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Research Article | Araştırma Makalesi

The First Report of Non-Indigenous Catfish, *Bagarius bagarius* (Family: Sisoridae) in the Inland Waters of Northeastern Iraq

Kuzeydoğu Irak'ın İç Sularında Yerli Olmayan Yayın Balığı *Bagarius bagarius*'un (Familya: Sisoridae) İlk Tespiti

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Abstract: A single specimen of *Bagarius bagarius* (Hamilton, 1822), a freshwater catfish native to the Indian subcontinent, has been documented for the first time in the inland waters of Iraq. The individual was caught by angling from the Sirwan River (Diyala Province, northeastern Iraq; 34°20'46.22"N, 45°10'23.82"E) on 3 July 2024 and, and measured 370 mm in total length. This discovery represents the first confirmation of this non-native species in Iraqi freshwater ecosystems and highlights the increasing role of the global aquarium trade in facilitating aquatic species invasions. The unintended introduction of *B. bagarius* into this ecosystem is likely attributable to ornamental fish trade, which has been implicated in translocation of more than 1,000 freshwater species in more than 125 countries. Such trade practices pose significant challenges for natural resource managers to identify and mitigate potential invasive species due to the extreme diversity of taxa traded.

Keywords
- Sirwan River
- Catfish
- Biodiversity
- New occurrence
- Aquarium trade

Özet: Hint yarımadasına özgü bir tatlı su yayın balığı olan *Bagarius bagarius*' un (Hamilton, 1822) tek bir örneği Irak'ın iç sularında ilk kez belgelenmiştir. Birey, 3 Temmuz 2024 tarihinde Sirwan Nehri'nden (Diyala Eyaleti, kuzeydoğu Irak; 34°20'46.22"N, 45°10'23.82"E) olta balıkçılığı ile yakalanmış ve toplam uzunluğu 370 mm olarak ölçülmüştür. Bu keşif, yerli olmayan bu türün Irak tatlı su ekosistemlerindeki ilk teyidini temsil etmekte ve küresel akvaryum ticaretinin sucul tür istilalarını kolaylaştırmadaki artan rolünü vurgulamaktadır. *B. bagarius*' un bu ekosisteme istem dışı girişinin, 125'ten fazla ülkede 1000'den fazla tatlı su türünün yer değiştirmesinde rol oynayan, süs balığı ticareti yoluyla ilişkilendirilmesi muhtemeldir. Bu tür ticaret uygulamaları, ticareti yapılan taksonların aşırı çeşitliliği nedeniyle, potansiyel istilacı türlerin belirlenmesi ve azaltılması hususunda, doğal kaynak yöneticileri için önemli zorluklar teşkil etmektedir.

Anahtar kelimeler
- Sirwan Nehri
- Yayın Balığı
- Biyoçeşitlilik
- Yeni vaka
- Akvaryum ticareti

1. INTRODUCTION

Bagarius bagarius (Hamilton 1822), also known as the goonch catfish, is a freshwater species that sometimes enters brackish water (Riede, 2004). *B. bagarius* (goonch) is primarily native to the Indian subcontinent (e.g., Ganges-Brahmaputra-Meghna river systems in India, Bangladesh, Nepal, and Bhutan) (Baensch & Riehl, 1985). However, there are reports of its presence in other Asian regions, though these are often debated due to taxonomic confusion with other *Bagarius* species (e.g., *B. yarrelli*, *B.*

suchus). From outside the Indian subcontinent, this species is reported from Southeast Asia. It is recorded from the Mekong River Basin in Cambodia (Rainboth, 1996; Kottelat, 2001), Laos (Kottelat, 2001), and Myanmar (Burma) (Talwar & Jhingran, 1991; Roberts, 1993). It is also reported from Indonesia at Sumatra (Kottelat et al., 1993) and Malaysia (Ng & Tan, 1999).

The maximum total length reported for this species is 2300 mm (Shrestha, 1994). Roberts (1983) suggested that the individuals of this species reach maturity at 80.5-192 mm for males and 80-185 mm for females. It is known as “Baghair” or “Bagh mach” in Bangladesh. In Bangla, the term “Bagh” refers to a tiger.

The freshwater catfish, *B. bagarius*, is imperative in Pakistan, Nepal, Bangladesh, Bhutan and India both as food and game fish, and there has been no exception to genetic deterioration for this species. This species plays an important role in the top-down management of the riverine food chain (Rabbani et al., 2023). This species is considered as Near Threatened (NT) in the IUCN (International Union for Conservation of Nature) Red Lists (Saha et al., 2021).

The business in freshwater ornamental fishes runs throughout more than 125 countries, includes well over 1000 discrete, widely obtainable species, and is conquered by species instigated from freshwater habitats (Evers et al., 2019). The great number of fish species in trade forms challenges in recognizing possibly invasive species, which is of specific worry to natural resource administrators. In reaction to the trade variety, invasion science research has focused on recognizing the features of species, habitats, and vectors that increase invasion success (Chan et al., 2019; Lawson & Hill, 2022). Generally, vital forecasters of infiltration achievement comprise bringing about pressure (Lockwood et al., 2009), preceding incursion history (Moyle & Marchetti 2006), and climatic resemblance (Bomford et al., 2010), which are knowledgeable by species features such as maximum body size and thermal tolerance (Schofield & Kline, 2018; Lawson & Hill, 2022).

Characteristics such as maximum body size can lead to pet neglect when a species grows too large for the tank dimensions (Holmberg et al., 2015). Pet desertion is a chief transmitter for incidents of ornamental fish outside of production areas, but is usually problematic to perceive (Magalhães et al., 2021). Large maximum body size should disturb procreate pressure because numerous hobbyists will lack the care needs of these species. Additionally, because catfish species may be let go at larger body sizes, existence and ecological influences may be augmented following discharge (Liang et al., 2020). Moreover, to sufficiently prevail over the propagation and survival pressure following release, climatic factors must also be appropriate to establish them effectively (Tuckett et al., 2023).

The only exotic fish introductions that might established via aquarium trade reported from the freshwater system in Iraq are those of *Pangasianodon hypophthalmus* (Sauvage 1878) (see Khamees et al., 2013), *Mollienesia latipinna* (Lesueur 1821) (see Al-Faisal & Mutlak, 2015), and *Atractosteus spatula* (Mutlak et al., 2017), and oscar, *Astronotus ocellatus* (Jawad et al., 2022). In the freshwater system of Iraq, three cichlid species were documented, *Oreochromis aureus* (Steindacher, 1864) (Mutlak & Al-Faisal, 2009) *Oreochromis niloticus* (Linnaeus 1758) (Al-Faisal & Mutlak, 2015), and *Coptodon zillii* (Gervais 1848) (Al-Sa’adi, 2007).

In the current report, we document the presence of another ornamental aquarium species, *B. bagarius* in the open waters of the Sirwan River, Diyala Province, northeastern Iraq. This arrival proposes the occurrence of a possibly harmful species in the inland waters of Iraq.

2. MATERIALS AND METHODS

A single specimen of *B. bagarius* (Figures 1a, b), a species native to the Indian subcontinent, was caught from Sirwan River, near Al-Islah Village (ca. 7 km north of Jalawla township, north of Diyala Province, northeastern Iraq (34°20'46.22"N,45°10'23.82"E) (Figure 2). The fish specimen was attained by a fisherman working in the area described above on 3rd July 2024. The specimen was identified according to Talwar and Jhingran (1991). While the specimen was with the fisherman, it was inspected, measured, and photographed, but it was not kept. The nomenclature was done as described by Eschmeyer et al. (2024). A series of morphometric measurements were made using a ruler in 1 mm increments (Table 1). The morphometric measurements were recorded as follows: Total length (TL), from the tip of the snout to the posterior tip of the caudal fin; Standard length (SL), from the tip of the snout to the posterior end of the hypural bones (caudal fin base); Head length (HL), from the tip of the snout to the posterior margin of the operculum; Eye diameter (ED), horizontal measurement across the eye; Interorbital distance (IOD), horizontal distance between the dorsal margins of the eyes; Predorsal fin length (PredL), from the snout tip to the anterior origin of the dorsal fin; Prepectoral fin length (PrepL), from the snout tip to the anterior origin of the pectoral fin; Prepelvic fin length (PrepelvL), from the snout tip to the anterior origin of the pelvic fin; Preanal fin length (PreanalL), from the snout tip to the anterior origin of the anal fin; Preadipose fin length (PreadL), from the snout tip to the anterior origin of the adipose fin; Caudal peduncle length (CPL), from the posterior end of the anal fin base to the caudal fin base; Caudal peduncle depth (CPD), minimum vertical depth of the caudal peduncle; Body depth (BD), maximum vertical depth of the body, measured at the deepest point.

Figure 1. Specimen of *B. bagarius* from the Sirwan River, north of Diyala Province, northeastern Iraq. A, directly after catch; B, Later after the hook and line were removed.

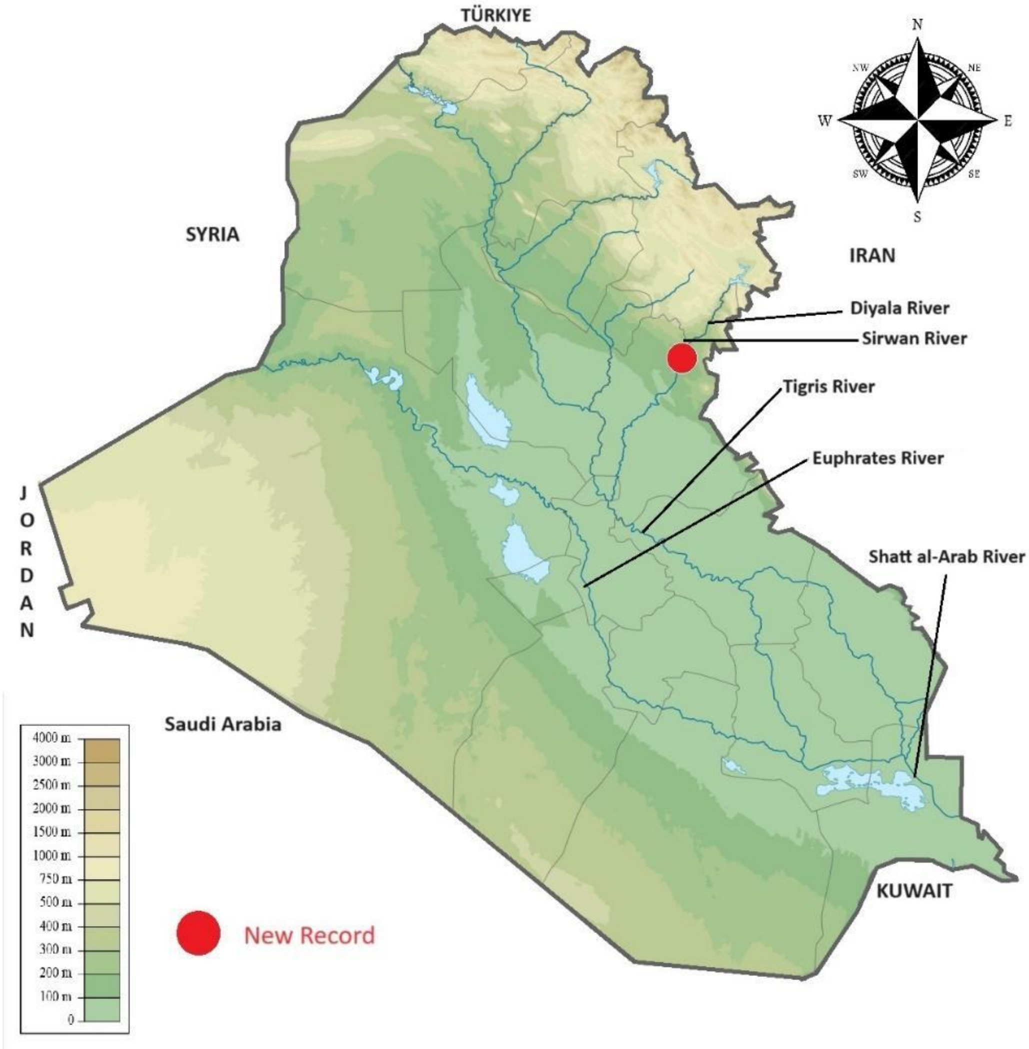

Figure 2. Map showing the collecting locality of *B. bagarius* from the Sirwan River, north of Diyala Province, northeastern of Iraq.

