to reduce millions of tons of carbon emissions annually (Budzianowski, 2012). Conservation practices such as diversified cropping systems and rotational grazing further contribute to carbon sequestration by improving soil health and increasing carbon retention (Thamarai et al., 2024). Precision farming technologies optimize input use, reducing emissions while maintaining high productivity (Balasundram et al., 2023). Emerging soil carbon credit programs also offer financial incentives for farmers adopting carbon-negative practices, promoting widespread adoption (Yang et al., 2021).

Given the increasing urgency to address climate change, this study explores the effectiveness of carbon-negative agricultural practices across different agroecosystems. It examines the environmental and economic feasibility of these methods compared to conventional farming (Fawzy et al., 2020). Additionally, it evaluates the role of policy frameworks and incentives in supporting large-scale implementation (Lumactud et al., 2022). The hypothesis underlying this research is that integrating multiple carbon-negative practices in agricultural systems can achieve net-negative emissions while ensuring food security and enhancing soil health (Smith et al., 2019). Economic viability remains a critical factor in determining the success and scalability of these practices (Goglio et al., 2020).

Practical applications of carbon-negative agriculture are already being implemented in various regions. Farmers are adopting regenerative practices such as rotational grazing, organic amendments, and agroforestry to enhance carbon sequestration and improve ecosystem resilience (McLaren, 2012). Governments and private institutions are investing in research and development to refine these strategies and create scalable solutions (Churkina et al., 2020). Future research should focus on refining economic models for carbon-negative agriculture, assessing long-term soil carbon dynamics, and developing policy interventions that support its large-scale adoption (Fuss et al., 2018).

As climate change mitigation becomes an increasingly urgent global priority, agriculture must play a central role in achieving carbon negativity. By integrating science-based solutions with policy incentives and sustainable practices, it is possible to transform agricultural landscapes into carbon sinks while ensuring food security for future generations (The Royal Society, 2018). The transition to carbon-negative agriculture is not only an environmental necessity but also an opportunity to create resilient and sustainable food systems worldwide (IPCC, 2020).

Expanding the adoption of carbon-negative agricultural methods requires strong policy support, financial incentives, and scientific innovation (Petersen et al., 2013). Governments must prioritize sustainable land management strategies, while research institutions should continue exploring ways to improve carbon sequestration efficiency in various agricultural settings (FAO, 2016). Additionally, international cooperation is essential to ensure widespread adoption of these techniques, particularly in regions that are most vulnerable to climate change impacts (Tisserant & Cherubini, 2019). By addressing these challenges and opportunities, carbon-negative agriculture can become a cornerstone of global climate action, ensuring a sustainable and resilient future for both the environment and human societies (Terlouw et al., 2021).

2. Theoretical Framework and Literature Review

Carbon-negative agriculture is emerging as a critical component in climate change mitigation, integrating agricultural practices with negative emissions technologies (NET). The theoretical foundation of carbon-negative agriculture is rooted in the dual approach of reducing greenhouse gas (GHG) emissions and actively sequestering atmospheric carbon through biological and technological interventions (Fawzy et al., 2020). The conceptual framework encompasses multiple disciplines, including agroecology, soil science, and carbon cycle modeling, emphasizing the role of sustainable land management practices, innovative carbon sequestration technologies, and policy-driven incentives.

The primary theoretical constructs include negative emissions technologies (NET), which involve bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), soil carbon sequestration, and biochar application (Jeswani et al., 2022). Carbon cycle dynamics integrate agricultural systems with carbon capture and utilization mechanisms, enhancing the efficiency of carbon storage within terrestrial ecosystems (Budzianowski, 2012). Sustainable intensification and regenerative agriculture focus on improving productivity while reducing environmental footprints through conservation tillage, cover cropping, and precision farming (Northrup et al., 2021)

The role of agriculture in climate change mitigation has been extensively studied, with increasing emphasis on negative emissions technologies (Figure 1). The application of biochar and soil carbon sequestration techniques has demonstrated significant potential in offsetting agricultural emissions. Biochar, derived from pyrolyzed biomass, enhances soil fertility while acting as a stable carbon sink (Cao et al., 2022). Studies indicate that integrating biochar with microbial fuel cells can further optimize energy efficiency while reducing carbon emissions.

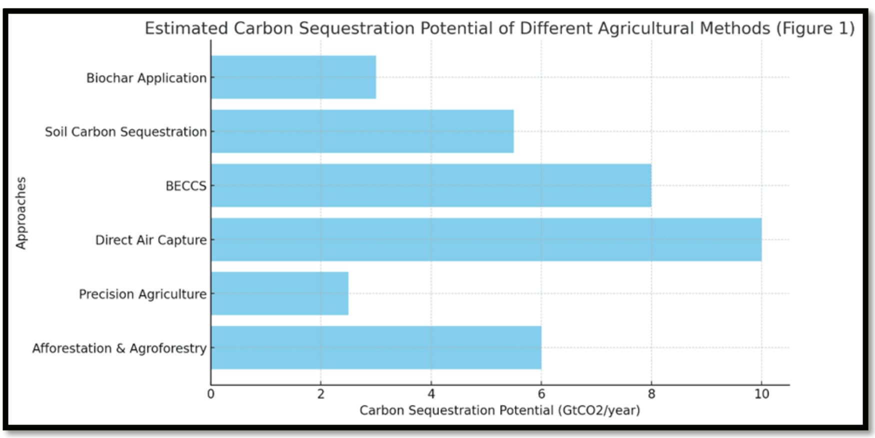
Moreover, BECCS is identified as a high-impact approach within carbon-negative agriculture. By leveraging biomass as an energy source while capturing and storing the resultant CO_2, BECCS effectively contributes to net-negative emissions. A comparative analysis by Full et al. (2021) highlights the efficiency of BECCS in reducing emissions from energy-intensive agricultural processes.

Soil carbon sequestration is one of the most effective nature-based solutions for climate mitigation. Enhanced soil organic matter through conservation agriculture improves soil structure, increases microbial diversity, and fosters carbon retention (Northrup et al., 2021). Several studies emphasize the synergistic role of cover cropping and reduced tillage in enhancing carbon sequestration potential. Additionally, afforestation and agroforestry practices contribute to carbon storage by integrating perennial vegetation within agricultural landscapes (Villa & Bernal, 2018). However, policy frameworks and economic incentives are essential to facilitate large-scale adoption of these practices.

Recent advancements in precision agriculture, genetic modifications for carbon-efficient crops, and digital monitoring systems have further refined the implementation of carbon-negative farming. Emerging technologies such as microbial-assisted carbon sequestration and carbon-negative hydrogen production from biomass illustrate the diverse avenues through which agricultural systems can transition towards climate-positive outcomes (Thamarai et al., 2024). Furthermore, DACCS is gaining traction as a complementary technology in agricultural landscapes. The direct capture of atmospheric CO_2 through engineered systems provides a scalable solution to offset residual emissions from agricultural activities (Gasser et al., 2015). However, concerns regarding energy requirements and economic feasibility remain critical barriers to widespread deployment.

The literature underscores the transformative potential of carbon-negative agriculture in addressing climate change. While significant progress has been made in the development and implementation of negative emissions technologies, challenges such as economic viability, land-use competition, and technological scalability persist. Future research should focus on optimizing integrated approaches, improving policy frameworks, and enhancing financial mechanisms to support large-scale adoption. A holistic strategy that combines technological innovations with sustainable agricultural practices is imperative to achieve long-term climate resilience and food security.

Figure 1. Estimated Carbon Sequestration Potential of Different Agricultural Methods (Jeswani et al., 2022; Fawzy et al., 2020; Northrup et al., 2021; Cao et al., 2022)



This figure illustrates the estimated carbon sequestration potential of various agricultural methods discussed in the text, highlighting their role in mitigating climate change.

3. Carbon-Negative Farming Practices: Principles and Methods

Carbon-negative farming encompasses a suite of agricultural strategies designed to remove more carbon dioxide (CO_2) from the atmosphere than is emitted during production. This approach integrates biochar application, soil carbon sequestration, conservation tillage, crop and microbial genetic innovations, and emerging carbon capture technologies into existing food systems to mitigate climate change while improving soil health and productivity.

One of the most promising carbon-negative techniques is the application of biochar—a stable, carbon-rich material derived from the pyrolysis of organic waste. Biochar not only enhances soil fertility and water retention but also provides long-term carbon storage, with residence times in soil spanning hundreds to thousands of years (Ayaz et al., 2025). Its effectiveness depends significantly on the feedstock used and the conditions of pyrolysis. Moreover, it supports microbial activity and nutrient cycling, contributing to ecosystem resilience (Ayaz et al., 2025).

Soil carbon sequestration, another central pillar of carbon-negative agriculture, involves adopting best management practices (BMP) that increase soil organic matter. These include cover cropping, reduced tillage, agroforestry, and organic amendments. Such practices not only sequester carbon but also enhance soil fertility and structure. According to Paustian et al. (2019), global implementation of best management practices on croplands and grasslands could sequester 4–5 GtCO annually, potentially rising to 8 GtCO with future innovations.

Innovative technologies further amplify these impacts. For instance, conservation agriculture combined with digital farming tools, precision inputs, and electrified machinery could reduce row crop emissions by up to 71%, while maintaining high yields (Northrup et al., 2021). These strategies help transition agricultural systems towards net-negative emissions through a combination of emission reductions and enhanced carbon sinks.

Microbial fuel cells (MFC) using agricultural waste-derived biochar are an emerging technology that aligns with the principles of the circular economy. These systems not only generate renewable energy during wastewater treatment but also utilize biochar as a sustainable electrode material, contributing to both energy efficiency and carbon removal (Cao et al., 2022).

However, the scalability and environmental trade-offs of carbon-negative technologies must be carefully assessed. As Jeswani et al. (2022) note, large-scale deployment of NET including biochar and soil carbon sequestration must consider land, water, and energy inputs to avoid unintended ecological consequences. Life cycle assessments (LCA) remain crucial in evaluating the overall sustainability of these interventions.

In summary, carbon-negative farming relies on integrative practices and technologies that enhance carbon sequestration while supporting agricultural productivity. As climate goals become more urgent, these solutions offer pathways for the agricultural sector to contribute actively to global carbon neutrality and beyond.

4. Measuring and Assessing Carbon-Negative Impacts

The accurate measurement and assessment of carbon-negative impacts are crucial for validating the effectiveness of climate mitigation strategies in agriculture. Reliable metrics not only inform policy and funding mechanisms but also ensure accountability and continuous improvement in land management practices. This section explores key methodologies and tools for evaluating carbon-negative interventions, focusing on biochar, soil carbon sequestration, and emerging bioelectrochemical systems.

Soil carbon sequestration, one of the most extensively studied biological negative emission strategies, requires robust measurement, reporting, and verification (MRV) frameworks to track carbon stock changes over time. According to Paustian et al. (2019), soil organic carbon (SOC) assessments involve a combination of field sampling, laboratory analysis, and modeling approaches. Standardized protocols such as remote sensing, eddy covariance towers, and long-term field trials support accurate carbon accounting. Yet, spatial heterogeneity and time lags in sequestration benefits present ongoing challenges.

Biochar amendments, due to their long-term stability in soils, offer a quantifiable method of carbon removal. Ayaz et al. (2025) emphasize the role of life cycle assessment (LCA) in determining the net carbon footprint of biochar systems. This includes emissions from feedstock sourcing, pyrolysis conditions, application logistics, and co-benefits such as improved crop yields or reduced fertilizer use. LCAs have shown that biochar can achieve net carbon removals ranging from hundreds to over 3000 kg CO-eq / ton, depending on system boundaries and assumptions (Jeswani et al., 2022).

Advanced technologies like microbial fuel cells (MFCs) using agricultural waste-derived biochar contribute to circular economy models while enabling energy and carbon flux monitoring. Cao et al. (2022) illustrate how integrating biochar into MFC systems enables simultaneous wastewater treatment, energy production, and carbon capture. Electrochemical performance indicators such as Coulombic efficiency and power density serve as indirect proxies for carbon utilization efficiency.