3. RESULTS

The specimen of *B. bagarius* measured as 370 mm in total length and showed the following characteristics: the body is dorsally convex and gradually tapering towards the tail. The ventral side is compressed with light yellow in colour. The mouth is equipped with an adhesive labial organ with which the fish cling to the rocks. There are four pairs of barbels around the mouth, with the premaxillary barbels being the largest. Eyes are small located near the posterior end of the head. The spiracles are wide and deep. Pectoral fins base anterior to the ventral-posterior edge of the operculum. The anterior base of the dorsal fin is located slightly anterior to the base of pelvic fin. The anterior end of the adipose fin is positioned anterior to the base of the anal fin. The body colour is olive deep brown with dark blotches. Body skin is thickened with unculiferous tubercles. Fins are well developed and have a light yellowish grey colour. All fins have black spots.

The morphometric measurements were made using a ruler in 1 mm increments, following the methods of Talwar and Jhingran (1991) and shown in Table 1.

Table 1. Morphometric measurements (mm) of *B. bagarius* collected from the Sirwan River, northeastern Iraq.

Characters	Present study	Roberts, 1983	Paul et al., 2019
Total length (TL)	370	-	161 — 210
Standard length (% in TL)	328 (88.6%)	40.8 — 192	-
Head length (% in SL)	230 (70.1%)	-	-
Eye diameter (% in HL)	20.5 (8.9%)	21.3 — 24.2	-
Interorbital distance (% in HL)	73.8 (32.1%)	9.0 — 12.0	-
Predorsal fin length (% in SL)	139.3 (42.5%)	-	-
Prepectoral fin length (% in SL)	123 (37%)	-	-
Prepelvic fin length (% in SL)	164 (50%)	-	-
Preanal fin length (% in SL)	254.2 (77.5%)	-	-
Preadipose fin length (% in SL)	234 (71.3%)	-	-
Caudal peduncle length (% in SL)	36.9 (11.2%)	4.3 — 5.5	-
Caudal peduncle width (% in SL)	33 (10.1%)	19.4 — 24.7	-
Body depth at the dorsal fin (% in SL)	86.1 (26.3%)	5.6 — 7.2	-

4. DISCUSSION

The maximum total length of *B. bagarius* can reach 2300 mm (Shrestha, 1994). The total length of the specimen described here is 370 mm, which is well below the total length reported. Our specimen (328 mm SL) is larger than that of Roberts (1983) (40.8—192 mm SL) and Paul et al. (2019) (161—210 mm SL).

In his taxonomic revision of the South and Southeast Asian sisorid catfish genus *Bagarius*, Roberts (1983) noted that *B. bagarius* and *B. yarrelli* are morphologically similar externally, but distinguishable by the position of the adipose fin. Roberts (1983) provided a photographic reference of *B. bagarius* in his work, and emphasized the considerable intraspecific variation in color patterns of this species. Similarly, Dutta and Sheik (2017) and Ng and Kottelat (2021) provided photographs of *B. bagarius*. The three photos provided by Roberts (1983), Dutta and Sheik (2017) and Ng and Kottelat (2021) differ from each other. Consequently, the observed colour differences between the Iraqi specimen and the specimen described by Roberts (1983) may reflect this natural variability.

In *B. bagarius*, the adipose fin commences far back over the anal fin, on a vertical through the base of the third or fourth anal-fin ray, while in *B. yarrelli* it begins near or in front of a vertical line through the anal fin origin. He also suggested that both *B. yarrelli* and *B. bagarius* showed a wide colour variation making the distinction of these two species very difficult.

The goonch, *B. bagarius* can be harmful if it becomes a successful invasive species, and it can make a maintainable population. The goonch is a carnivorous fish; it feeds on small fishes, prawns, frogs, insects (Rahman, 1989; 2005). Therefore, *B. bagarius* is also important as a predator in top-down control of riverine food web. As most of the population of Iraq does not consume catfish species, the impact on this species will be minimal. Additionally, this fish could damage fishing nets due to the presence of sharp pectoral fin spines.

There are no published records of established populations of *B. bagarius* outside its native range in the Indian subcontinent. Furthermore, the species has not been reported in Iranian freshwater systems (Jouladeh-Roudbar et al., 2015; Esmaeili et al., 2018; Esmaeili, 2021; Eagderi et al., 2022; Çiçek et al., 2024) or Turkish freshwater systems (Çiçek et al., 2024). Consequently, the hypothesis that *B. bagarius* specimens reached Iraqi freshwaters via Iran or Türkiye lacks empirical support and cannot be accepted.

It is difficult to tell precisely how the specimen of *B. bagarius* was introduced and how it penetrated the Sirwan River, north of Diyala Province, northeastern Iraq, but it is known that these fish are considered among the ornamental fish and can be obtained from the ornamental fish shops, especially from the countries in the Indian subcontinent (Bidisha & Angsuman, 2014; Sinha & Jamal, 2015; Paul et al., 2019).

Recently, the aquarium trade in Iraq has become very popular with the easing of regulations for importing fishes into Iraq and an increase of aquarium shops (personal observation). The goonch is sold in these shops, mainly in large cities like Baghdad and Basrah. Catfish species are usually sold in the Aquaria shop for the purpose of cleaning the tank. Aquarists regularly get rid of the large-sized catfish due to the size limit in the aquaria shop. Therefore, they liberate the catfish fish specimens into the open water bodies. It is also possible that the specimen of the goonch was released, because it reached a large size in a short period of time and became too large to keep in the aquarium. The current finding signifies the introduction of the fifth Iraqi case of the exotic species blamed on aquarium trade.

A recent survey of ornamental fish shops across major Iraqi cities (e.g., Baghdad, Basrah, Erbil) revealed that over 60% of traded species are non-native, originating primarily from Southeast Asia, South America, and the Indian subcontinent. Commonly sold species include *Pangasianodon hypophthalmus* (Asian shark catfish), *B. bagarius* (goonch), and *O. niloticus* (Nile tilapia), alongside popular aquarium staples like *Carassius auratus* (goldfish) and *Poecilia reticulata* (guppies). Approximately 45% of shop owners reported limited awareness of the species' invasive potential, with many customers releasing oversized or unwanted fish into local waterways. Import records further indicate lax regulatory oversight, with 30% of shops sourcing stock from unverified suppliers, exacerbating the risk of accidental introductions (Jawad et al., 2022).

In the case of the settlement of ***B. bagarius*** in the freshwater system of Iraq, the dealings of this species with local species require to be investigated chiefly with those that necessitate comparable ecological settings. Throughout the management strategies in progress in the Euphrates-Tigris Rivers in Iraq, a distinct consideration should be adopted to report any invasive species and present a management policy to eradicate them from the habitat.

The observation of ***B. bagarius*** in Iraq should lead to adopting strong actions to control the importation of species in the aquarium trade, which is accountable for the admission to new habitats for many fish, plant and invertebrate species worldwide (Rixon et al., 2005). Recently, the aquarium trade in Iraq fascinates numerous people, and, therefore, many native Indian subcontinent fish species are imported to big cities such as Baghdad and Basrah. The release of possibly harmful species, e.g., the goonch, in the many rivers and streams of Iraq will have an influence on the biodiversity.

Examples of the ecological disruption caused by catfish have been reported for many species of this group. The introduction of invasive catfish species, such as the walking catfish (*Clarias batrachus*), has profoundly disrupted aquatic food webs in non-native habitats. As opportunistic benthic predators, these catfish consume a wide range of prey, including native fish eggs, larvae, crustaceans, and benthic invertebrates, leading to trophic cascades and declines in native biodiversity. For example, in Florida, *C. batrachus* has reduced populations of native sunfish (Centrarchidae) and crayfish (*Procambarus* spp.) through direct predation, altering energy flow and competitive dynamics (Courtenay & Stauffer, 1990; Mendoza et al., 2022). Their ability to survive in hypoxic conditions and traverse terrestrial habitats further exacerbates their spread, enabling colonization of isolated water bodies and intensifying pressure on vulnerable ecosystems.

Beyond predation, invasive catfish modify habitats by destabilizing sediments during foraging, which increases turbidity and reduces light penetration, thereby suppressing primary producers like phytoplankton and submerged macrophytes (Simberloff et al., 2013). This degradation of water quality cascades through the food web, impairing species reliant on clear-water conditions. In the Philippines, *C. batrachus* invasions have been linked to declines in endemic gobies (Gobiidae) and shrimp, disrupting traditional fisheries and local livelihoods (Lodge et al., 2016). Mitigation efforts, such as targeted removals and public awareness campaigns, face challenges due to the species' rapid reproduction and adaptability (Hill & Sowards, 2015). Addressing these impacts requires integrated strategies that combine ecological monitoring, stricter biosecurity, and community engagement to restore food web integrity.

Management Recommendations: To mitigate the ecological risks posed by invasive catfish species, banning imports of large-bodied catfish (e.g., *Bagarius* spp., *C. batrachus*) through stricter trade regulations is critical, as such species often outgrow aquaria and are prone to release into natural waterways (Evers et al., 2019). Concurrently, public awareness campaigns should emphasize the ecological consequences of pet abandonment, targeting hobbyists and vendors via workshops, signage in pet stores, and social media outreach (Lodge et al., 2016). For example, campaigns could highlight case studies of invasive catfish disrupting local fisheries, such as *B. bagarius* predation on native fish in Iraq (Jawad et al., 2022). Combining import bans with education reduces propagule pressure while fostering community stewardship, offering a dual approach to safeguarding aquatic ecosystems.

Guidelines to prevent the introduction of unwelcome aquarium species, as well as the education of all members in the aquarium trade industry, should be brought with better authority (Knight, 2010). A competent system needs to be put in place to screen the introduction of fishes to identify possibly harmful species before their release to the aquarium market (Rixon et al., 2005).

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

LJ; Conceptualization; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing original draft; writing review and editing. Ahmed MHAD: Observation, obtaining information about the fish specimen. SSG: fish species identification and confirmation, reading the first draft of the manuscript. OFAS: Observation, obtaining information about the fish specimen.

ETHICS STATEMENT

This work is based on personal fish catch. Therefore, ethical aspects are not applicable.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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Research Article
Araştırma Makalesi

The Potential of Ornamental Fish Culture in Biofloc Technology with Different C/N Ratio and Multi-Criteria Decision Making Model: An Example of Goldfish (*Carassius auratus*)

Biyoflok Teknolojisinde Farklı C/N Oranı ve Çok Kriterli Karar Verme Modeli ile Akvaryum Balığı Yetiştiriciliğinin Potansiyeli: Japon Balığı (*Carassius auratus*) Örneği

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Abstract: Biofloc technology (BFT) has become an agenda to meet the need for protein food and ornamental aquaculture with the increasing interest in sustainable aquaculture. In this context, the current study focused on BFT for ornamental goldfish (*Carassius auratus*), which has commercial value. The study was conducted with control and two different C/N ratios (15:1 and 20:1). On the other hand, increasing the C/N ratio had a positive effect on total suspended solids and total bacteria count in the culture water. The specific growth rate and weight gain were observed to be significantly higher at a high C/N ratio. The feed conversion ratio was lower in the C/N 20 group, indicating a more efficient feed utilization. According to the liver histological results, the vacuolization symptom is more severe in BFT groups. Considering all the results, the suitability of *C. auratus* cultivation in the BFT system with a C/N ratio of 20 was proven according to nine different evaluation criteria. In conclusion, rearing C. auratus in BFT systems is advised due to its economic and ecological benefits.

Keywords
- Ornamental aquaculture
- Sustainable aquaculture
- Nitrogenous compounds
- Fish
- Histology

Özet: Biyoflok teknolojisi (BFT), yalnızca protein ihtiyacını karşılamak için değil, aynı zamanda akvaryum balığı yetiştiriciliği için de gündeme gelmiştir. Bu bağlamda, mevcut çalışma ticari değere sahip bir tür olan Japon balığı (*Carassius auratus*) üzerine odaklanmıştır. Kontrol grubu ve iki farklı C/N oranı (15:1 ve 20:1) ile gerçekleştirilen çalışmada, BFT gruplarında azot döngüsü hızlı bir şekilde gerçekleşmiştir. Diğer yandan, C/N oranının artırılması, kültür suyunda toplam askıda katı madde ve toplam bakteri sayısı üzerinde olumlu bir etki göstermiştir. Büyüme performansı açısından, yüksek C/N oranında spesifik büyüme hızı ve ağırlık artışı önemli ölçüde daha yüksek gözlemlenmiştir. Yem değerlendirme oranı ise C/N 20 grubu için daha düşük oranla daha verimli bir sonuç göstermiştir. Karaciğer histolojik sonuçlarına göre, vakuolizasyon semptomunun BFT gruplarında daha şiddetli olduğu tespit edilmiştir. Tüm sonuçlar göz önünde bulundurulduğunda, 20 C/N oranına sahip BFT sisteminde *C. auratus* yetiştiriciliğinin uygunluğu dokuz farklı değerlendirme kriterine göre kanıtlanmıştır. Sonuç olarak, *C. auratus*'un BFT sistemlerinde yetiştirilmesi hem ekonomik hem de ekolojik açıdan önerilmektedir.

Anahtar kelimeler
- Süs balıkları yetiştiriciliği
- Sürdürülebilir su ürünleri yetiştiriciliği
- Azotlu Bileşikler
- Balık
- Histoloji

1. INTRODUCTION

The main purpose of the growth in aquaculture is to produce more without increasing the use of basic natural resources such as water and soil and harming the environment (Mizuta et al., 2023). Another goal is to design systems that provide an appropriate cost/benefit ratio to support economic and social sustainability (Avnimelech, 2009). With reduced access to water resources, many alternative strategies for sustainable systems in aquaculture are being studied (Turcios and Papenbrock, 2014) and the flow-through system is a production model that has been discussed in recent years in terms of sustainable water use (Cullis et al., 2018). Recirculating aquaculture systems (RASs) use significantly less water than traditional flow-through farming systems (Ahmed and Turchini, 2021), but they involve high initial investment and operating costs, as well as management challenges, which can pose economic and logistical difficulties (Zhang et al., 2024).

Feeding costs in aquaculture facilities constitute approximately 60-70% of total production costs (Verdegem et al., 2023). Fish meal and fish oil, which are gold ingredients for protein and lipid sources, have become extremely finite items in aquafeeds. With biofloc technology (BFT), it is possible to reduce feed costs in aquaculture, the use of high water volumes, and mitigate potential environmental pollution with effluent water (Avnimelech, 1999). The BFT concept is a partially innovative method in which a suitable living environment is provided for heterotrophic bacteria (Crab et al., 2012). Thus, bacteria remove ammonia from the water and form a floc that aquatic organisms can consume. The appropriate C/N ratio in water for heterotrophic bacteria is directly or indirectly (via feed content) provided by an external carbon source added (Zhao et al., 2024). Different kind of C sources such as molasses, sucrose, and starch were used in previous studies (Minaz and Kubilay, 2021). It has been reported that successful results were obtained with the C/N ratio between 10:1 and 20:1 (Panigrahi et al., 2018; Xu et al., 2016). Additionally, temperature is vital for the proliferation of bacteria in BFT systems (Avnimelech, 1999; Minaz et al., 2023). In order to adapt to the living standards of heterotrophic bacteria, water must be at adequate temperatures. Therefore, breeding warm water fish in BFT systems can provide more economic advantages. BFT systems in aquaculture are utilized not only for food production but also for ornamental fish cultivation (Besen et al., 2021; da Cunha et al., 2020; Yu et al., 2020). Biofloc systems can play a crucial role in farming ornamental species by optimizing water quality and maintaining fish health (Wang et al., 2015). The microorganisms' ability to biologically process waste into nutrients improves feed efficiency and promotes sustainable production (Faizullah et al., 2015). Additionally, it can reduce disease pressure, minimizing the need for antibiotics. However, proper biofloc management is necessary as water turbidity can be undesirable for aesthetic species. In this context, goldfish (*Carassius auratus*) has high value with its interesting color and is one of the most popular ornamental species in the world (Sinha and Asimi, 2007). The improvement of skin pigmentation in goldfish cultured in biofloc technology enhances the overall appeal of the fish (da Cunha et al., 2020).

In biofloc terms, the 'waste'—nitrogen formed by uneaten feed and feces from the cultured organisms—is converted into protein feed available for the same aquatic organisms. This feature enables the minimization of water exchange without compromising water quality, thereby reducing the total amount of nutrients discharged into the environment (Lezama-Cervantes and Paniagua-Michel, 2010). Despite its well-documented benefits in commercial aquaculture, the application of BFT in the ornamental fish industry remains underexplored. Ornamental fish species, including goldfish, are among the most widely traded species globally, yet their production still relies heavily on traditional systems that require frequent water exchanges, leading to increased operational costs and environmental concerns. Given the rising demand for sustainable and cost-effective production systems in the ornamental fish industry, investigating the applicability of BFT for goldfish production is essential. This study hypothesizes that different C/N ratios in BFT systems can significantly influence the growth performance, liver histology, and water quality parameters of goldfish (*Carassius auratus*). To address this hypothesis, the study compares two C/N ratios (15 and 20) against a control group to determine the most suitable protocol for goldfish culture in BFT systems. Additionally, this study employs the PROMETHEE method, a multi-criteria decision-making model, to evaluate the effectiveness of different BFT treatments systematically. This model integrates key parameters, including water quality variables, histological indicators, and growth performance metrics, to establish a comprehensive ranking of BFT conditions. By utilizing this structured approach, the study aims to provide a scientifically sound recommendation for optimizing BFT systems in ornamental fish aquaculture.

2. MATERIAL and METHODS

This study was carried out over a period of four weeks at the Aquaculture Application and Research Center in Recep Tayyip Erdoğan University, Türkiye. Current study was checked and approved by the Ethical Local Committee of the Recep Tayyip Erdogan University (Decision No: 2023/05). The methods were carried out in accordance with the relevant guidelines and regulations.

2.1. Experimental design

The fish were transferred to the facility 14 days before the trial to adapt to environmental conditions. During this adaptation period, the biofloc system was initiated by inoculating the tanks with aquarium water to promote the gradual development of a heterotrophic bacterial community. Three treatments were tested in triplicates, consisting of two BFT groups with C/N ratios of 15 (C/N 15) and 20 (C/N 20) and a control group. A total of 240 healthy goldfish (*Carassius auratus*), with an average weight of 3.27±0.19 g, were used in this study. The fish were obtained from a local aquarium shop, and before the experiment, all individuals were examined for bacterial and parasitic diseases to ensure their health status. Each aquarium had a volume of 100 L, with dimensions of approximately 40 cm in width, 100 cm in length. The fish were fed twice daily (10:00 A.M. and 04:00 P.M.) at a rate of 4% of their biomass. The commercial diet used in the study was specifically formulated for goldfish, and its composition is provided in Table 1. The feed pellets had a diameter of approximately 1.5 mm , and no additional vitamins or supplements were added to the formulation since the study primarily focused on the effects of the C/N ratio. The feed was stored in a closed jar in a dry environment to maintain its quality. The composition of the feed included various cereals, vegetable protein extracts, derivatives of vegetable origin, fish and fish derivatives, oils and fats, minerals, algae, and yeasts. The trial was conducted in a controlled indoor environment where the air temperature was regulated. A 12-hour light and 12-hour dark photoperiod was applied throughout the study. Starch was used as the carbon source to maintain the appropriate C/N ratio in the BFT groups, with a carbon content of 45%. The C/N ratio was calculated based on a previously determined model (Crab et al., 2012). For the control group, water was treated using an aquarium filter system (sand bed), and 80% of the water was renewed weekly. All aquaria were continuously aerated for 24 hours using an air stone system connected to a central air pump. Any water loss due to evaporation was replenished accordingly.

Table 1. Analytic constituents of commercial feed.

Components		Content
Crude protein (%)		28
Crude oils and fats (%)		3.5
Crude fibre (%)		2.0
Moisture (%)		7.0
Additives (IU/kg)	Vitamin A	16000
	Vitamin D	1890
Trace elements (mg/kg)	Manganese ($MnSO_4 \cdot H_2O$)	81
	Zinc (H_2O_5SZn)	48
	Iron ($FeSO_4 \cdot H_2O$)	31

2.2. Water quality parameters and growth performance

Water temperature, dissolved oxygen (DO), pH, and electrical conductivity (EC) were daily measured as routine water quality parameters by a portable multi-parameter (Hach, HQ40D 58258-00). The weight of total suspended solids (TSS) was measured by filtering 50 mL of aquarium water through glass fiber Whatman GF/F filter paper with 45 um pore size. The filter papers were then dried at 60 °C for 24 hours and TSS was calculated based on the final weight of filter glass. TSS measurements were conducted every other day throughout the experimental period. The volume of settling flocs was measured once every two days by Imhoff cone (Avnimelech and Kochba, 2009). A sedimentation period of 15 minutes was allowed to measure settleable solids. Ammonia, nitrite, and nitrate were measured weekly using a spectrophotometric method (Rice et al., 2017). Commercial test kits were used for these analyses: Hach LCK 304 for ammonia, Hach NitriVer® 2 for nitrite, and Hach NitraVer® 6 for nitrate. The total bacterial count was performed on a plate count agar (PCA) at the end of the study with three replicates.