In the context of row-crop production, Northrup et al. (2021) propose a combined assessment approach that integrates emissions reduction metrics with soil health indicators. By coupling digital agriculture tools, greenhouse gas (GHG) modeling, and in-field sensor networks, these systems can evaluate both avoided emissions and enhanced carbon storage.

However, methodological limitations persist. The complexity of carbon cycling, delayed climate benefits, and variability in environmental conditions require dynamic, site-specific assessments rather than static carbon accounting models. As Jeswani et al. (2022) point out, LCAs must address indirect effects, such as changes in land use, albedo, and biodiversity, to provide a more holistic sustainability evaluation.

In conclusion, measuring carbon-negative impacts demands interdisciplinary tools combining environmental science, engineering, and data analytics. The credibility and scalability of carbon-negative farming depend on transparent, science-based assessment frameworks that align with global climate and sustainability goals.

5. Policy and Market Incentives for Carbon-Negative Farming

The successful adoption and scaling of carbon-negative farming practices rely not only on technological viability but also on supportive policy frameworks and functioning carbon markets. Incentivesboth regulatory and market-based are essential to motivate farmers, investors, and other stakeholders to transition towards practices that remove more CO_2 than they emit.

Public policy instruments play a pivotal role in enabling carbon-negative agriculture. Governments can implement subsidies, tax credits, and direct payments for verified carbon sequestration efforts, such as biochar application or soil carbon enhancement (Paustian et al., 2019). These incentives reduce the financial burden of adopting new technologies and compensate for delayed climate benefits. Additionally, agro-environmental schemes and sustainable land management programs can integrate carbon farming goals into broader climate and rural development agendas.

A key mechanism for scaling these practices is the development of voluntary and compliance carbon markets. Verified carbon-negative actions, such as long-term soil organic carbon storage or the use of biochar, can generate carbon credits that are sold to buyers seeking to offset emissions. Jeswani et al. (2022) emphasize the importance of robust measurement, reporting, and verification (MRV) systems to ensure transparency and credibility in such markets. However, challenges remain regarding permanence, leakage, and additionality, which must be addressed in regulatory design.

Emerging technologies like biochar-based microbial fuel cells (MFC) and biohydrogen systems offer additional opportunities for integrated climate and energy policies. These systems not only sequester carbon but also contribute to renewable energy production, making them attractive for multi-benefit funding schemes such as green bonds and sustainable development grants (Cao et al., 2022).

In the private sector, ecosystem service markets and corporate carbon neutrality goals have opened new funding streams. For instance, agricultural companies and food retailers are increasingly investing in carbon farming as part of their environmental, social, and governance (ESG) strategies (Northrup et al., 2021). These market-based incentives can create demand for low-carbon or carbon-negative products, such as "climate-smart grains" or "carbon-neutral fertilizers."

Still, long-term scalability requires institutional alignment across sectors. Policies must be designed to support farmers with education, technical assistance, and access to carbon marketplaces. At the same time, international climate agreements and national-level commitments such as Nationally Determined Contributions (NDC) should explicitly recognize carbon-negative farming as a climate mitigation pathway (Ayaz et al., 2025).

In conclusion, a robust blend of public policies, private investments, and transparent carbon markets is essential to unlock the full potential of carbon-negative farming. These incentives not only help decarbonize agriculture but also support broader goals of sustainability, rural livelihoods, and climate resilience.

6 Case Studies and Empirical Evidence

The practical implementation of carbon-negative farming practices is supported by a growing body of empirical research and real-world case studies. These studies reveal not only the technical potential of such practices but also the environmental co-benefits, implementation challenges, and contextual variability across regions.

One widely cited case is the application of biochar in microbial fuel cells (MFC), which exemplifies the intersection of waste valorization, renewable energy production, and carbon removal. Field trials have demonstrated that biochar derived from agricultural residues can be used as a cost-effective electrode material in microbial fuel cells, enhancing both power generation and wastewater treatment efficiency (Cao et al., 2022). For instance, experiments with rice plant microbial fuel cells showed simultaneous increases in bioelectricity output and reductions in methane emissions, confirming the dual benefit of energy recovery and GHG mitigation.

Soil carbon sequestration (SCS) remains a cornerstone strategy in carbon-negative farming, with extensive empirical backing. A meta-analysis by Poeplau and Don (2015) demonstrated that the cultivation of cover crops in Europe resulted in an average increase of 0.32 t C/ha/year. Complementary studies across the United States, Spain, Japan, and Bangladesh support the efficacy of conservation tillage, organic amendments, and crop diversification in increasing soil organic carbon stocks over both 20- and 100-year horizons.

A study by Ryals and Silver (2013) in California's Mediterranean grasslands found that the application of composted organic matter increased net primary productivity by 20–40% while reducing net GHG emissions by up to 0.6 t CO_2 e/ha/year. These findings underscore the climate-smart potential of integrating waste-based soil amendments with regenerative grazing systems.

In terms of perennial cropping systems, research by Agostini et al. (2015) highlighted increases in soil organic carbon levels between 0.63–1.88 t C/ha/year, far exceeding the 0.25 t C/ha/year threshold needed for carbon neutrality in biofuel systems. This suggests that transitioning from annual to perennial systems could be a significant lever for climate mitigation.

However, not all evidence is unequivocally positive. Some studies report potential trade-offs, including the risk of soil carbon saturation, reversibility of stored carbon, and increased N_2O emissions under certain management conditions (Fuss et al., 2018). Moreover, spatial variability in soil type, climate, and cropping system significantly influence outcomes, necessitating site-specific adaptation and monitoring protocols.

Overall, the empirical literature provides robust support for carbon-negative farming approaches, but it also emphasizes the need for long-term monitoring and policy alignment to ensure durability and scalability of benefits.

7. Conclusion and Future Prospects

Carbon-negative farming represents a transformative opportunity for aligning food production systems with global climate mitigation goals. Through a combination of soil carbon sequestration, biochar application, conservation agriculture, and bioenergy-integrated technologies, it is possible to design agricultural systems that not only feed the planet but also remove carbon from the atmosphere (Paustian et al., 2019; Ayaz et al., 2025). Empirical studies and pilot implementations across diverse agro-ecological zones have demonstrated the technical and ecological viability of these approaches (Ryals & Silver, 2013; Poeplau & Don, 2015).

Yet, realizing the full potential of carbon-negative agriculture depends on several interlinked factors. First, robust monitoring and verification systems are needed to ensure that reported carbon removals are real, additional, and permanent (Jeswani et al., 2022). Advances in remote sensing, soil sensors, and machine learning offer new frontiers for scalable, cost-effective monitoring tools.

Second, policy and market mechanisms must evolve to reward farmers not only for yield but also for their ecosystem services. Carbon credit systems, green subsidies, and regenerative agriculture incentives are critical levers in this transition (Northrup et al., 2021). Furthermore, incorporating carbon-negative strategies into national climate targets (NDCs) and food security plans can enhance policy coherence.

Technological innovation remains central. New applications such as microbial fuel cells using biochar, HyBECCS (Hydrogen Bioenergy with Carbon Capture and Storage), and enhanced weathering techniques promise to expand the carbon-negative toolkit (Cao et al., 2022; Full et al., 2021). However, environmental trade-offs, such as potential nutrient imbalances or land-use conflicts, must be carefully assessed via comprehensive life cycle analyses (Jeswani et al., 2022).

Looking ahead, transdisciplinary collaboration will be key. Scientists, farmers, policymakers, technologists, and communities must co-create adaptive, context-specific solutions that maximize co-benefits. Investments in research, education, and capacity building especially in climate-vulnerable regions will help democratize access to carbon-negative innovations.

In conclusion, while challenges remain, the future of carbon-negative farming is both promising and urgent. With the right mix of innovation, governance, and commitment, agriculture can shift from being a carbon source to becoming a powerful climate solution restoring ecosystems, enhancing resilience, and securing food for generations to come.

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Chapter 3

ENVIRONMENTAL MANAGEMENT OF MARINE FISH FARMING IN TÜRKIYE: CURRENT STATUS AND LEGAL APPROACHES

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Introduction

In the pursuit of healthy and balanced nutrition, aquatic products hold an important place as an indispensable source of nutrients for many human body functions such as heart health, brain functions, and the nervous system. Today, as natural fish stocks in the seas have been exploited to their maximum sustainable level through fishing, and fish catches can no longer meet the increasing demand, aquaculture has gained importance (FAO 2020, Anonymous 2024a).

Aquaculture is regarded as a critical sector for global food security. In response to projections that the world population will exceed 9 billion, the limited availability of current resources and environmental changes driven by anthropogenic factors necessitate that this sector sustainably increase food supply. Research shows that aquatic products not only contain important components for human health—such as long-chain polyunsaturated fatty acids, vitamins, and micronutrients—but also have a lower carbon footprint compared to other forms of animal production (Dikel and Demirkale 2023, Genç et al. 2025).

Global aquaculture, which has significantly expanded over the past 30 years, stands out as one of the fastest-growing sectors in food production and now supplies more than half of the world's seafood demand (Kimbrell and Stevenson 2023). According to the FAO (2024) report, total aquatic production reached a record level of 223.2 million tons in 2022, with 57% of this production coming from aquaculture. This growth once again highlights the strategic importance of the sector in terms of food security and sustainability. FAO (2025) emphasizes that aquaculture activities can collaborate with agriculture and other sectors to improve efficiency and sustainability by using innovative management systems and production practices. This approach will also optimize the sustainable use of resources by addressing the complex interconnections among different resource users.

Aquaculture is described as a unique sector that encompasses all aquatic ecosystems (freshwater, brackish/estuary, and sea) and is closely interconnected with terrestrial ecosystems such as those providing feed sources. It has been stated that the aquaculture sector makes significant contributions to achieving the Sustainable Development Goals (SDGs)/Agenda 2030 (Troell et al. 2023). However, accurate data is necessary to assess and monitor the social, economic, and environmental performance of the aquaculture sector. Transparency and data reporting are also crucial for maintaining the trust of consumers and other stakeholders in the industry. EU environmental legislation has established the regulatory framework for aquaculture. This framework aims to minimize the potential environmental impacts of aquaculture activities and to ensure that such activities do not cause significant harm to ecosystems or biodiversity (Anonymous 2025a, b).

The aim of this review study is to evaluate the current state of fish farming conducted particularly in the seas of Türkiye, as well as the legal regulations concerning the environmental management of this type of aquaculture.

Sustainable Aquaculture and the Environment

Aquaculture production, both globally and in Türkiye, plays a vital role in ensuring food security and providing a sustainable source of protein. Sustainability, environmental awareness, and technological innovation have come to the forefront in aquaculture production at both the global level and in Türkiye. These trends are reported to shape the future of aquaculture by helping the sector become more sustainable, efficient, and environmentally friendly. Türkiye's strategic use of its geographical location and state-supported aquaculture programs position the country as a significant player in the global seafood market (Anonymous 2024b, c).

Sustainable aquaculture requires a holistic and collaborative approach that considers environmental, social, and economic dimensions. To advance aquaculture management, it is important to adopt best management practices, participate in certification programs, invest in innovative technologies, prioritize social responsibility, ensure economic viability, and involve stakeholders in decision-making processes. By implementing these strategies and recommendations, aquaculture operators can contribute to a more sustainable future for the sector while enhancing their environmental performance, social responsibility, and economic sustainability (Rani and Padmaja 2024). Tosun et al. (2024) stated that aquaculture has emerged under the principles of blue growth and sustainability to address global challenges in fish populations, and that sustainable practices need to be integrated into the industry to mitigate the environmental and socio-economic impacts of aquaculture. 'Blue Transformation' is a strategic initiative by FAO that supports sustainable aquaculture production. This strategy aims to protect marine and freshwater ecosystems, ensure food security, promote economic development, and enhance environmental sustainability. Its core objective is to minimize the environmental impacts of aquaculture while safeguarding the livelihoods of coastal communities and contributing to global food security.