At the end of the four-week trial period, the fish were collected to calculate final weights (FW), specific growth rate (SGR), weight growth rate (WGR), and feed conversion ratio (FCR). Fish weights were measured with a precision scale at the beginning and end of the study for growth performance calculations. Growth parameters were calculated as per the following equations:

$$SGR\%/d = (ln\, ln\, FW - ln\, ln\, IW\,)/t \times 100$$

$$WGR = (FW - IW)/FW \times 100$$

$$FCR = FI/WG$$

Where, FW (g) and IW (g) are the weights of fish in the final and initial stages of the trial, respectively. In addition, FI (g), WG (g), and t (day) represents feed intake, weight gain of fish, and trial period (4 weeks), respectively.

2.3. Histological examination

Anesthetized fish (60 mg/L clove oil) were cut from the abdomen and liver tissues were fixed in 10% neutral buffered formalin. Fixed tissues were transferred into 50% ethyl alcohol after 48 hours. Liver tissues were passed throughout the alcohol series and placed one night in the liquid paraffin at 65 °C. The next day, livers were embedded into the paraffin. Samples were cut with a thickness of 5 µm using a microtome. Samples taken from microscope slides were subjected to alcohol and xylene series again. Before this process, paraffin was removed at 65 °C. Then, tissue sections were stained with hematoxylin and eosin. Tissues covered with cover-slip were examined under a light microscope (Minaz et al., 2022).

2.4. Multi-criteria decision model-PROMETHEE

A multi-criteria decision model (MCDM) was used to determine which of the two C/N ratio scenarios was more beneficial (Demirel et al., 2021). This model includes a total of 4 basic phases: (1) examination of biofloc on *C. auratus*, (2) formulation of evaluation criteria and weights for each C/N ratio, (3) scoring two C/N ratios depending on evaluation criteria, and (4) final decision the best C/N ratio with PROMETHEE method. This model considers a set of evaluation criteria for each alternative. Each evaluation criterion contains several weight values, the sum of which is "1" (It means percentage importance of criteria).

2.4.1. Determination of evaluation criteria and its weight percentage

According to the MCDM principle, alternatives must be evaluated based on predetermined criteria. The decision maker evaluates and reaches a conclusion by considering these criteria. The evaluation criteria for determining the optimal C/N ratio are based on water quality, bacterial community, fish growth performance, and the histological state of the fish. In this study, we identified 9 different evaluation criteria, which were categorized into three main headings: (1) water quality parameters, (2) growth performance, and (3) histological alterations. The evaluation criteria and their weightings, determined by expert opinion based on their importance factor, are presented in Table 2. In the model, both quantitative parameters and qualitative parameters that could be quantified were used to determine the evaluation criteria. The weight values for each criterion were established based on expert opinion, reflecting the importance of each factor. To ensure accuracy in the MCDM analysis, a clear and structured process was followed for determining the weights. A panel of experts, all highly knowledgeable in aquaculture and fish welfare, was consulted to assess the relative significance of each criterion. These experts were selected due to their extensive experience and specialized expertise in histological and blood parameter analysis. The Analytic Hierarchy Process (AHP) was employed to compile expert opinions and assign weights, as this method effectively captures expert judgment while minimizing potential biases. A total of 15 experts independently reviewed and evaluated the criteria to finalize the weights. In the multi-criteria decision analysis of groups with two different C/N ratios using biofloc technology, a Consistency Index (CI) of 0.013 and a Consistency Ratio (CR) of 0.010 were obtained, indicating an acceptable level of consistency in the prioritization of the ratios based on various criteria. In PROMETHEE software, the weight scores of the criteria must always add up to 1 (Ozturk, 2018). Therefore, weight scores are distributed according to the importance of the criteria. The most effective criteria in choosing the best C/N ratio are SGR, FCR, ammonia, and nitrite. Because the growth performance of the fish is the primary parameter showing the effectiveness of the biofloc, while ammonia and nitrite are indicators of toxicity for fish.

Table 2. Evaluation criteria and weighting scale.

Criteria number	Evaluation criteria	Weight value	Preference function
C1	Nitrate	0.05	Linear
C2	Nitrite	0.15	V-shape
C3	Ammonia	0.15	V-shape
C4	Temperature	0.05	Linear
C5	Total bacteria	0.05	Linear
C6	Settleable solids	0.05	Linear
C7	SGR	0.15	V-shape
C8	WGR	0.10	Linear
C9	FCR	0.15	V-shape
C10	Histology	0.10	Level

2.4.2. Selection of best C/N ratio based on PROMETHEE analysis

The best C/N ratio for *C. auratus* culture in the BFT system was determined based on the PROMETHEE decision model (Visual PROMETHEE 1.1.0.0). Firstly, the evaluation criteria and the weight values of these criteria were determined. Afterwards, a decision matrix was created. The PROMETHEE decision model allows decision-makers to either select a particular option based on an evaluation factor or restrict the evaluation factor to predetermined values. The approach involves a seven-step process to arrive at a decision.

(1) The data matrix is prepared using equations 1, 2, and 3. Criterion weights are determined for k number criteria (k=10 in the current study).

$$w = w_1, w_2, \ldots, w_k \quad (1)$$

$w: criteria\ weight$

$$c = f_1, f_2, \ldots, f_k \quad (2)$$

$c: criteria\ weight$ and $f: function$

$$S = (A, B, C, \ldots) \quad (3)$$

$S: decision\ alternatives$

(2) Preference functions for the criteria are determined according to Equation 4 (linear preference function) and Equation 5 (usual preference function).

$p(d) = \{0\ d \le q\ (d-p)/(p-q)\ q < d \le p\ 1\ d > p\ (d-p)/(p-q)$ (4)

$q: indifference\ value$

$p: sufficient\ biggest\ difference$

$q: difference\ between\ two\ decision\ alternatives$

$p(d) = \{0\ d \le 0\ 1\ d > 0$ (5)

(3) The common preference function for decision alternatives “x” and “y” is calculated with Equation 6.

$p(x,y) = \{0\ f(x) \le f(y)\ p[f(x) - f(y)]\ f(x) > f(y)$ (6)

According to Equation 6, it is determined whether the evaluation factor is maximization or minimization.

(4) The preference index of “x” and “y” decision options evaluated according to the k-number criterion was calculated using Equation 7.

$$\pi(x,y) = \sum_{i=1}^{K} w_i P_i(x,y) \quad (7)$$

(5) Determining positive φ^+ and negative φ^- advantages for alternatives with Equations 8 and 9.

$$\varphi^+(x) = \frac{1}{n-1}\sum \pi(x,y) \quad (8)$$

$$\varphi^-(x) = \frac{1}{n-1}\sum \pi(y,x) \quad (9)$$

(6) Partial priorities are determined with PROMETHEE I. Equations 10 and 11 show the difference between “x” and “y” decision alternatives. If any of the following conditions occur, decision option “x” is indistinguishable from decision option “y”.

$$\varphi^+(x) = \varphi^+(y) \quad (10)$$

$$\varphi^-(x) = \varphi^-(y) \quad (11)$$

Similar to the example below, if any of the conditions in Equation 12, 13,14 occur, the “x” decision option is superior to the “y” decision option.

$$\varphi^+(x) > \varphi^+(y)\ and\ \varphi^-(x) < \varphi^-(y) \quad (12)$$

$$\varphi^+(x) > \varphi^+(y)\ and\ \varphi^-(x) = \varphi^-(y) \quad (13)$$

$$\varphi^-(x) < \varphi^-(y)\ and\ \varphi^+(x) = \varphi^+(y) \quad (14)$$

In the condition where decision alternative "x" cannot be compared with decision alternative "y", equations 15 and 16 are used.

$$\varphi^+(x) > \varphi^+(y)\ and\ \varphi^-(x) > \varphi^-(y) \quad (15)$$

$$\varphi^+(x) < \varphi^+(y)\ and\ \varphi^-(x) < \varphi^-(y) \quad (16)$$

(7) The ranking of decision options is performed with PROMETHEE II. The exact priorities of the decision options are determined by Equation 17. All calculated priority values are sorted from high priority to low priority. Thus, all decision options are evaluated in a similar way and a complete ranking is obtained.

$$\varphi(x) = \varphi^{+}(x) - \varphi^{-}(x) \quad (17)$$

The decisions given in equations 18 and 19 can be reached according to the full priority value calculated from the "x" and "y" decision alternatives.

$$\varphi(x) > \varphi(y) \quad (18)$$

Decision alternative "x" is superior.

$$\varphi(x) = \varphi(y) \quad (18)$$

Decision alternatives "x" and "y" are not superior.

2.5. Statistical analyzes

All data are presented as the means ± standard deviation (SD). As a preliminary test, it was proven that the data sets exhibited normal distribution based on the Kolmogorov-Smirnov test. Student T-test was used for the comparison of total bacteria counts between groups. In addition, significant differences between groups for growth performance were determined with one-way ANOVA test. In case of significant differences between C/N groups, the Tukey post-hoc test was used to assess differences. Differences were considered statistically significant when the calculated p value was <0.05. All analyses were performed in SPSS software (Version 23, IBM Corp., Armonk, New York, USA).

3. RESULTS

3.1. Assessment of water quality

The water quality parameters measured over the study period are shown in Table 3. Accordingly, no significant differences were observed between the groups in terms of temperature, pH, DO, EC and settleable solids (P>0.05). On the other hand, the total bacteria count and TSS were significantly higher in the C/N 20 group than C/N 15 group (P<0.01). Even though ammonium concentrations were relatively higher in the biofloc groups in the first two weeks, there was a rapid decrease in the third week (Figure 1). On the contrary, a rapid increase was noted as of the third week in the control. Nitrite and nitrate concentrations increased rapidly in the biofloc groups, especially after the third week. The control group showed lower results than the BFT groups initially and then remained stable throughout the trial.

Table 3. Routine water quality parameters monitored throughout the study. C/N 15: biofloc group with 15 C/N ratio, C/N 20: biofloc group with 20 C/N ratio. EC: electrical conductivity, DO: dissolved oxygen, TSS: total suspended solids.

	Control	**C/N 15**	**C/N 20**
pH	7.19±0.56	6.93±0.72	6.95±0.70
Temperature (°C)	29.07±0.25	28.50±0.73	28.45±0.55
DO (mg/L)	6.75±0.27	7.28±0.26	7.12±0.21
EC (µS/cm)	113.68±15.4	140.1±15.3	150.93±45.2
Settleable solids (mL/L)		10.25±2.12	13.91±3.30
TSS (mg/L)		346.45±38.8^{b}	456.24±48.4^{a}
Total bacteria (log CFU/mL)		10.56±0.41^{b}	12.46±0.27^{a}

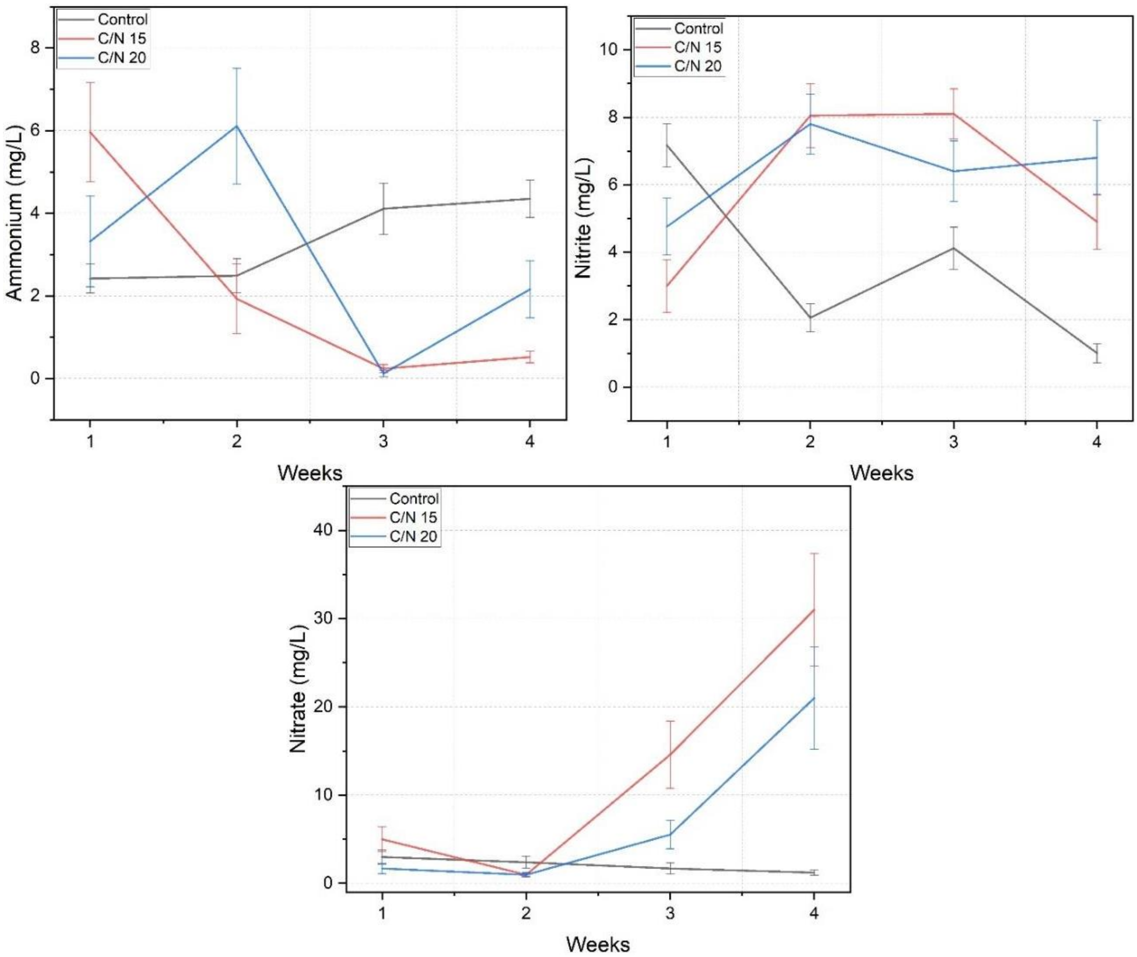

Figure 1. Changes in ammonium, nitrite and nitrate depending on time (4 weeks). C/N 15: biofloc group with 15 C/N ratio, C/N 20: biofloc group with 20 C/N ratio.

3.2. Growth performance of fish

Table 4 shows the growth performance parameters of goldfish. Final weights did not differ significantly between groups ($p>0.05$). However, the specific growth rate and weight gain ratios were significantly higher in the BFT group with C/N 20 compared to the other two groups ($p<0.01$). In addition, a significant difference was observed in terms of FCR between the control and C/N 20 group ($p<0.05$).

Table 4. Growth performance parameters of goldfish. C/N 15: biofloc group with 15 C/N ratio, C/N 20: biofloc group with 20 C/N ratio. IW: initial weight, FW: final weight, SGR: specific growth rate, WGR: weight growth, FCR: feed conversion ratio.

Growth performance	Control	C/N15	C/N20
IW	3.35±0.35	3.21±0.17	3.24±0.08
FW	5.47±1.11	4.98±1.18	6.84±1.01
SGR	$1.43±0.12^{b}$	$1.31±0.21^{b}$	$2.08±0.14^{a}$
WGR	$38.75±5.27^{b}$	$35.54±4.78^{b}$	$52.63±6.41^{a}$
FCR	$1.96±0.32^{a}$	$1.72±0.41^{ab}$	$1.37±0.25^{b}$

*Values in the same row with different superscripts are significantly different.

3.3. Histological assessment of liver tissue

Liver histological examinations of goldfish in BFT and control treatments are shown in Figure 2. No histological differences were noted between the groups. More severe vacuolization symptoms were observed only in the liver tissues of the C/N 20 group compared to the control and C/N 15 groups.

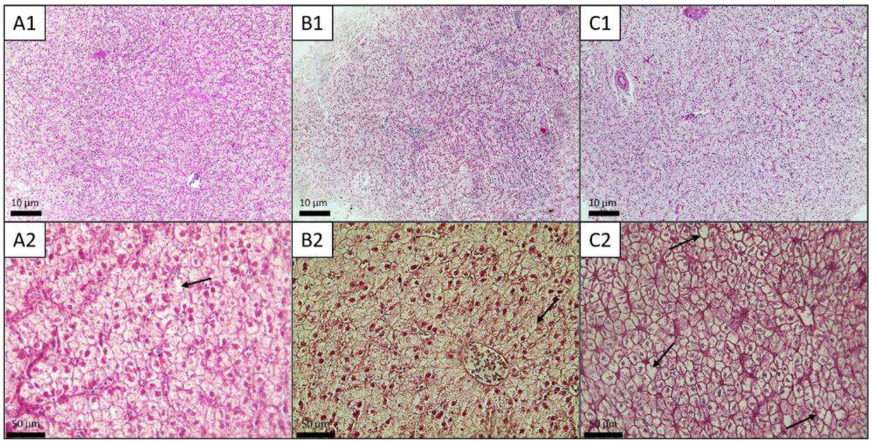

Figure 2. Histological comparison between BFT and control groups. A: Control, B: biofloc group with 15 C/N ratio (C/N 15), C: biofloc group with 20 C/N ratio (C/N20) groups. 1: 4x and 2: 10x magnification. Arrow: vacuolization.

3.4. Determination of the best C/N ratio (PROMETHEE-MCDM)

In accordance with the PROMETHEE decision model, the alternatives were ranked based on their respective scores, as presented in Table 5. Depending on the positive and negative superiority values, the control group is the least preferable alternative. Additionally, the C/N 20 ratio is the most preferable alternative depending on the evaluation criteria. Figure 3 presents the distribution of criteria affecting the ranking of treatments. The main criteria that make C/N 20 treatment the preferable alternative are the variables related to growth performance.

Table 5. Ranking of culture alternatives for *C. auratus.*

Treatments	$\varphi^+(i)$	$\varphi^-(i)$	$\varphi(i)$	Ranks
Control	0.1464	0.4189	-0.2726	3
C/N 15	0.3077	0.3433	-0.0356	2
C/N 20	0.4873	0.1791	0.3082	1

$\varphi^+(i)$ positive superiority values
$\varphi^-(i)$ negative superiority values
$\varphi(i)$ final superiority values

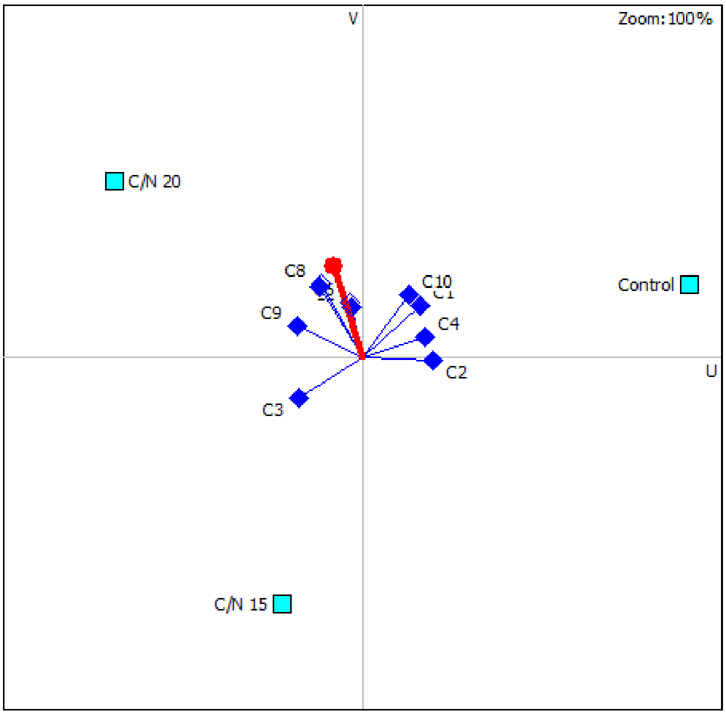

Figure 3. Distribution of criteria affecting the ranking of treatments.

4. DISCUSSION

Physicochemical water parameters are an important factor for the health of cultured organisms in aquaculture (Khanjani et al., 2021). In the current study, the pH level was within the acceptable range (around 7) for goldfish. The pH level in BFT systems is generally more stable compared to conventional systems (Boyd et al., 2011). However, significant fluctuations can occur, especially during the initial stages of the nitrogen cycle, which may impact other physical and chemical water quality parameters. Water temperature was also appropriate and within the optimum range for goldfish (between 22-30 °C) throughout the study (Avnimelech, 2009; Fraser et al., 2002). In BFT systems, the concentration of DO must be at adequate levels to meet the needs of the cultured organism and bacteria (Khanjani et al., 2020). High DO concentrations in the control group in the present study can be attributed to a low microbial community (Mirzakhani et al., 2019). The EC values increased with increasing C/N ratios due to the high organic matter concentrations resulting from C/N ratio adjustment (Crab et al., 2012). In BFT systems, TSS affects growth and survival rate of cultured organisms (Qiao et al., 2018). Low TSS concentrations (<100 mg/L) prevent sustainable high water quality and negatively affect the nitrification process (Gaona et al., 2017). However, if TSS is above 800 mg/L, it may cause blockages in the gills of fish (Schveitzer et al., 2013). In the current study, TSS concentrations (300-500 mg/L) were within appropriate levels for BFT systems. TSS, as an indicator of biofloc volume, increases with more incubation time and higher C/N ratio (Harun et al., 2019; Panigrahi et al., 2018). The fundamental principle of the BFT system relies on the development of a heterotrophic bacterial community stimulated by the added carbon source. An increased C/N ratio serves as an indicator of microbial growth and elevated electrical conductivity (EC) (Khanjani et al., 2021).