Although Türkiye has significant potential in aquaculture production, it faces challenges similar to those encountered globally, such as sustainability, pollution, overfishing, and climate change. It has been reported that in order to ensure future growth of the sector, sustainable fisheries must be strengthened, particularly by preventing illegal fishing and reducing environmental impacts (Anonymous 2023, Çöteli 2024). In other words, as aquaculture production rapidly increases, the quality of the water resources used for farming is becoming increasingly important. In this context, traditional aquaculture practices have been associated with a range of environmental issues that can have far-reaching consequences for aquatic ecosystems. One of the main concerns is the discharge of wastewater from aquaculture operations, which can lead to water pollution through the release of excessive nutrients, organic matter, and chemical contaminants. Pollutants in net cage systems primarily originate from feed and fish feces (White et al. 2017). In areas with insufficient water circulation, high nitrogen and phosphorus emissions from aquaculture production (Olaussen 2018) disrupt the balance of aquatic ecosystems, leading to eutrophication, harmful algal blooms, and a decline in water quality (Mungkung et al. 2015, Gupta et al. 2019). Another major environmental issue associated with traditional aquaculture practices is the depletion of wild fish stocks used as feed in aquaculture operations (White 2021, Rani and Padmaja 2024).

The impacts of fish farming under unsuitable conditions in net cages on receiving environments can include negative changes in water quality, algal blooms, organic enrichment of the receiving sediment, and, more broadly, degradation of the environment due to changes in hydrological patterns, drainage, physical structures, and the uncontrolled use of chemical substances. Studies on the effects of waste from net cage aquaculture on the water column have shown that this type of farming increases nutrient levels and suspended solids in the environment, while decreasing light penetration, dissolved oxygen, electrical conductivity, and pH values (Pulatsü and Topçu 2012). In addition, the use of pharmaceuticals—mainly antibiotics, disinfectants, and antiparasitics for hygienic control—has been reported to affect non-target species and alter local biodiversity, with concerns that these environmental impacts may increase in the future due to climate change (Tello et al. 2010, Bacher 2015, Rodriguez-Luna et al. 2021).

According to Markus (2024), marine aquaculture has made significant progress in recent years, and this progress has been accompanied by increasing competition for suitable farming areas. In response to the growing competition and conflict over marine space, aquaculture activities have moved further offshore. While these developments have limited the available space for aquaculture and, in some cases, posed a barrier to expansion, they have also led to calls for clearer terms and concepts to better define aquaculture zones. According to the researcher, it will be necessary in the future to develop a multidimensional set of assessment criteria for determining the suitability of aquaculture areas.

To prevent pollution caused by fish farming in sea cage systems, it is necessary to protect water quality and ecosystems and to take measures for sustainable production through environmental management. In this context, the Environmental Impact Assessment (EIA) is a decision-making tool aimed at promoting measures for evaluating aquaculture projects and their potential impacts. The Trophic Index (TRIX), which serves as a comprehensive measurement tool for assessing eutrophication in aquatic ecosystems, was originally developed for the Adriatic and Tyrrhenian Seas. However, it is now widely applied in various marine ecosystems such as the Baltic, North, and Mediterranean Seas to evaluate eutrophication trends and environmental health. In a study conducted by Yılmaz et al. (2025), it was revealed that the TRIX values, based on multi-year monitoring in two designated aquaculture regions in the Aegean and Mediterranean Seas, remained below the critical threshold for eutrophication risk, indicating stable environmental conditions. The study's findings emphasize the necessity of continuous TRIX-based monitoring to reduce ecological risks associated with sustainable aquaculture, as is currently being practiced. Verep and Balta (2023), on the other hand, stated that Turkish seas possess different oceanographic characteristics; therefore, using the same criteria for depth, current velocity, and distance from shore when establishing marine cages may not be appropriate.

Marine Aquaculture in Türkiye

Marine fish farming in Türkiye began in the 1980s with the cultivation of seabream (*Sparus aurata*) juveniles collected from the wild in net cages. In particular, seabream juveniles gathered from nature were raised in wooden cages placed in enclosed bays and gulfs around Bodrum, Muğla. This was later followed by the initiation of seabass (*Dicentrarchus labrax*) farming activities. At the beginning of the 2000s, the initiation of farming *Brown meagre*, *Dentex*, *Sharpsnout seabream*, and *Bluefin tuna* in the Aegean and Mediterranean Seas gave a significant boost to aquaculture in Türkiye. In parallel with the rapid development of marine aquaculture techniques, net cage production, and fish feed technology, several legal regulations were introduced. Over the past two decades, land-based ponds operating with high-salinity groundwater near the coast have also been established for marine fish farming. In addition to these, there are farms for tuna fattening and facilities engaged in mussel cultivation (Anonymous 2024b, Doğan and Çanak 2024).

Türkiye holds a significant position in aquaculture within the Mediterranean basin. As of 2022, Turkey's total aquaculture production reached approximately 850,000 tons, according to the FAO (2024) report (Figure 1). A large portion of this production was obtained from species such as seabream (*Sparus aurata*), seabass (*Dicentrarchus labrax*), and trout (*Oncorhynchus mykiss*) (Table 1). In 2023, total aquaculture production reached 1,007,920.60 tons/year, representing a 7.6% increase compared to 2022. Of this, 72.1% (399,529 tons/year) came from marine aquaculture, while 27.9% (154,333 tons) was produced in inland waters. The most important cultivated fish species were trout in inland waters with 156,431 tons, and seabass and seabream in marine waters with 160,802 tons and 154,011 tons respectively. The combined production of Turkish salmon and trout also exceeded 222,000 tons (Table 1).

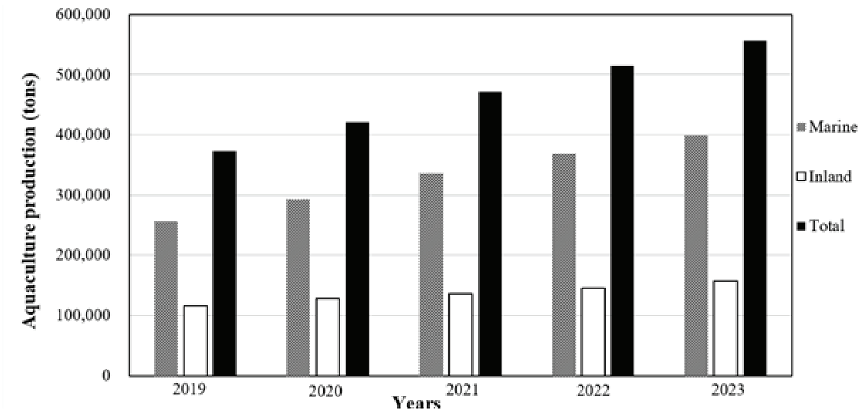

Figure 1. *Aquaculture production in Türkiye (BSGM 2024)*

Table 1. *Aquaculture production by species in Türkiye (TUIK 2024a)*

Species	2019	2020	2021	2022	2023
Seabass	137.419	148.907	155.151	156.602	160.802
Trout (inland)	116.053	127.905	135.732	145.649	156.431
Seabream	99.730	109.749	133.476	152.469	154.011
Trout (marine)	9.411	18.182	31.509	45.454	66.055
Mussel	4.168	4.037	4.585	5.469	8.738
Granyose (yellow mouth)	3.375	7.428	5.913	4.771	6.149
Tuna	2.327	4.338	4.952	3.879	3.674
Other	873	865	368	512	427
Total	373.356	421.411	471.686	514.805	556.287

As the largest producer of rainbow trout, seabass, and seabream in Europe and the second-largest exporter of seabass and seabream in the world, Türkiye exports the majority of its farmed fish not for domestic consumption but to generate high value-added foreign currency income. Among the exported products, seabass ranks first, followed by seabream. Exports are made to more than eighty countries, with 55% going to EU member states. In addition, mussels, shrimp, and other shellfish also hold a significant share. In 2023, aquaculture products produced in Türkiye were exported to 95 countries worldwide (Doğan and Çanak 2024, TUIK 2024a).

Thanks to its geographical advantages, Türkiye is rapidly increasing its production capacity. While seabream and seabass are farmed in the warm waters of the Aegean and Mediterranean Seas, trout farming is concentrated in the colder inland waters. Muğla and İzmir provinces, in particular, stand out as major centers in marine aquaculture. In addition, new aquaculture projects are being developed in the Black Sea and Eastern Anatolia regions. Türkiye's aquaculture sector holds great potential not only for domestic consumption but also for export (TUIK 2024b).

Fish Farms Operating in Turkish Marine Waters

Table 2 presents the number and project capacities of active marine fish farms in 2019, showing that the number of large-capacity farms in marine aquaculture is higher than those in inland water production.

Table 2. *Distribution of aquaculture farms by production capacity (BSGM 2024)*

Group	Capacity Group (tons)	Number of facilities	Total project capacity (tons/year)
Marine	0-50	121	3.391
	51-100	16	1.315
	101-250	17	2.935
	251-500	60	21.856
	501-1000	157	143.334
	1001>	153	363.490
	Total	554	536.321
Inland	0-50	1066	18.492
	51-100	122	10.876
	101-250	248	49.672
	251-500	165	72.554
	501-1000	140	121.817
	1001>	2	3900
	Total	1831	277.311

Marine+inland	0-50	1187	21.883
	51-100	138	12.191
	101-250	265	52.607
	251-500	225	94.410
	501-1000	297	265.151
	1001>	155	367.390
	Total	2385	813.632

Figure 2 shows the distribution of fish farms operating in Turkish marine waters based on their production capacities (tons/year), using data obtained from BSGM (2024).

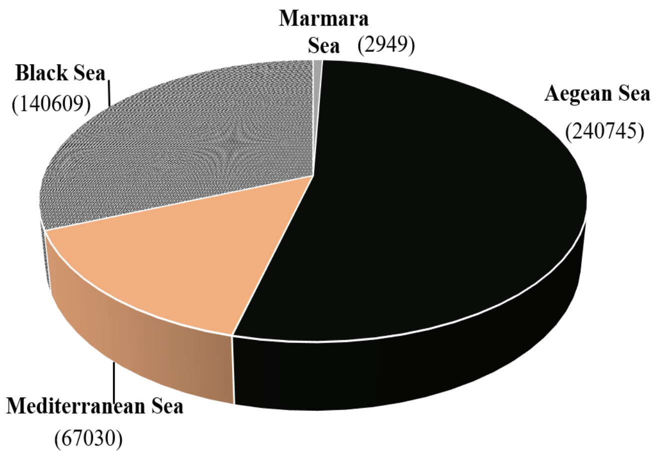

Figure 2. *Distribution of fish farms operating in Turkish marine waters by production capacity (tons/year) (BSGM 2024) (Numbers in brackets indicate production capacity)*

Environmental Management of Marine Fish Farms in Türkiye

Since the quality of fish life is directly related to the quality of the water they live in, maintaining their health depends on a clean aquatic environment. Although marine cages in Türkiye have been relocated from environmentally sensitive areas, enclosed bays, and nearshore zones since 2006, the lack of coastal zone management plans—and consequently, the conflict and competition over area allocation between the tourism and aquaculture sectors—has been reported as one of the major constraints to the development of marine aquaculture (FAO 2009).

There are significant differences between countries regarding the requirements for Environmental Impact Assessment (EIA) or environmental monitoring in aquaculture (Phillips et al. 2009). Environmental Impact Assessment (EIA) refers to the evaluation of the potential environmental effects of any proposed project or development plan, taking into account both the positive and negative impacts on interconnected socio-economic, cultural, and human health aspects (FAO 2021).

In Turkey, entrepreneurs who wish to engage in fish farming must first prepare the necessary documents required by the Provincial Directorate of Agriculture and Forestry and then apply for a permit from the Ministry of Agriculture and Forestry. For facilities that will operate in marine environments, water samples must be collected from the intended production areas and analyzed at an authorized laboratory as part of the initial permitting process by the Ministry. The characteristics of water samples analyzed according to -Standard Water Quality Methods- and the parameters shown in the table below are evaluated to determine whether they meet the Marine Aquaculture Water Quality Criteria specified in Annex 1a of the Fisheries Aquaculture Regulation and its Implementation Principles (Circular 2006/1), published in the Official Gazette on 29.06.2004, numbered 25507, to assess whether they are suitable for marine aquaculture. After this stage, depending on the production tonnage of the marine cage project, farms with a production capacity exceeding 1,000 tons/year must undergo a rigorous Environmental Impact Assessment (EIA) process before starting production. Marine fish farms with a production capacity below 1,000 tons/year can proceed with investment after undergoing oceanographic/biodiversity and ecological evaluation processes. Among the required documents for this application is a compliance certificate confirming conformity with the “Environmental Impact Assessment (EIA) Regulation.”