Ammonia and nitrite nitrogen are stressors that affect organisms in the intensive aquaculture environment (Tovar et al., 2000). Therefore, the maximum acceptable values for ammonia and nitrite nitrogen concentration are 0.1 and 5 mg/L, respectively (Boyd, 2017). Contrary to these low concentrations, long-term exposure is only harmful when the nitrate concentration exceeds 60 mg/L (Miranda-Filho et al., 2009). While ammonia decreased rapidly in the BFT groups after the second week, it increased in the control group in the current study. Heterotrophic bacteria in the biofloc systems remove ammonia concentration faster than nitrifying bacteria (Hargreaves, 2006; Minaz and Kubilay, 2021). The growth rate and biomass efficiency per unit substrate of heterotrophic bacteria are higher than nitrosomonas and nitrobacter. It has also been claimed that heterotrophic bacteria in BFT systems can consume ammonia nitrogen for growth and reproduction (Yun et al., 2012). As a result of the ammonia conversion, nitrite and nitrate concentrations showed an increasing trend in the BFT groups over time. Since the denitrification process of heterotrophic bacteria is longer, the removal rate of ammonia nitrogen cannot reach 100% and their nitrogen removal efficiency is in the range of 77-98% (De Schryver and Verstraete, 2009). The C/N ratio is very important in BFT systems for the stability of operation. The C/N ratio greater than 10:1 in aquaculture has shown that it can assimilate 0.2 g of nitrogen per square meter per day depending on several factors such as temperature, biomass, and illumination level (Azim and Little, 2008). Similarly, it was determined that the BFT system with sufficient C/N ratio completely converted 10 mg/L ammonia nitrogen within 5 hours (Asaduzzaman et al., 2008). Similar to our study, C/N ratio above 15:1 had a decreasing effect on ammonia concentration (Wang et al., 2015).

In the current study, the BFT system affected growth performance. Particularly in the C/N 20 group, specific growth rate and weight gain ratios were significantly improved. The higher floc volume observed in the C/N 20 group suggests that these flocs could serve as a potential feed source. Consequently, the significantly lower FCR in the C/N 20 group compared to the control may be attributed to this effect (Panigrahi et al., 2018). Biofloc mass has previously been used as an additive to commercial feeds, with results of improved FCR (Khanjani et al., 2021; Mirzakhani et al., 2019). A study on another species from the same family reported that weight gain rate (WGR) and specific growth rate (SGR) increased as total suspended solids (TSS) concentration rose, reaching an optimal threshold at 800 mg/L. However, when TSS levels exceeded 1000 mg/L, growth performance began to decline, indicating that 800 mg/L serves as a critical limit for optimal fish growth (Qiao et al., 2018). The increase in C/N ratio positively affected SGR, WGR and protein efficiency ratio for *C. auratus* (Wang et al., 2015). However, in another study conducted on fish of similar size to our study, a positive result of SGR was observed in favor of the BFT group (Faizullah et al., 2015). Biofloc can respond to the protein and other nutrients that fish need (Avnimelech, 1999). Bioflocs contain poly-beta-hydroxybutyrate organic compounds as well as chlorophylls, phytosteroids and carotenoids (De Schryver et al., 2010). In addition, organic particles contained in biofloc support the growth of protozoa and algae in the floc (Emerenciano et al., 2012). As a result, this creates a variety of foods available for consumption by fish (Cavalcante et al., 2017). Considering its effect on BFT systems, using biofloc as a feed additive instead of fishmeal may increase weight in fish (Kuhn et al., 2009).

The liver is a reliable indicator tissue in the evaluation of nutritional metabolism in fish (Ostaszewska et al., 2005). To the best of our knowledge, the current study is the first on the histological evaluation of BFT in *C. auratus*. In the current study, significant differences in liver tissue among the groups were due only to vacuolization. More severe vacuolization was observed in the liver tissues in the C/N 20 group. The literature findings report that the over vacuolization symptoms represent high nutritional yield and energy storage rather than a pathological finding (Fontagné et al., 1998; Mosconi-bac, 1987; Segner and Witt, 1990). Therefore, it is expected that the size and volume of hepatocytes may be a physiological response to an excess of dietary energy (Najdegerami et al., 2016). B-cells in aquatic crustaceans are primarily involved in the storage of nutrients and metabolic processes (Vogt, 2021). Previous BFT studies on shrimp have reported an increase in B cells in biofloc groups (Kaya et al., 2019; Suita et al., 2015). The vacuolization observed in fish hepatocytes resembles the endocytosis and vacuole formation processes in crustacean B cells. In both groups of organisms, intracellular vacuoles are associated with metabolic waste processing, detoxification, and nutrient storage. This similarity suggests that biofloc consumption may influence cellular processes related to metabolic regulation across different aquatic species. This finding also indicates that biofloc may play a role in modulating the immune system, similar to its effects observed in shrimp.

As a new approach in the field of aquaculture, the PROMETHEE-MCDM is a model designed for decision-makers to rank a limited number of alternatives according to conflicting criteria (De Smet et al., 2009). It has the potential in BFT studies to rank all alternative scenarios based on important criteria for the system and organism. In the current study, PROMETHEE-MCDM suggested that the C/N 20 BFT system is the most feasible alternative for the *C. auratus* culture. The positive superiority of C/N 20 was achieved, especially thanks to the growth performance criteria (C7-C9). According to the criteria, the growth performance variables were determined according to the opinion of experts from the academy and private farms. Expectedly, the growth performance of the cultured organism has been considered as one of the criteria of high weight value in this study. On the other hand, water quality parameters (ammonia and nitrite), which are of great importance for the sustainability of the BFT system, were weighted according to their toxicity potential (Kim et al., 2019; Tomasso, 1994). Although growth performance parameters were observed to be lower in the C/N 15 group, the ammonia concentration in the system made this alternative superior to the control. The PROMETHEE method provides a structured and transparent ranking process, allowing for a more objective evaluation of multiple criteria. Its ability to integrate both qualitative and quantitative data makes it a valuable tool in complex decision-making scenarios, such as aquaculture system optimization. Additionally, PROMETHEE has been increasingly applied in the aquaculture sector to assess different production strategies, sustainability measures, and management decisions (Minaz et al., 2024; Minaz, 2024). Based on the findings obtained through this model, the use of a 20 C/N ratio in BFT-based goldfish culture is supported as the most favorable option.

5. CONCLUSION

The current study aimed to explain the suitability of biofloc technology in ornamental aquaculture. In both BFT groups, the nitrogen cycle occurred much faster than in the control group. Increasing the C/N ratio increased TSS and total bacterial loads. The growth and nutrient utilization performance of *C. auratus* was higher in the group with a C/N ratio of 20:1. Hepatic vacuolizations were observed more severely in fish on BFT treatments, which is an indicator for higher accumulation of energy. According to the multi-criteria decision-making method, C/N ratio of 20 for *C. auratus* is the best applicable method in *C. auratus* aquaculture. In conclusion, the use of biofloc systems in Japanese fish farming offers economic benefits by lowering feed costs, conserving water, reducing disease risks, and enhancing productivity. However, its effectiveness depends on proper management and the maintenance of optimal rearing conditions.

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CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

AUTHOR CONTRIBUTIONS

Mert Minaz: Conceptualization, Visualization, Writing - Original Draft, Data Curation.

ETHICAL STATEMENTS

Current study was checked and approved by the Ethical Local Committee of the Recep Tayyip Erdogan University (Decision No: 2023/05)

DATA AVAILABILITY STATEMENT

All datasets used during the current study are available from the corresponding author on reasonable request.

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Research Article | Araştırma Makalesi

First Detection of *Eustrongylides excisus* in Mosquito Fish (*Gambusia holbrooki*) from Lake Eğirdir

Eğirdir Gölündeki Sivrisinek Balığı'nda (*Gambusia holbrooki*) *Eustrongylides excisus*'un İlk Tespiti

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Abstract: In this study, the presence of *Eustrongylides excisus*, one of the zoonotic nematodes, was determined for the first time in *Gambusia holbrooki* from Lake Eğirdir. 70 *Gambusia holbrooki* samples were examined macroscopically for *Eustrongylides excisus* infection. The four parasite samples were recorded in 4 fish, one in each fish. The parasitic species identification was performed using the classical method on *E. excisus* samples isolated from the host fish, then PCR was performed on 18S rDNA. As a result of molecular analyses, 18S rDNA loci fragment of *E. excisus* was determined to be 941 bases long and registered to the NCBI data system with accession number PP333225. The taxonomic position of the present isolates and other *Eustrongylides* isolates registered in NCBI was evaluated through a phylogenetic analysis. It was determined that the isolates in this study had similar sequences to the *Eustrongylides* samples previously reported from Türkiye. In addition, the isolates of this study were found to have close similarity to *Eustrongylides* isolates from countries geographically close to Türkiye, such as Iran and Italy, while the similarity rate with *Eustrongylides* isolates from countries such as China, Brazil and India was found to be low. As a result of this study, it was determined for the first time that *Gambusia holbrooki* plays a role as an intermediate host in the life cycle of *E. excisus*. In addition, the sequences belonging to the 18S rDNA locus of *E. excisus* samples from host fish were identified and contributed to the determination of the genetic characteristics of the parasite species.

Keywords
- DNA
- *Eustrongylides exicus*
- *Gambusia holbrooki*
- Lake Eğirdir

Özet: Bu çalışmada Eğirdir Gölü *Gambusia holbrooki*'sinde zoonotik nematodlardan biri olan *Eustrongylides excisus*'un varlığı ilk kez tespit edilmiştir. 70 *Gambusia holbrooki* örneği *Eustrongylides excisus* enfeksiyonu açısından makroskopik olarak incelendi. Her balıkta bir tane olmak üzere 4 balıkta dört parazit örneği kaydedilmiştir. Parazit tür teşhisi, konak balıktan izole edilen *E. excisus* örnekleri üzerinde klasik yöntem kullanılarak yapılmış, daha sonra 18S rDNA üzerinde PCR gerçekleştirilmiştir. Moleküler analizler sonucunda, *E. excisus*'un 18S rDNA lokus fragmanının 941 baz uzunluğunda olduğu belirlenmiş ve NCBI veri sistemine PP333225 erişim numarası ile kaydedilmiştir. Mevcut izolatların ve NCBI'da kayıtlı diğer *Eustrongylides* izolatlarının taksonomik konumu filogenetik bir analiz ile değerlendirilmiştir. Bu çalışmadaki izolatların daha önce Türkiye'den bildirilen *Eustrongylides* örnekleriyle benzer dizilere sahip olduğu belirlenmiştir. Ayrıca bu çalışmadaki izolatların İran ve İtalya gibi Türkiye'ye coğrafi olarak yakın ülkelerden elde edilen *Eustrongylides* izolatları ile yakın benzerlik gösterdiği, Çin, Brezilya ve Hindistan gibi ülkelerden elde edilen *Eustrongylides* izolatları ile benzerlik oranının ise düşük olduğu tespit edilmiştir. Bu çalışma sonucunda *Gambusia holbrooki*'nin *E. excisus*'un yaşam döngüsünde ara konak olarak rol oynadığı ilk kez tespit edilmiştir. Ayrıca, konak balıklardaki *E. excisus* örneklerinin 18S rDNA lokusuna ait sekanslar tanımlanmıştır.

Anahtar kelimeler
- DNA
- *Eustrongylides exicus*
- *Gambusia holbrooki*
- Eğirdir Gölü

1. INTRODUCTION

The mosquitofish, *G. holbrooki,* was globally introduced into freshwater ecosystems in the early 1920s for the purpose of biologically controlling malaria (Krumholz, 1948). Due to their high tolerance to environmental factors, they may thrive in many categories of water quality (Pyke, 2005). This species is extremely invasive and has been documented in the freshwater bodies of several regions. It has had significant detrimental impacts on ecosystems and the local fish populations (Pyke, 2008).

G. holbrooki was first introduced to Lake Amik (Hatay) in order to combat malaria in Türkiye, and then the species was inoculated into many water resources (Ekmekçi et al., 2013; İnnal, 2022). This fish generally leads a benthopelagic life, feeding on zooplankton, small insects and eggs and larvae of other fish (Alp et al., 1994; Balık et al., 2006).

The parasites which belong to genus *Eustrongylides* (Dioctophymatidae, Nematoda) have a heteroxenous life cycle. Fish-eating birds are the main hosts of the parasites and are known to harbor adult forms of the parasite. These birds spread the parasite eggs with their faeces into water sources. Oligochaetans eat these eggs and the eggs develop into the larval stages, L1 to L3. Second hosts are mostly fishes and rarely amphibians or reptiles. The hosts eat these infected Oligochaetes, *Lumbriculus variegatus*, *Tubifex tubifex* or *Limnodrilus* spp. Parasite larvae develop into L4 larval forms in the abdominal cavity, internal organs and muscle tissues of second hosts. When infected secondary intermediate hosts are ingested by aquatic birds, L4 stage parasites develop into mature stage in craw or intestine of the definitive hosts (Bjelić-Čabrilo et al., 2013; Coyner et al., 2002; Measures, 1988).

Adult *Eustrongylides excisus* individuals can cause zoonosis in humans. They can become infected by eating raw or undercooked infected fish containing larvae of this species. The larvae can cause intestinal pain, inflammation, and even perforation of the intestinal wall (Guardone et al., 2021; Ljubojevic et al., 2015; Mazzone et al., 2019; Özmen et al., 2021).

Determining the diversity of host fishes of *Eustrongylides excisus* is of obvious importance for other organisms in the aquatic ecosystem and for humans. In addition, correct species identification of the larval parasite is also important. Identification of *Eustrongylides excisus* larvae based on their anatomical-morphological characteristics may be insufficient. In this case, molecular markers such as genetic characteristics of the larval nematode samples provide strong support (Guardone et al., 2021; Pekmezci and Bolukbas, 2021; Xiong et al., 2013; Youssefi et al., 2020). Identification of the genetic characteristics of this species also contributes to the understanding of biological characteristics and relatedness levels of populations in different localities too.

In this study, the host fish *Gobius holbrooki* from Lake Eğirdir was investigated for *Eustrongylides excisus* infection. The present research contributed to the host fish diversity of the parasite species, the zoonosis phenomenon and the identification of genetic characteristics.

2. MATERIAL AND METHODS

2.1. Study area

Lake Eğirdir, located between latitudes 35°37′41N and 38°16′55N and longitudes 30°44′39E and 30°57′43E, is the second largest freshwater lake in Türkiye (Alp et al., 1994; Geldiay and Balık 2009). Lake Eğirdir has an area of 482 km^2 with a maximum depth of 6-7 m and an average depth of 3.5-4 m (Dogan et al., 2025). (Figure 1).

2.2. Sampling

Within the scope of the research, *Gambusia holbrooki* samples were caught from Lake Eğirdir using special beach nets with a 5 mm mesh size. The beach nets had a wing length of 5 m, a wing height of 1.5 m and a bag mouth length of 5 m (Figure 2).

Before the parasitological examination of *G. holbrooki* samples, their lengths and weights were measured. Then, *G. holbrooki* samples were examined for *Eustrongylides excisus* macroscopically and with a stereo microscope. The anatomical and morphological features of the specimens were examined and identified according to Moravec (Moravec, 1994). Out of 70 samples, this parasite was detected in 4 samples and were fixed in 70% ethanol for molecular studies.

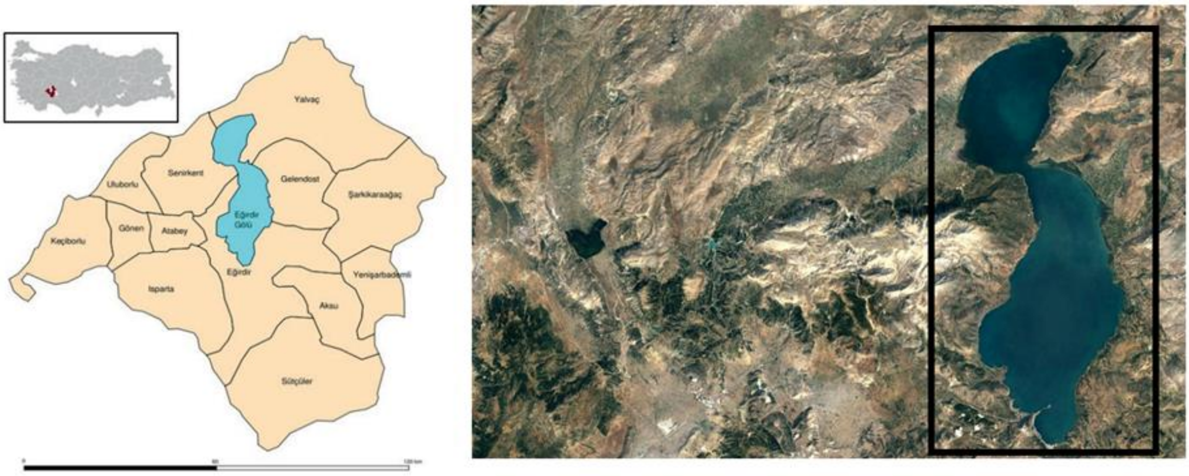

Figure 1. Location map of the Eğirdir Lake (from Google Earth).

Figure 2. Collection of *Gambusia holbrooki* samples (original).

2.3. DNA extraction, PCR assays and DNA sequencing

DNA extractions were performed with the High Pure PCR Template Preparation Kit (Roche Applied Science) following the manufacturer's instructions, quantified and visualized on 1,5 % agarose gel. The PCRs were performed using the 2x PCR Master Mix kit (Thermo Scientific, Carlsbad, California, USA). For the amplification of the nuclear ribosomal internal transcribed spacer (ITS) region gene, the primes 18SF (5' TTGGATGATTCGGTGAGGT 3') and 28SR (5' AACCGTTAGTAATATGCT 3'). PCR reactions were performed using 1-2 µl of genomic DNA, 12.5 µl of 2x PCR Master Mix (Thermo Scientifc, Carlsbad, California, USA), 1 µM of each specific primer, and nuclease-free water (Thermo Scientific, Carlsbad, California, USA), with a final volume of 25 µl. The PCR development conditions were 95 °C/5 min (95 °C/30 s, 53 °C/45 s, 72 °C/ 90 s, repeated 35×), 72 °C/10 min The PCR products were visualized on 1,5 % agarose gel with TBE buffer (0.045 M Tris-borate, 0.001 M EDTA pH 8.0). Sequenced in two directions with an automated sequencer and the same primers. The sequence of the sample has been registered in the GenBank database with accession number, PP333225.

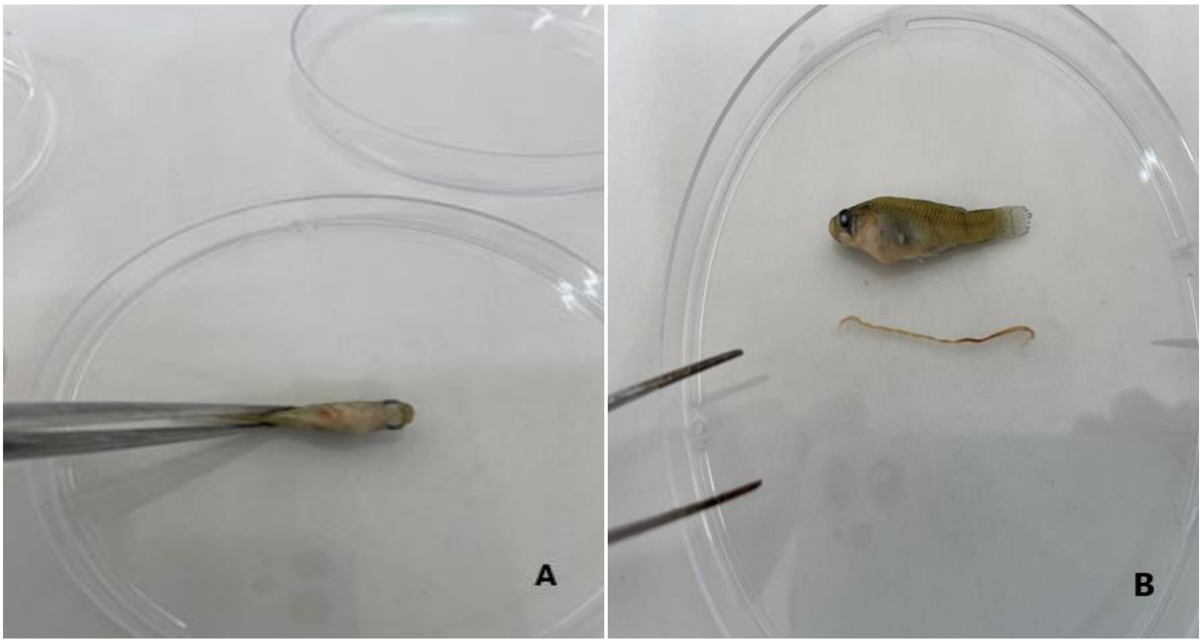

Figure 3. Parasitic examination at *Gambusia holbrooki* samples (original).