The objectives of the legal regulations regarding marine aquaculture projects and the establishment of EIA guidelines in Türkiye are presented below:

A- Legislation on Aquaculture Permits and Areas

- The aim of the “Environmental Law No. 2872” dated August 9, 1983, is to ensure the protection of the environment, which is the common asset of all living beings, in line with the principles of sustainable environment and sustainable development. Under the law (Chapter Three - Measures and Prohibitions Related to Environmental Protection); “It is essential to ensure the protection and use of the country’s marine, underground, and surface water resources, as well as aquaculture areas, and to protect them against pollution. The Ministry is responsible for the creation and coordination of policies related to wastewater management. The recipient environment standards for aquaculture areas are determined by the Ministry of Agriculture and Rural Affairs. Fish farms in marine waters cannot be established in enclosed bays and gulfs that are considered sensitive areas, as well as in natural and archaeological site areas."

- The "Cultural and Natural Heritage Protection Law" published in the Official Gazette No. 18113 dated July 23, 1983, includes the relevant policy decision (725) concerning aquaculture facilities in areas covered by this law.

- The purpose of the "Regulation on the Implementation of the Coastal Law," published in the Official Gazette dated April 4, 1990, and numbered 3621, is to determine the coastal boundary line in seas, natural and artificial lakes, and rivers; to regulate the use and protection of coasts; and to establish the principles of planning and implementation for areas gained through land reclamation and drainage, as well as for coastal strips that are a continuation of the shores of seas and lakes. In the third section of the regulation (Planning and Construction on the Coast, in the Sea, and on Land Gained Through Reclamation and Drainage), facilities for the production and cultivation of aquatic products are also included among the structures and facilities that, due to their nature, cannot be constructed in any location other than the coast.

- In areas covered by the "Regulation on the Preparation and Approval of Zoning Plans in Cultural and Tourism Protection and Development Zones and Tourism Centers," which came into force upon its publication in the Official Gazette dated November 3, 2003, and numbered 25278, zoning plans of all scales for lands gained through reclamation and drainage in seas, lakes, and rivers falling under the scope of Coastal Law No. 3830/3621 and the relevant regulation are approved by the Ministry of Culture and Tourism pursuant to Article 7 of the Tourism Incentive Law No. 4957/2634.

- According to Article 10, Paragraph 4 of the "Regulation on the Implementation of Articles 17 and 18 of the Forest Law," published in the Official Gazette dated September 15, 2011, and numbered 28055, it is stated that — *in connection with fish production carried out on lake and sea surfaces, permission may be granted for the construction of guard huts, storage units, net spreading areas, and hatcheries within areas classified as forest land.*

- The purpose of the "Regulation on the Protection of Wetlands," published in the Official Gazette dated April 4, 2014, and numbered 28962, is to establish the principles for the protection, management, and improvement of wetlands located within Türkiye's land boundaries and continental shelf, as well as the principles of cooperation and coordination among the institutions and organizations responsible for these matters. The regulation includes:

Article 15 – Paragraph (2) states: *"Regarding wastewater discharge, the provisions of the Regulation on Water Pollution Control, published in the Official Gazette dated 31/12/2004 and numbered 25687, shall apply; and in aquatic product production areas, the provisions of the Regulation on Aquatic Products, published in the Official Gazette dated 10/03/1995 and numbered 22223, shall be applied.*

- The purpose of the *Communiqué on the Designation of Enclosed Bays and Gulfs in the Sea as Sensitive Areas Where Fish Farms Cannot Be Established* (2007) is to establish the principles and guidelines for identifying enclosed bays and gulf areas in the sea that are classified as sensitive areas with a high risk of eutrophication, where fish farms cannot be established, pursuant to Article 9(h) and Provisional Article 2 of the Environment Law No. 2872 dated 9 August 1983. However, the Communiqué concerning its repeal was published in the Official Gazette dated 28 October 2020 and numbered 31288.

B- Legislation Related to the Environmental Impact of Aquaculture Facilities

- The purpose of the *Regulation on the Control of Water Pollution*, published in the Official Gazette dated 31 December 2004 and numbered 25687, is to establish the legal and technical principles necessary to prevent water pollution in a manner consistent with the goals of sustainable development, in order to protect and ensure the optimal use of the country's groundwater and surface water resources. This Regulation covers the classification of water environments by quality and intended use; the planning principles and prohibitions related to the protection of water quality; the principles for wastewater discharge and discharge permits; the principles concerning wastewater infrastructure facilities; and the procedures and principles for monitoring and inspection to prevent water pollution. In the Second Section (Principles for the Protection of Waters), the necessary measures to protect aquatic product production areas are outlined. In the Fourth Section (Planning Principles and Prohibitions Related to Water Quality), the *Pollution Prohibitions Regarding Seas* are detailed in Articles 23 and 24. In Article 23, Paragraph (h), it is stated that it is mandatory to obtain the opinion of the Ministry of Environment and Urbanization for the potential area identification studies conducted by the

Ministry of Agriculture and Forestry for aquaculture purposes in coastal and offshore areas.

- The title of the *Regulation on Surface Water Quality Management* published in the Official Gazette dated 30 November 2012 and numbered 28483 has been changed to *Regulation on Inland Water Quality.* Within the scope of the regulation, the *Coastal Water Quality Criteria, Eutrophication Criteria for the Aegean and Mediterranean Coastal and Transitional Waters,* and *Eutrophication Criteria for the Black Sea and Marmara Coastal and Transitional Waters* have been provided.

- The *Communiqué on the Repeal of the Communiqué on the Monitoring of Fish Farming Facilities in the Sea* was published in the Official Gazette dated 28 October 2020 and numbered 31288.

- The *Regulation on Environmental Inspection,* published in the Official Gazette dated 12 June 2021 and numbered 31509, covers environmental inspections to be carried out in all land areas within the borders of the Republic of Türkiye, including free and exclusive economic zones, as well as in the seas within the country's sovereignty, in maritime jurisdiction areas subject to judicial authority, and in related waters, natural or artificial lakes, reservoir lakes, and rivers. It also includes the procedures and principles related to administrative sanctions to be applied in accordance with the Environmental Law No. 2872.

- The purpose of the *Environmental Impact Assessment (EIA) Regulation*, published in the Official Gazette dated 29 July 2022 and numbered 31907, is to regulate the administrative and technical procedures and principles to be followed in the Environmental Impact Assessment (EIA) process. The EIA process includes the steps required for the environmental impact assessment of a planned project, covering the application, pre-construction, construction, operation, and post-operation stages. In Article 7 of the Regulation;

a) Projects listed in Annex-1,

b) Projects for which a *"EIA Required"* decision has been made,

c) In cases where an increase in capacity and/or expansion of area is planned for projects that are exempt from evaluation or legally exempt from the EIA, it is mandatory to prepare an EIA report for the new capacity of the project, along with the total of the existing project capacity and capacity increases, if the project is included in the list of projects in Annex-1.

In the list of projects subject to Environmental Impact Assessment

(EIA), aquaculture projects with a production capacity of 1,000 tons/year or more are included.

Projects subject to preliminary environmental review and assessment include:

- Aquaculture projects with a production of 30 tons/year or more,
- Aquatic product farming projects other than aquaculture (e.g., shellfish, mollusks, and arthropods).

The purpose of the *Regulation on the Environmental Management of Fish Farms Operating in Marine Areas*, published in the Official Gazette dated 28 October 2020 and numbered 31288, is to identify sensitive marine areas where fish farms cannot be established and to establish the procedures and principles for monitoring their environmental impact and managing their environmental footprint. In Section Three (Sensitive Areas, Absorption Capacity, and Restrictions), the provisions regarding *areas where fish farms cannot be established* are set out in Article 5. According to this article, the parameters and criteria for sensitive areas in bays and gulfs where fish farms cannot be established are specified in **Table 2,** while the parameters and criteria for non-sensitive areas in bays and gulfs with high water exchange potential and strong currents are specified in **Table 3.** In marine areas where any of the parameters listed in these tables are not met, the establishment and operation of fish farms is strictly prohibited.

Table 2. *Parameters and criteria for sensitive areas in bays and gulfs where fish farms cannot be established (Anonymous 2020a)*

Parameter	Criteria
Distance from the shore*	≤ 1250 m
Depth	≤ 40 m
Current speed	≤ 0.1 m/s
Distance between farms**	≤ 1000 m

* *The distance from the shore is calculated from the nearest landmass, without distinguishing between islands and the mainland.*

** *In Joint Aquaculture Areas, this criterion does not apply to consolidated fish farms with a total production capacity of up to 4,000 tons/year.*

Table 3. *Parameters and criteria for areas outside sensitive zones in bays and gulfs where fish farms cannot be established (Anonymous 2020a)**

Parametre	Kriter
Distance from the Shore**	≤ 500 m
Depth***	≤ 30 m
Current Speed	≤ 0,1 m/s
Distance Between Farms****	≤ 1000 m

* *For new species to be cultivated, these criteria shall be determined by the Ministry upon the proposal of the Ministry of Agriculture and Forestry.*

** *The distance-from-shore criterion for fish farms to be established around islands shall be determined by the Ministry upon the proposal of the Ministry of Agriculture and Forestry.*

*** *The depth criterion does not apply to fish farms practicing polyculture.*

**** *In Joint Aquaculture Areas, this criterion does not apply to consolidated fish farms with a total production capacity of up to 4,000 tons/year.*

Article 6 of the same regulation outlines the principles for *"Determining the Risk of Eutrophication."* According to this article, the potential eutrophication risk caused by fish farms operating in marine environments is determined using the **TRIX Index,** based on the following parameters and calculation method:

TRIX Index = (Log (Chlorophyll-a x % O_2 x TIN x TP) + 1.5) x 0.833

Chl-a = Chlorophyll-a concentration (μg/L)

DO%sat = Dissolved Oxygen saturation (%)= |DO% – 100|

TIN = Dissolved Inorganic Nitrogen (μg/L) N-(NO_3+NO_2+NH_4), (μg/L)

TP = Total Phosphorus (μg/L)

For determining the eutrophication risk of the marine environment where the fish farm operates, the average TRIX Index values of the analyzed samples are taken into account in the assessment. As presented in **Table 4,** it is stated that fish farms can be established in marine areas where no eutrophication risk is detected according to the TRIX Index.

Table 4. *Eutrophication risk scale (Anonymous 2020a)*

TRIX Index	Eutrophication Status	Explanation
< 4*	No Eutrophication Risk	Aquaculture is permitted
4 – 5*	Low Eutrophication Risk	Aquaculture is allowed for existing facilities; no new facilities
5 - 6*	Eutrophication Risk Present	No new aquaculture facilities; restrictions on existing facilities
> 6*	High Eutrophication Risk	No aquaculture permitted; existing facilities must cease operation

*For the Black Sea, it is applied as +1.

Article 7 of the Regulation states that *"The absorption capacity of the aquaculture area or bays/gulfs is determined by taking into account factors such as depth, current speed, water exchange potential, seawater quality, and other activities within the impact area."* In this context, the absorption capacity of the aquaculture area or bays/gulfs is determined through scientific studies to be conducted in the region and is submitted to the Ministry during the Environmental Impact Assessment (EIA) application process. The total production amount to be carried out in aquaculture areas or bays/gulfs cannot exceed the absorption capacity determined for these areas. It is stated that the absorption capacity studies to be conducted in aquaculture areas or bays/gulfs will be carried out or commissioned by academic institutions specialized in marine sciences/biology or by Research Institutes affiliated with the Ministry of Agriculture and Forestry.

Article 8 of the "Regulation on the Environmental Management of Fish Farms Operating in the Seas" states:

a) *"It is prohibited to establish and operate fish farms in marine areas with high eutrophication risk,"* as determined by the TRIX Index mentioned in Article 6 of the relevant regulation, considering the current, depth, and water exchange capacities of the marine areas where fish farms operate, as referenced in Article 5 of the same regulation.

b) According to the provisions of the relevant regulation, fish farming activities established in areas suitable for fish farming in the sea must be stopped if the marine area becomes a sensitive area.

c) Due to non-compliance with the provisions of the relevant regulation, the establishment of a fish farm is not permitted within 1000 meters of the marine area where a fish farm has been shut down for being deemed unsuitable.

d) The establishment of new fish farms is not permitted in marine areas identified as having a low eutrophication risk according to the TRIX Index specified in Annex-4 of the relevant regulation.

e) According to Annex-4 of the relevant regulation, marine areas where fish are farmed and identified as having eutrophication risk, due to their potential to become sensitive areas, will not be allowed to establish new fish farms. Additionally, production in existing fish farms will be restricted. The restriction involves reducing the production capacities of fish farms in bays or gulfs by at least 20% and in other areas by at least 10%, or relocating them to newly selected (rotational) areas. The areas for rotational relocation will be determined after obtaining the Ministry's approval. If there is no eutrophication risk remaining in a restricted marine area, the restriction imposed on the area will be lifted as per the provisions of the regulation.

f) With the relevant legal regulation, the Ministry of Environment, Urbanization, and Climate Change aims to ensure the most suitable site selection for fish farms in marine environments, focusing on environmental sustainability. This is done by considering the potential environmental impacts of fish farms operating in our seas and is carried out by the Directorate of Marine and Coastal Management and Provincial Directorates under the General Directorate of Environmental Management, which is affiliated with the Ministry. In selecting the most suitable locations, areas outside previously designated sensitive marine zones will be chosen. Additionally, while marine fish farms continue their operations, their potential impacts on the marine environment are continuously monitored. In this context, in areas where marine fish farms are densely operating, ecological assessments are conducted by academic institutions or organizations specialized in marine biology. These assessments evaluate the presence of flora, fauna, and habitats, as well as the influence on the dynamic structure and the physical, chemical, and biological characteristics of the water. Ecological reports are prepared both before and after the establishment of the farms to assess the environmental impact.

For effective environmental management, documents and reports such as the Fish Farms Monitoring Report, Environmental Management Plan, Environmental Impact Assessment (EIA) Certificate, and the Compliance Certificate linked to a 5-year permit must be prepared. If these mandatory documents are not submitted, marine fish farms are subject to legal penalties under the Environmental Law. This is because, in order to prevent potential negative impacts on the marine area and to ensure harmony with the surrounding marine environment, the operation must fulfill certain requirements related to sustainable production and environmental management.

Article 10 of the "Regulation on the Environmental Management of Fish Farms Operating in the Seas" states: "*Fish farms are obliged to establish the necessary technical infrastructure for monitoring activities before and after the start of operations, to have measurements and analyses carried out, to report the results of these analyses, and to keep the necessary records, in accordance with the procedures and principles set forth in this Regulation*." Within the scope of the article, it is stated that, in order to determine in detail the impacts of fish farms on the marine environment and to monitor changes over time, annual monitoring studies must be conducted in the water column and sediment based on the parameters specified in Table 5, and the results must be submitted to the relevant Provincial Directorate. If the evaluation of the monitoring results indicates issues requiring prohibitions or restrictions, these must be reported to the Ministry. New fish farms are required to submit their initial Fish Farm Monitoring Report to the Administration by attaching it to the Environmental Management Plan before starting operations. Fish farms are required to carry out the water column monitoring studies specified in Table 5 every May, and the sediment monitoring studies every two years in May. Newly established fish farms are obligated to perform all measurements and studies in May prior to the start of their operations (Anonymous 2020a). The same article states that the monitoring study may be determined through a joint effort in aquaculture production areas. In such cases, all fish farms within the aquaculture production area may prepare a joint monitoring program and submit it to the Ministry, but it can only be implemented after receiving the Ministry's approval.

Table 5. Parameters to be measured in monitoring studies *(Anonymous 2020a)*

Parameters
Water column analysis
1. Total dissolved inorganic nitrogen (µg/L)
2. Total phosphorus (µg/L)
3. Chlorophyll-a (µg/L)
4. Dissolved oxygen (%)
5. Secchi depth (m)
6. Sea water temperature (°C)
7. Sea water salinity (ppt)
Sediment analysis
1. Physical properties and grain size analysis
2. Redox potential (at the sampling stage)
3. Total organic carbon (mg/kg)
4. Total phosphorus (mg/kg)
5. Beggiatoa (number/g)

As stated above, the legislation has been simplified by combining the "Communiqué on the Designation of Enclosed Bays and Gulfs Considered Sensitive Areas Where Fish Farms Cannot Be Established in Marine Areas" and the "Communiqué on the Monitoring of Aquaculture Facilities Established in Marine Areas" into a single regulation, titled the "Regulation on the Environmental Management of Fish Farms Operating in the Seas," which has been put into effect. With this latest regulation, which has been tailored to the conditions of our country, a number of new provisions have been introduced.

- Among the criteria in the "Communiqué on the Designation of Enclosed Bays and Gulfs Considered Sensitive Areas Where Fish Farms Cannot Be Established in Marine Areas," the depth requirement has been changed to 40 meters, and the distance from shore to 1250 meters, while a new criterion of inter-farm distance ≤ 1000 meters has been added (Table 2). In the same communiqué, the number of TRIX index categories has been increased from three to four, allowing the eutrophication status to be categorized according to these values (Table 4).

- The water column analyses under the "Communiqué on the Monitoring of Aquaculture Facilities Established in Marine Areas" have been updated, with pH, Suspended Solids, Ammonium Nitrogen, Total Nitrogen, and Total Organic Carbon analyses removed and replaced with the parameters presented in Table 5. In the most recent communiqué, sediment analyses have been detailed. While the previous communiqué only required the analysis of total organic carbon in sediments, the analyses listed in Table 5 have been added to the monitoring program. Additionally, the “Communiqué on the Monitoring of Aquaculture Facilities Established in Marine Areas” states that water column analyses should be conducted once a year in August, while sediment measurements of the specified parameters should be performed every three years in August. With the “Regulation on the Environmental Management of Fish Farms Operating in the Seas,” it has been stipulated that fish farms must carry out water column monitoring studies every May, and sediment monitoring studies every two years in May.

C- The Environmental Management Perspectives and Expectations of Marine Fish Farm Owners

In the Eighth Fisheries Workshop (Anonymous 2020b), it was stated that fish farm owners operating in the seas have issues and expectations arising from the legislation. The conclusions related to these issues are summarized below:

- Producers are disturbed by the negative views of the tourism sector regarding the activities of farms located close to the shore, as well as the portrayal of these activities as environmentally polluting in the media. In this context, the legality of production and the environmental protection efforts through measurements and analyses should be clearly communicated to the public to counter these approaches.

- Another issue mentioned is the long duration of procedures that new fish farming facilities must follow, based on state bureaucracy. Reducing bureaucracy in the EIA processes according to the conditions is a common view of the producers. Therefore, the mentioned processes should aim to facilitate entrepreneurship, and standard rules should be established for a more practical and faster decision-making process regarding environmental management views and permits that would slow down operations.

- Producers also have expectations of being more involved as stakeholders in the process, especially in the creation of draft legal regulations.

- In the detection and monitoring of marine water pollution, it has been stated that the contribution of aquaculture should be clearly determined, and the producers in the region should be transparently informed about this matter.

- It has been expressed that in order to reduce costs for environmental monitoring, collective sampling should be provided for farms located at close distances, and the sample analyses requested by various public institutions should also be coordinated and consolidated.

- Another expectation is the request for the Ministry of Agriculture and Forestry to take the initiative in establishing regional laboratories for the environmental impacts, early diagnosis, and control of fish diseases in the seas.

D- Evaluation of EIA Applications of Marine Fish Farms for the 2020-2025 Period

In the last five years in Türkiye, 43 marine fish farms have applied to the Ministry of Environment, Urbanization, and Climate Change for an Environmental Impact Assessment (EIA) report, and none of these farms have been issued a negative EIA report (Anonymous 2025c). Of these marine fish farms, 40 were issued a positive EIA report, and 2 were given a "No EIA required" report. One marine fish farm applied for a coastal protection fill permit for an adaptation facility, and was issued a "EIA required" report, with its application being put on hold for the duration specified in the regulations to prepare the EIA report. In this study, only the fish farms that applied for an EIA report have been considered, and the regional distribution of the applications is shown in Figure 3.

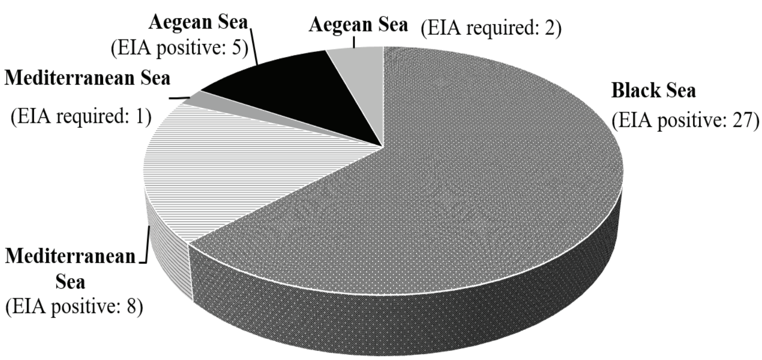

Figure 3. *Distribution of the EIA application results of marine fish farms for the 2020-2025 period*

The absence of negative EIA reports in the EIA applications from the last five years can be interpreted as an indication that the EIA reports were carefully prepared by the authorized firms, and this is also seen as a positive factor for the future of the businesses. As can be seen in the figure, although the highest number of marine farms is in the Aegean Sea, the highest number of EIA applications from the last five years came from the Black Sea Region.

Conclusion

Aquaculture is a valuable source of marine product production, but it has also brought environmental challenges. In this context, in the early years of aquaculture in sea cage farms in Türkiye, negative news regarding the effects of aquaculture was particularly found on social media. This situation was caused by the fact that priority areas had not yet been clearly defined and the lack of ecological baseline data before the establishment of aquaculture businesses and prior to the legal requirement for EIA and environmental monitoring systems. According to Anonymous (2024d), the main reasons for the conflict between aquaculture and tourism in Türkiye are the rapid growth of the aquaculture sector and the inadequate legal framework. The expansion of aquaculture near coastal tourism facilities and aesthetic/recreational concerns have been identified as factors escalating this conflict. Furthermore, these conflicts arise from different perceptions of individuals, collectives, private companies, and the state regarding the potential environmental and quality of life impacts of aquaculture. In this context, it would be beneficial for the General Directorate of Environmental Management to monitor the activities of fish farming operations at sea via satellite using important technologies such as satellite technology, or to systematically update rotation areas to be created in terms of carrying capacity. Continuous monitoring of idle capacity and excessive capacity usage of marine fish farms, and the development of macro planning and methods for efficient and sustainable capacity use that is suitable for carrying capacity, are also important.

In May 2021, under the "Strategic Guidelines" adopted by the European Commission for the 2021-2030 period for a more sustainable and competitive EU aquaculture, the vision was adopted that EU aquaculture should become an even more competitive and resilient sector by 2030 and become a global reference for sustainability. In the context of the aquaculture sector, it has been mentioned that the continuation of the negative image of aquaculture facilities and areas, low synergy with existing activities (such as fishing, tourism, processing industry) and protected areas, and the inability to optimize the production potential in areas designated for aquaculture production, as well as the underutilization of these areas, are among the impacts (Anonymous 2024e). Some of the effects mentioned in the guidelines align with the ongoing issues and shortcomings in the environmental management of aquaculture activities in Türkiye.

Large-scale marine aquaculture facilities and their potential environmental impacts require the implementation of certain environmental management rules for sustainability. Since aquaculture requires good environmental conditions, environmental regulations in Türkiye should not be seen as a factor limiting growth in the sector, and the issues encountered in practice as a result of new regulations should not be overlooked, as they will create positive long-term added value. In this context, legal regulations related to the environmental management of aquaculture in Türkiye should aim to contribute to the long-term, more sustainable, and less conflictual development of aquaculture.

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Chapter 4

APPROACHES TO MANAGING HEAVY METAL-CONTAMINATED SEDIMENTS IN AQUATIC ECOSYSTEMS

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Introduction

Sediment is a naturally occurring material formed through the process of sedimentation in aquatic environments such as rivers, lakes, and oceans. It comprises a mixture of sand, silt, clay, organic matter, and inorganic minerals. Sediments can be categorized into riverine, lacustrine, or marine types, depending on their specific aquatic habitat. Typically, sediments found in freshwater systems like rivers and lakes have a higher organic matter content, while marine sediments exhibit elevated salinity levels. Due to the intricate interactions between sediment and the surrounding water, pollutants present in these environments tend to adsorb onto sediment particles, leading to accumulation and storage within the sediment matrix (Albarano et al. 2020). The U.S. Environmental Protection Agency (EPA) defines contaminated sediment as “soil, sand, and organic matter or minerals that settle at the bottom of a water body and contain toxic or hazardous substances that may negatively impact human health or the environment” (USEPA 2001).

In aquatic settings, heavy metals can enter the water column in various forms, including soluble, colloidal, and suspended states, or through migration from sediment. Consequently, sediment acts as both a sink and a source of pollutants. When heavy metals are released into the water, only a small fraction remains dissolved, while over 90% is retained in the sediment via processes such as adsorption, hydrolysis, and the formation of solid compounds with carbonates, sulfates, and sulfides. This retention positions sediment as the ultimate sink for heavy metals, often resulting in concentrations that exceed those found in the overlying water. Changes in the physical, chemical, and biological conditions of the sediment-water interface can trigger the release of these pollutants back into the aquatic environment (Kutuniva et al. 2019, Yi et al. 2019).

Heavy metals are sequestered in sediments through various mechanisms, including adsorption to particle surfaces, ion exchange, precipitation, and complexation with organic matter. The chemical forms and binding affinities of these metals are modulated by a range of physicochemical and biological processes. (Akcil et al. 2015). However, under specific physicochemical conditions—such as variations in redox potential, pH, salinity, and organic matter concentrations—heavy metals bound in sediment can be re-released into the water column, posing significant risks to public health (Samani et al. 2015).

Benthic organisms can assimilate heavy metals present in sediment, leading to bioaccumulation along the food chain, which poses health risks to humans through the consumption of contaminated aquatic products

(Pulatsü and Topçu 2012, 2015). Numerous studies indicate that prolonged exposure to heavy metals can disrupt gene expression, impair repair mechanisms, decrease enzymatic activities, and elevate cancer risks (Kim et al. 2015). A functional gene microarray (GeoChip) encompassing over 10,000 functional genes has revealed that metal contamination detrimentally impacts the diversity and functionality of microbial communities in sediment, leading to an increased prevalence of metal-resistant and sulfate-reducing populations (Kang et al., 2013). Furthermore, analysis of 16S rRNA sequences indicates that exposure to heavy metal contamination significantly modifies the composition and structure of sediment microbial communities (Yin et al., 2015).

The issue of heavy metal pollution in rivers and lakes has emerged as a critical global concern. In this context, effective sediment management is essential due to the role of sediments as reservoirs for heavy metals, which are integral components of aquatic ecosystems and are consumed by aquatic organisms. Given the complexity of heavy metal pollution and the unique characteristics of various contaminated areas, the selection of appropriate remediation methods is equally diverse.

This chapter will explore three key aspects within aquatic ecosystems: a) Factors influencing the release of heavy metals from sediment, b) Techniques for assessing heavy metal concentrations in sediments, and c) Current remediation strategies employing chemical and biological technologies for the removal or stabilization of metals from contaminated sediments.

Factors Influencing the Types and Distribution of Metals in Sediment

The distribution of heavy metals within sediment is influenced not only by terrestrial inputs but also by the physicochemical and biological characteristics of the ecosystem. While total metal concentrations can serve as a useful indicator for identifying sources, the bioavailability and toxicity of these metals are largely determined by their specific chemical forms in the sediment matrix. In sediments, metals may exist in various states, including being occluded within amorphous materials, adsorbed onto clay surfaces or iron/manganese oxyhydroxides, incorporated into the lattice structures of secondary minerals such as carbonates, sulfates, or oxides, or forming complexes with primary minerals like organic matter or silicates. The chemical forms of exchangeable carbonates and iron-manganese oxides exhibit weak binding affinities for heavy metals, thereby enhancing the availability of these metals for uptake by organisms. To assess heavy metals in sediments, several sequential extraction procedures have been developed, which categorize them into five distinct fractions: extractable and exchangeable, carbonate-bound, iron and manganese oxides-bound, organic matter-bound, and residual metals (Hou et al. 2013, Chang et al. 2014). The primary environmental factors that influence the distribution of metals in aquatic ecosystem sediments are outlined below:

Effect of pH Levels

In sediment environments, a specific pH threshold governs the mobility of heavy metals, with trace metals being released only when this threshold is reached. Consequently, even under similar pH conditions, the potential mobility of heavy metals can differ significantly (Table 1).

As sediment pH decreases, the competition between H^+ ions and dissolved metals for binding sites becomes more pronounced. This dynamic reduces the adsorption capacity and bioavailability of metals, ultimately enhancing the mobility of heavy metals. Notably, even minor fluctuations of just a few pH units can dramatically shift the fixation percentage of heavy metals on sediment particles from complete retention (100%) to none (0%). The degradation of organic matter and the oxidation of acid-volatile sulfides often lead to a decline in sediment pH from an initially neutral state to levels as low as 1.2. Such changes can facilitate the release of certain metals back into the water column, even when water conditions appear stable (Peng et al. 2009, Hu et al. 2013).

At low pH levels, the negative surface charges associated with organic matter, clay particles, and iron-manganese-aluminum oxides diminish, while carbonates, sulfides, and iron-manganese oxide fractions may dissolve. Conversely, at elevated pH levels, the formation of stable metal complexes becomes increasingly challenging (Wang et al. 2015). When carbonates are present in sediments, they not only facilitate the direct precipitation of metals but also serve as effective buffers against declines in pH. In surface sediments, processes such as the degradation of organic matter, oxidation of acid-volatile sulfides, and the oxidation of other reduced species (e.g., NH_4^+, Mn^{2+}, Fe^{2+}, and HS^-) can lead to a reduction in pH, which in turn promotes the mobilization of heavy metals (Gang et al. 2018).

Table 1. *Limit pH values controlling the mobility of different metals in sediment (Peng et al. 2009)*

Metal species	**pH limit**
Zn	6.0–6.5
Cd	6.0
Ni	5.0–6.0
As	5.5–6.0
Cu	4.5
Pb	4.0
Al	2.5
Fe	2.5

Effect of Organic Matter Types

Organic matter (OM) plays a crucial role in aquatic systems as a nutrient source for microorganisms and significantly influences the retention and release of metals in sediment. In eutrophic environments, organic matter and sulfate concentrations are often elevated. Sulfate-reducing bacteria utilize simple organic molecules for energy, and sulfur has the potential to bind with metals in anoxic sediment conditions (Clark et al. 1998).

In sediments, organic compounds are frequently found in particulate form and are vital for the transformation of heavy metals. In certain river or lake sediments, a considerable proportion of heavy metals is bound to organic matter, with the solubility of this organic matter typically dictating the mobility of the metals. In general, the complexation of metal ions with insoluble organic compounds markedly diminishes their mobility, while the formation of soluble metal complexes with dissolved organic compounds enhances their mobility. In natural aquatic systems, organic matter predominantly consists of humic and fulvic substances. The complexation reactions between heavy metals and organic complexants are considered pivotal pathways that dictate the speciation and bioavailability of metals, thereby influencing the mobility of trace metals within these environments (Peng et al. 2009).

Effect of Oxidation-Reduction Potential

Oxidation-Reduction Potential (ORP) is a critical parameter influencing the speciation and mobility of redox-sensitive heavy metals. Arsenic (As) is particularly significant, as it exists in multiple oxidation states depending on the prevailing environmental redox conditions. The mobility of heavy metals varies according to the cation exchange capacity of the sediment, with the general order of mobility being Cs >Zn>Cd >Fe>Ag> Co>Mn (Lores and Pennock 1998).

Effect of Other Factors

In addition to pH, organic matter, and oxidation-reduction potential, other variables such as temperature, salinity, metal species, and retention time also play significant roles in the distribution of heavy metals in sediments. For instance, variations in cation exchange capacity among different metals can alter their mobility potential. Generally, as temperature increases, the adsorption of heavy metals in sediment tends to decrease. Similarly, rising salinity levels in pore water can reduce the total adsorption of heavy metals due to competitive interactions with other cations (Garnier et al. 2006).

Evaluation of Heavy Metal Contamination in Sediments

To assess the extent of metal contamination, total metal content values should be compared against background reference values. Some studies utilize average continental crust values as background levels, while others prefer average continental shale values. Shale is often favored for reference due to its natural richness in fine-grained material, which correlates with the association of heavy metals in sediments. An alternative approach involves using reference values for target metals derived from sediment samples that are mineralogically and texturally similar to unpolluted sediments in the study area, having undergone comparable wear, erosion, transport, and sedimentation processes. Reference samples are usually obtained from unpolluted adjacent areas or from deeper sediment layers that were deposited during pre-industrial periods (Abrahim and Parker 2008, Haynes and Zhou 2022).

Various calculation methods have been developed to measure the degree of heavy metal contamination in sediments, and these methods are outlined below. These methods typically convert numerical results into broad descriptive contamination groups that range from low to high. Such methods are commonly used to categorize in-situ contamination levels of sediments in relation to water environment protection.

- **Enrichment Factor (EF)**

A common approach to estimate anthropogenic impact in sediments is to calculate the enrichment factor for metal concentrations above unpolluted background levels. The EF calculation normalizes the measured heavy metal to a reference metal (usually Fe, Al, or Si) found in the same sediment. It is known that heavy metals tend to accumulate in the clay and silt fractions of sediments, and the Enrichment Factor (EF) is used to normalize the variability in the clay plus silt: sand ratio and differences in mineralogy. The most commonly used normalization elements are Fe and Al, which are associated with clay and silt-sized particles and are found in relatively high natural concentrations in sediments. Therefore, they are typically not enriched by anthropogenic sources (Chen et al. 2007). The EF is calculated as follows:

$$EF= [C_m/R_m] / [C_t/R_t]$$

Where; C_m: Measured metal concentration, R_m: Geochemical background values of measured (Fe or Al), C_t: The concentration of the examined metal in the natural background (often taken as shale or the natural crust) and R_t is the concentration of reference metal in the natural background (Table 2).

- Geoaccumulation index (Igeo)

$$I_{geo} = \log_2[C_n/(1.5 \times B_n)]$$

Where C_n: The measured concentration of the heavy metal (n) in the sediment, B_n: The geochemical background value of element n (often in shale). The factor of 1.5 is introduced to account for variations in background levels (Table 2).

Table 2. *Contamination levels of sediments based on enrichment factor (EF) and geoaccumulation index (I_{geo}) (Chen et al. 2007, Peng et al. 2009)*

EF	**Degree of contamination**	I_{geo}	**Degree of contamination**
<1	None	<0	Uncontaminated
1-3	Minor	0-1	Uncontaminated to moderate
3-5	Moderate	1-2	Moderate
5-10	Moderately severe	2-3	Moderate to strong
10-25	Severe	3-4	Strong
25-50	Very severe	4-5	Strong to extreme
>50	Extremely severe	>5	Extreme

- Contamination factor (CF) and degree of contamination (C_d)

CF is the simplest index and is the ratio obtained by dividing the heavy metal concentration in the sediment by the concentration in the background (Hakanson 1980):

$$CF = C_x/C_b$$

Where; C_x: Measured metal concentration, C_b: Geochemical background values of metals. The overall degree of sediment contamination (Cd) is the sum of all contamination factors (Hakanson 1980):

$$C_d = (CF1+ CF2+ CF3+....CFx)$$

Since C_d values are dependent on how many contaminant metals are measured, Abrahim and Parker (2008) modified the formula by defining the degree of contamination (mC_d) as the sum of all the contaminant factors for a given set of sediment pollutants divided by the number of analyzed pollutants.

$$mC_d = (CF1+ CF2+ CF3+..... CFn)/n$$

n= Number of measured metal

Table 3. *Contamination levels of sediments based on contamination factor (CF) and degree of contamination (mC_d) (Abrahim and Parker 2008)*

CF	**Degree of contamination**	**mC_d**	**Contamination level**
<1	None	<1.5	None
1-3	Minor	1.5-2	Low
3-6	Considerable	2-4	Moderate
>6	High degree	4-8	High
		8-16	Very high
		16-32	Extremely high
		>32	Ultrahigh

- **Pollution load index (PLI)**

PLI = (CF1 x CF2 x CFn)1/n

CF: Contamination factor

n: Total number of metals (Suresh et al. 2012)

PLI >1 indicates heavy metal pollution exists while a value <1 suggests no pollution (Ghaleno et al. 2015).

- **Potential ecological risk index (PERI) and ecological risk factor (ERF)**

PERI =CF x T_f

Where; CF: Contamination factor for the examined metal, T_f: Toxic response factor for the given metal. T_f values for heavy metals in sediments are Hg 40, Cd 30, As 10, Cu 5, Pb 5, Cr 2 and Zn 1 (Hakanson 1980). The ecological risk factor is the sum of the individual PERIs and is an overall risk index for the sediment containing a number of contaminating metals:

ERF= (PERI1+ PERI2+ PERI3…)

The ecological risk degree for individual metals and all pollutant metals in a sediment is shown in Table 4 (Guo et al. 2010).

Table 4. *Potential ecological risks in sediments as classified by categories for potential ecological risk index (PERI) and ecological risk factor (ERF) (Guo et al. 2010)*

PERI	Risk level	ERF	Risk level
<40	Low	<150	Low
40-80	Moderate	150-300	Moderate
80-160	Considerable	300-600	Severe
160-320	High	>600	Serious
>320	Very high		

- Sediment quality guidelines (SQGs)

Extensive research has been undertaken to evaluate the effects of sediment contamination on the biological activity of benthic organisms, aimed at safeguarding these species in lake, river, estuary, and marine ecosystems. From these investigations, Sediment Quality Guidelines (SQGs) have been established. SQGs serve as quality benchmarks to ascertain the acceptable limits of pollutant concentrations within aquatic ecosystems and have been formulated for a range of toxic substances, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs).

These values may indicate (i) chemical concentrations at which adverse biological effects are unlikely to occur or (ii) levels at which effects such as acute toxicity are expected. Two primary methodologies are commonly employed in this context. The first is the National Oceanic and Atmospheric Administration (NOAA) approach, which provides Effect Range-Low (ER-L) and Effect Range-Median (ER-M) values (Long et al. 2006). The second is the Florida Department of Environmental Protection (FDEP) method, which offers Threshold Effect Level (TEL) and Probable Effect Level (PEL) values (MacDonald et al. 2000).

According to the Sediment Quality Guidelines (SQG) established by the United States Environmental Protection Agency (USEPA), sediments are categorized as “non-polluted,” “moderately polluted,” and “heavily polluted.” Within this classification framework, the Threshold Effect Level (TEL) denotes a concentration below which adverse effects are infrequently observed, while the Probable Effect Level (PEL) signifies a concentration above which adverse effects are commonly anticipated (MacDonald et al. 2000). Table 5 presents TEL and PEL values for selected heavy metals.

Table 5. *TEL and PEC Values for Selected Heavy Metals (MacDonald et al. 2000)*

HM / SQGs	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
TEL	5.9	0.596	37.3	35.7	35.0	0.174	18.0	123
PEL	17.0	3.53	90.0	149.0	197.0	91.3	36	315.0

Methods for Heavy Metal Management in Sediments

A- In Situ Management Technologies

In situ remediation technology encompasses a range of techniques that facilitate the direct remediation of contaminated sediments without the need to transport them to rivers, lakes, or ports. Based on various remediation principles, in situ remediation can be categorized into physical remediation, chemical remediation, bioremediation, and combined (hybrid) remediation. This approach is less disruptive, offering advantages such as feasibility, cost-effectiveness, and rapid implementation.

1. Physical Remediation

Physical remediation involves the direct or indirect management of heavy metal contamination in sediments through the use of physical tools and specific engineering techniques. Key in situ physical management methods include capping, electrokinetic remediation, and the establishment of impermeability barriers.

Capping aims to minimize resuspension and bioavailability of contaminants. Passive capping typically employs inert materials such as sand, clay, silt, organic carbon, and crushed stone placed over geotextiles. However, in sensitive habitats and marine environments, the toxic risks associated with pollutants may persist (Knox et al. 2012). Certain capping materials can adversely affect benthic macrofauna, leading to significant declines—up to 90%—in the diversity, abundance, and biomass of benthic species (Raymond et al. 2020). Conversely, active capping involves the use of capping materials that chemically react with sediment pollutants to facilitate degradation or binding (Libralato et al. 2018).

2. Chemical Remediation

Chemical remediation entails the application of chemical additives to stabilize heavy metals within sediments. Frequently utilized chemical additives comprise phosphates, clay minerals, biochar, sulfides, silicocalcium materials, iron-based compounds, aluminum salts, industrial waste, and nanomaterials. The mechanisms for immobilizing heavy metals include adsorption, oxidation, reduction, ion exchange, complexation, precipitation, and various chemical reactions (Khalid et al., 2016). While chemical remediation is a rapid, straightforward, and relatively cost-effective method, the introduction of large quantities of chemicals poses a risk of secondary environmental pollution.

Phosphate compounds utilized in chemical remediation can be classified into two categories: soluble and insoluble phosphates. Soluble phosphates, such as phosphoric acid and ammonium, sodium, and potassium phosphates, can interact with metal ions to form insoluble metal phosphate salts. Insoluble phosphates, including hydragirite and members of the apatite family (e.g., hydroxyapatite), are common examples. Hydroxyapatite, in particular, is recognized as a cost-effective reactive medium for generating mineral precipitates that limit the bioavailability of most metals and radionuclides. However, excessive or improper application of phosphates may lead to water eutrophication and other ecological risks (Zhou and Xu 2007).

Recently, novel nanomaterials have gained attention due to their enhanced efficacy in environmental cleanup. These nanomaterials include carbon-based variants such as nano-scale biochar, nano black carbon, multi-walled carbon nanotubes, and C60, as well as metal-based nanomaterials like nano-scale zero-valent iron (nZVI) and metallic oxide nanomaterials, alongside nano mineral materials (Zhang et al. 2021a).

3. Bioremediation Technologies

Although heavy metals cannot be destroyed or biodegraded, they can be transformed into less toxic species through physicochemical and/or biological processes. Consequently, bioremediation has emerged as an environmentally sustainable and cost-effective method for remediating heavy metal-contaminated sediments (Kapahi and Sachdeva 2019; Rahman and Singh 2020). This technique relies on the interactions between metals and microorganisms or plants to convert toxic metals into less mobile forms. The biological mechanisms involved in this process include:

a) Phytoremediation

Phytoremediation employs plants and their associated rhizosphere microorganisms to remediate sediments contaminated with heavy metals. In this process, heavy metals may be stabilized by plant roots, absorbed and accumulated in plant tissues, volatilized into the atmosphere, or transformed within the rhizosphere. Based on the prevailing mechanisms within the plant-metal system, phytoremediation can be classified into phytostabilization, phytoextraction, phytofiltration, and phytotransformation. Among these approaches, phytoextraction is commonly utilized as a remediation technology, typically comprising three primary steps. The efficacy of phytoextraction is influenced by several factors, including the speciation and bioavailability of the metal, soil characteristics, plant species, and the presence of rhizosphere microorganisms (Awa and Hadibarata 2020; Ojuederie and Babalola 2017).

b) Remediation through Microorganisms

Microbial remediation involves the application of microorganisms to mitigate, eliminate, control, or transform contaminants present in polluted sediments. This approach is recognized for its safety, simplicity, and efficiacy; however, it is important to note that the process can be time-intensive, and its effectiveness can be challenging to predict (Peng et al. 2018).

Despite the general toxicity of heavy metals, microorganisms have evolved distinctive resistance mechanisms, with some developing metabolic pathways that enable them to exploit heavy metals for their cellular benefits. Detoxification strategies for heavy metals encompass several extracellular processes, including the exclusion of metals through extracellular barriers, binding of metals to extracellular polymeric substances, and intracellular sequestration of metals within the cytoplasm. Additionally, active transport systems and enzymatic detoxification processes play a crucial role in converting metals from highly toxic forms to less harmful states (Ahemad 2019).

- Bioleaching

Bioleaching, also known as microbial leaching, is a biotechnological process that employs acidophilic microorganisms to facilitate the dissolution of solid-phase heavy metals from sediment matrices. This technique primarily targets heavy metal fractions that are associated with iron or sulfur minerals within sediments. The microorganisms commonly utilized in bioleaching are part of consortia of iron- or sulfur-oxidizing bacteria, which include various groups. Additionally, certain archaea also play significant roles in this process. These microorganisms are adept at oxidizing iron or sulfur minerals, which results in the formation of an acidic environment conducive to the leaching of heavy metals (Akcil et al. 2015).

-Biosurfactant

Biosurfactants, which are produced by a variety of microorganisms including bacteria and fungi, are increasingly recognized as viable alternatives to chemical solvents, particularly synthetic surfactants. Their appeal lies in their low toxicity, high biodegradability, and favorable environmental compatibility. These amphipathic compounds possess surfactant properties that enable them to form complexes with metals.

One notable example is a glycolipid biosurfactant derived from the strain Burkholderia sp. Z-90, which has been effectively utilized as a bio-solvent for the extraction of mixed toxic metals such as Zn, Pb, Mn, Cd, Cu, and As from contaminated soils. Among these metals, Mn, Zn, and Cd have demonstrated superior removal efficiencies due to their high acid-soluble fractions and stronger complexation capabilities with the biosurfactant (Yang et al. 2016).

Despite their potential, the broader application of biosurfactant-based technologies remains constrained by the low production yields of these compounds. Future research efforts are therefore recommended to concentrate on optimizing fermentation parameters, including inoculum size, pH, temperature, mixing conditions, and media nutrients. These optimizations aim to enhance biosurfactant yields and broaden their applicability in environmental remediation (Jiang et al. 2020).

-Bioaccumulation

Bioaccumulation is a sophisticated and active mechanism through which microorganisms absorb and sequester heavy metal ions within their intracellular structures. The efficiency of this process is largely determined by metabolism-driven heavy metal transport systems. Heavy metals traverse bacterial membranes via ion pumps, protein channels, and carrier-mediated transport systems.

-Biosorption

Microorganisms, including bacteria, yeast, fungi, and algae, are extensively employed in the removal of heavy metals from wastewater, soil, and sediment (Bano et al. 2018; Moreira et al. 2019; Pradhan et al. 2019). The biosorption of heavy metals by microbial cells is a passive, metabolism-independent, and primarily reversible process. Both viable and non-viable microbial cells, along with microbial polysaccharides, are involved in biosorption. This process encompasses various interactions, such as physical adsorption, electrostatic and covalent interactions, complexation with exopolysaccharides, and ion exchange, either independently or in combination. Anionic groups present on bacterial cell surfaces—including hydroxyl, carboxyl, thiol, sulfonate, amine, amide, and phosphonate—along with extracellular polymers like polysaccharides, proteins, and humic substances, are believed to facilitate biosorption due to their strong binding affinities for heavy metals (Zhou et al. 2014; Li et al. 2017).

-Bioprecipitation

Bioprecipitation refers to microbial processes that convert soluble metal species into insoluble forms such as hydroxides, carbonates, phosphates, and sulfides, either independently or synergistically. Notably, this process does not rely on microbial metabolism and can occur with both living and dead cells. Bioprecipitation facilitates the direct binding of metal precipitates to microbial cells, with the occurrence and stability of bioprecipitates influenced by environmental factors like pH and redox potential. Under anaerobic conditions, sulfate-reducing bacteria can produce hydrogen sulfide from organic substrates, promoting the precipitation of metal ions and the formation of insoluble metal sulfides such as CuS, PbS, ZnS, and SeS in sediments (Li et al. 2017; Vogel et al. 2018).

-Biotransformation

Microorganisms interact with heavy metals and influence their biotransformation through various metabolic pathways, including oxidation-reduction, methylation-demethylation, and complexation. The impact of microorganisms on the accumulation and transformation of heavy metals is contingent upon the physicochemical properties of metal species and the geochemical conditions of contaminated environments. These microbially mediated transformations are essential for altering the solubility, mobility, bioavailability, and ecotoxicological effects of heavy metals in sediments by modifying their species and oxidation/reduction states (Lei et al. 2019; Dell'Anno et al. 2020).

In addition to microbial action, numerous plant species have demonstrated efficacy in removing heavy metals from contaminated sediments. Given the variability in metal properties, the species of microorganisms and/or plants involved, and the characteristics of the contaminated sediment, a singular bioremediation strategy may not suffice to restore environments affected by multiple metal pollutants. Consequently, it has been proposed that an integrated approach combining various biological mechanisms is often necessary for the effective bioremediation of metal-contaminated sediments (Awa and Hadibarata 2020).

4. Combined Rehabilitation Strategies

Heavy metal contamination in sediments presents a multifaceted challenge that cannot be adequately addressed through a singular rehabilitation technology. Consequently, the implementation of combined rehabilitation approaches, which integrate two or more remediation techniques, leverages the strengths of each method and enhances the overall effectiveness of the rehabilitation process. Typically, combined rehabilitation encompasses methodologies such as physico-chemical remediation, chemico-biological remediation, phytomicrobial remediation, and other integrative strategies. However, it has been observed that these combined approaches have not yet seen widespread application in sediment remediation practices (Peng et al. 2018).

Physical-chemical rehabilitation is a conventional method noted for its high efficiency and cost-effectiveness. This approach includes techniques such as electrokinetic remediation combined with acidification, flocculation, adsorption, ion exchange membranes, and permeable reactive barriers. Other methods may involve chemical solvent combinations or ultrasonic/microwave-assisted chemical treatments. While biological combined methods offer significant advantages, including lower costs and reduced environmental impact, they can be time-intensive and may exhibit variability in their rehabilitation efficiency. Chemico-biological combined rehabilitation encompasses strategies such as phytostabilizer-combined and phytoactivator-combined remediation. These methods aim to enhance phytostabilization and phytoaccumulation processes, thereby improving the overall effectiveness of heavy metal removal from contaminated sediments (Wood et al. 2016; Zhang et al. 2019).

Advantages and Disadvantages of Various In Situ Remediation Technologies

In situ remediation is recognized as a straightforward, effective, and cost-efficient approach; however, it carries the inherent risk of pollutants persisting in the environment and potentially being re-released. Among the various remediation methods, physical rehabilitation remains a traditional and widely employed technique. In contrast, newer active coating methods are still undergoing experimental validation and necessitate further investigation.

Chemical rehabilitation typically exhibits a relatively singular functionality and often incorporates composite additives to address mixed heavy metal contamination. However, these rehabilitation additives can introduce specific environmental risks, highlighting the critical need for research into green, environmentally friendly, and multifunctional remediation materials.

Bioremediation emerges as a promising technological application due to its ability to mitigate secondary pollution. Nonetheless, it is important to recognize that this technique is still in its developmental phase. Therefore, gaining insights into the mechanisms that enhance tolerance and extraction efficiency in both plants and microorganisms is vital for advancing research and development in this area. It has been suggested that integrating these various techniques to improve the efficiency of sediment remediation could become a prevalent focus in ongoing research efforts (Xu et al. 2022).

B- Ex Situ Management Technologies

Ex situ remediation techniques for sediments are generally regarded as more manageable than their in situ counterparts. However, the choice of ex situ methods is contingent upon the specific type and conditions of the sediment. Employing an inappropriate technique may adversely affect remediation results.

Sediment dredging is frequently viewed as the primary option for ex situ remediation of contaminated sediments. The selection of ex situ methods is typically guided by the sediment's unique characteristics, including contamination levels, sediment type, and environmental factors. For instance, washing techniques have proven effective for sediments rich in organic matter (Luo et al. 2019), while electrochemical remediation is acknowledged for its rapid and efficient removal of heavy metals (Beiyuan et al. 2017). Chemical extraction enables swift and effective contaminant removal from sediments (Kutuniva et al. 2019), whereas heat treatment facilitates the destruction of contaminants within the sediment matrix (Ye et al. 2019). Moreover, combined remediation strategies that integrate multiple technologies are considered a promising approach (Albarano et al. 2020).

Physical and Chemical Remediation

-Washing

Washing represents a relatively straightforward and practical ex situ treatment method for contaminated sediment, wherein detergents are introduced to facilitate the transfer of contaminants from the solid phase into the washing solution. Two primary mechanisms contribute to contaminant removal: (1) the dissolution or suspension of contaminants in the washing solution; and (2) the concentration of contaminants via particle size separation and gravity separation (Akcil et al. 2015). The effectiveness of contaminant removal can be enhanced through the application of high-pressure water jets, as well as various acids (e.g., nitric, sulfuric, hydrochloric, acetic) and chelating agents like ethylenediaminetetraacetic acid (EDTA) and surfactants (Peng et al. 2009).

-Electrochemical Remediation

Electrochemical remediation is particularly suitable for contaminated sediments characterized by low permeability and high clay and silt content, which exhibit a significant adsorption capacity. In such sediments, conventional remediation agents often face challenges in penetrating interaggregate regions (Ye et al., 2019). While electrochemical methods can be utilized in both in situ and ex situ contexts, numerous studies recommend their application for the ex situ remediation of dredged sediments due to their operational simplicity and controllability (Peng et al., 2018; Benamar et al., 2020).

-Chemical Extraction

Chemical extraction or flotation can be employed for the ex situ treatment of contaminated sediments; however, the efficiency of contaminant removal is significantly affected by sediment characteristics, including particle size, bubble dynamics, and the choice of extraction agents (Akcil et al., 2015; Peng et al., 2018).

-Bio-Slurry Reactor

Bio-slurry reactor remediation is a biological technology designed for contaminated sediments, featuring a large mobile reactor that creates favorable conditions to expedite the natural degradation of contaminants. This method offers superior heat transfer, isothermal conditions, minimal pressure drop, and enhanced scalability compared to traditional fixed-bed multi-tube reactors. It is particularly favored for scenarios requiring rapid and effective remediation when conventional biological treatments fall short (Pino-Herrera et al. 2017).

-Thermal Treatment

Thermal treatment encompasses processes such as thermal desorption, incineration, and vitrification. During thermal desorption, sediments are subjected to heat at temperatures ranging from 90°C to 500°C, leading to the concentration and collection of contaminants in liquid form, either retained on activated carbon or destroyed through combustion. Thermal destructive methods, such as incineration and vitrification, are employed to completely eliminate organic pollutants via oxidation. Additionally, calcined sediments with high clay content can be repurposed as pozzolanic supplementary cementing materials (SCMs) and geopolymer precursors, providing advantages for construction applications (Ferone et al. 2015; Peng et al. 2018).

Merits and Demerits of Various Ex Situ Remediation Approaches

Ex situ remediation technologies are characterized by high efficiency and ease of control compared to in situ methods; however, they may lead to water quality degradation and incur significant costs. Furthermore, there is a risk of secondary pollutants arising from the substantial environmental disturbances associated with these technologies. Among the various ex situ methods, washing is recommended for sediments with large, coarse particles, while electrochemical remediation is deemed most suitable for sediments with low porosity and strong adsorption capacities. Chemical extraction or flotation effectively manages contaminated sediments through the application of diverse chemicals. The bio-slurry reactor is gaining traction due to its rapid and safe remediation capabilities. Thermal remediation methods have demonstrated efficacy in addressing sediments heavily contaminated with organic matter and metallic pollutants, and the treated sediment can be reutilized as a recyclable construction material (Zhang et al. 2021b). Overall, ex situ remediation technologies contribute to sustainable resource utilization by enabling the repurposing of sediments for ecosystem restoration, construction materials (e.g., fill materials, partition blocks, paving stones), and agricultural applications (Xu and Wu 2023).

Future Projections on the Subject

- Advances in Bioremediation Through Omics Technologies

Recent advancements in bioremediation have shifted from traditional cultivation and biogeochemical processes to a technology-driven approach, supported by high-efficiency methodologies in molecular biology. Omics technologies—encompassing genomic, transcriptomic, metagenomic, and metabolomic analyses—offer valuable insights into the structures, functions, and dynamics of microorganisms involved in microbially mediated remediation. These data-intensive methods enhance our understanding of bioremediation efficacy at the molecular level, particularly within microbial communities.

Furthermore, insights from these technologies are crucial for developing engineering solutions to monitor and optimize bioremediation processes through gene expression analysis. Recent discoveries of metabolic diversity within biological systems also expand the potential for successful bioremediation outcomes. The advancements enabled by omics technologies are elucidating the molecular mechanisms of microbial remediation, thus providing promising strategies for addressing heavy metal contamination in sediments (Sun et al., 2021).

- **The Role of Nanotechnology in Enhancing Bioremediation**

Recent advancements in materials science and engineering have significantly improved our understanding of bioremediation mechanisms and their efficiency. Nanotechnology facilitates the use of nanoscale materials to create optimal conditions for the biotransformation of contaminants. Integrating nanotechnology into microbial processes presents a promising approach for elucidating microbial characteristics and enhancing the bioremediation of hazardous materials, including heavy metals. Additionally, nanotechnology-enabled sensors allow for real-time monitoring of heavy metal bioremediation efficiency, providing essential data for evaluating progress. Moreover, innovative nanomaterials can enhance bioavailability, supply essential nutrients, or generate signaling molecules that improve the efficiency of microbial processes. Interdisciplinary research that merges cutting-edge nanomaterials with microbial processes has been reported to foster significant advancements in developing sustainable solutions for the remediation of heavy metal-contaminated sediments (Sun et al. 2021).

Conclusion

Heavy metal contamination arises from both anthropogenic and natural processes, heightening the risk of these metals entering the food chain and accumulating in living organisms. As the imperative to remove heavy metal ions from sediments intensifies, the management of contaminated sediments has emerged as a significant environmental challenge.

Numerous studies have approached this issue through various methodologies (physical, chemical, biological) and applications (in situ, ex situ/on-site). These investigations reveal that traditional physicochemical methods—such as solvent extraction, evaporation, ion exchange, and reverse osmosis—are often prohibitively expensive and ineffective at low contaminant concentrations. In contrast, bioremediation, which employs bacteria, algae, and plants for the removal of heavy metals, has garnered attention as a viable green technology. The efficacy of bioremediation is influenced by factors such as the biological agents utilized, the properties of the target metals, and operational parameters. Nevertheless, comprehensive research is essential to tackle existing challenges and explore future prospects within the mechanisms of heavy metal bioremediation. It is anticipated that advancements in this field have been accelerated by innovative genetic engineering approaches, which will provide a scientific foundation for selecting the most appropriate remediation technology for specific scenarios.

Moreover, the necessity for large-scale studies to translate sediment remediation applications into practical solutions cannot be overstated. Legal challenges, negative public perceptions, and cost-related issues must also be carefully considered. While the management of contaminated sediments requires further investigation due to the inherent complexities of aquatic ecosystems, the literature review conducted in this study unequivocally indicates progress toward environmentally sustainable solutions.

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