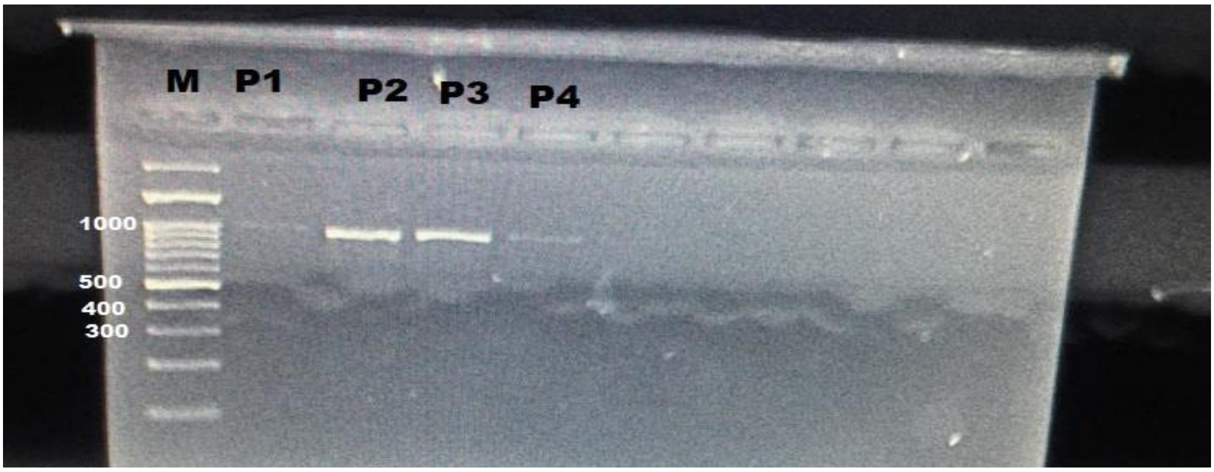

Figure 4. PCR gel image of the samples (original).

2.4. Phylogenetic analysis

The current sequence was edited using Bioedit (Hall, 2013). Data from the current study were matched with past 18S sequences of *Eustrongylides* spp. in GenBank using BLAST (Altschul et al., 1990). Using ClustalW in MEGA X, consensus sequences were aligned with other samples of *Eustrongylides* sequences (Kumar et al., 2018).

Phylogenetic analysis was performed using the Basic Local Alignment Search Tool (National Center for Biotechnology Information database) in comparison to GenBank sequences. Studies with *Eustrongylides* isolates in Türkiye, Italy, China, Japan, India, Iran, Japan, India, Iran and Brazil were constructed in the Bioedit programme to create a phylogenetic tree. The Mega-X was used to find the best model. And Maximum Likelihood method, and Tamura-Nei parameter method were determined (Kumar et al., 2018; Nei and Kumar, 2000). 1000 bootstrap re-saplings were used to produce a tree in MEGA-X. *Pellioditis morine* AJ867071(Derycke et al., 2005; Youssefi et al., 2020) and *Soboliphyme baturi* AY277895 (Rusin et al., 2003) were used as outgroups.

3. RESULTS

3.1. The case of infection

Eustrongylides excisus specimens were found in 4 of 70 (5.7%) *Gambusia holbrooki*. The four parasite samples were recorded in 4 fish, one in each fish. The average weight of the 16 male host fish examined in the study was 0.47 g, while the average weight of the 54 females was 0.249 g. The parasitic samples were recorded in the abdominal cavity and anus region of infected host fish, Figure 3a. The parasitic samples were a thick filamentous shape, reddish color and approximately 25 mm long, Figure 3b.

3.2. Anatomical and morphological characteristic features of the parasitic species

The anatomical and morphological features of the parasite samples were recorded. Accordingly, the general body shape of the parasite samples was thick and filiform. The body was covered with a thick cuticle. The cuticle had transverse striations. Additionally, there were rows of papillae on both lateral sides of the body. Around the mouth, there were two rows of six cone-shaped papillae each. The inner papillae were larger than the outer ones. The nerve ganglion was located at the level below the papillae. The intestine had a straight cylindrical shape. In the caudal region, there was a deep longitudinal groove. This species is dioecious. The posterior end of male individuals was oval-shaped. The spicule and spicule sheath were straight and smooth. The posterior terminal of female individuals was blunt. The genital opening was located in the lateral area of the posterior terminal. The genital canal was straight and muscular. As a result, based on these characteristics, the parasite samples were determined to belong to the species *Eustrongylides excisus*.

3.3. Molecular characteristic features of the parasitic species

DNA extraction, A260/A280 and A260/230 ratios were measured between 1.8-2.0 in measurements made with nanodrop. After this process, the PCR gel image was shown in Figure 4. In the gel image, it is seen that the targeted region proliferated. The PCR product showed an expected fragment of nearly 1000 bp in length. After the sequencing, all sequences were multiple aligned and compared in the bioedit programme. They all had the same sequence, there were no variations. After trimming, 941 base length sequences were obtained. NCBI BLAST analysis of the sequence confirmed that it was *Eustrongylides excisus*. It was registered in the NCBI genebankunder accession number, PP333225.

3.4. Phylogram analysis

The taxonomic position of the present and other *Eustrongylides* isolates registered in NCBI was evaluated through a phylogram analysis using the Maximum Likelihood method, MEGA-X program. According to the obtained data, it was determined that the isolates in this study had similar sequences to the *Eustrongylides* samples previously reported from Türkiye. In addition, the isolates of this study, were found to have close similarity to *Eustrongylides* isolates from countries geographically close to Turkey, such as Iran and Italy, while the similarity rate with *Eustrongylides* isolates from countries such as China, Brazil and India was found to be low (Figure 5).

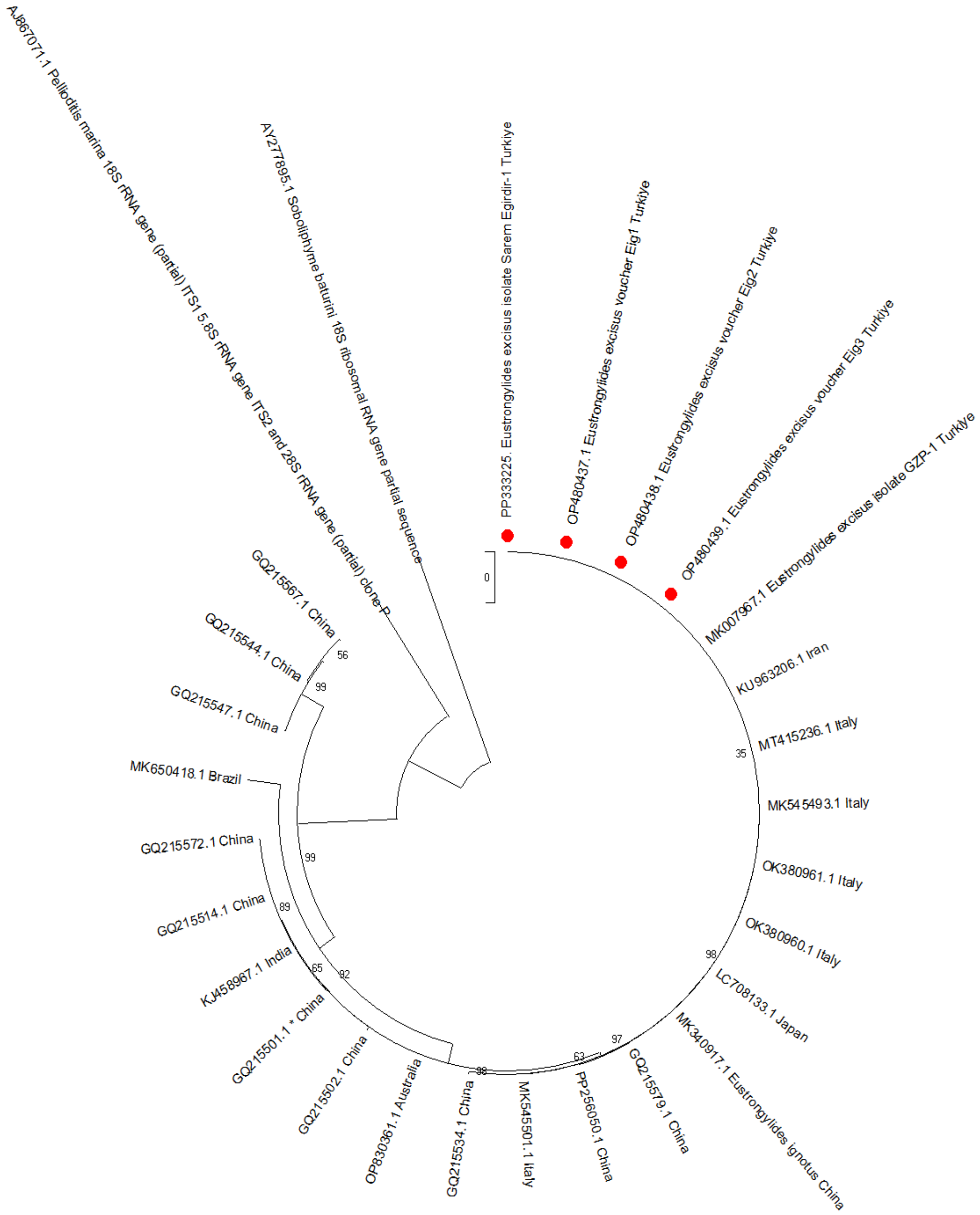

Figure 5. Phylogram tree based on 18S rDNA sequence data of *Eustrongylides* spp. from the present study and the GenBank database.

4. DISCUSSION

The mosquito fish, *Gambusia* sp. one of the world's invasive fish taxa. The fish taxon was reported to exist in at least 89 countries (Kurtul et al., 2022). This species poses a danger to water resources due to its long life span, rapid growth and reproduction, high egg production, attacking large fish, wide distribution and being the dominant species in water resources where it is inoculated (Polat et al., 2011). Benthopelagic mosquitofish feed on zooplankton, small insects and eggs and larvae of other fish. Insecta, Crustacea, Arachnida, Mollusca (Gastropoda), Plants (especially filamentous algae) and Detritus were detected in the digestive tract of *Gambusia holbrooki* (Sac, 2023). The food materials in the digestive system of host fish in the present research area have similar characteristics.

The parasitic species, *Eustrongylides excisus* was detected in *Carassius gibelio*, *Cyprinus* *carpio*, *Sander lucioperca*, *Atherina boyeri*, *Pseudophoxinus egridiri*, *Aphanius iconii*, *Knipowitschia caucasica* in Lake Eğirdir (Akcimen et al., 2014; Akcimen et al., 2018; Innal et al., 2019; Metin et al., 2014; Ozturk et al., 2002; Özmen et al., 2021; Ozturk and Ozturk, 2023) and the other localities (Aydogdu et al., 2024; Aydogdu et al., 2011; Bjelić-Čabrilo et al., 2013; Guven and Ozturk, 2018; Juhásová et al., 2019; Menconi et al., 2021; Novakov et al., 2013; Ozturk et al., 2001; Pekmezci and Bolukbas, 2021; Rahmati-Holasoo et al., 2024; Sattari, 2004; Soylu, 2005). In this study, *Eustrongylides excisus* was reported for the first time from *Gambusia holbrooki* in Lake Eğirdir, Türkiye, and also in the world.

As known, the parasite species completes its life cycle on water birds. According to the Water Bird Census Report of the Turkish Ministry of Agriculture and Forestry, a total of 83,382 birds belonging to 32 different species were reported in Lake Eğirdir in 2024 (Kosks, 2024). The richness of the aquatic birds fauna of Lake Eğirdir may have supported the infection of *Gambusia holbrooki* by *E.excisus*. In addition, this first record data of *E. excisus* in the present study has provided support for the effect of local ecological characteristics on biodiversity and the difference in parasite-host diversity in different geographic regions.

In current taxonomic studies, in addition to identifying species based on their anatomical and morphological characteristics, using molecular markers has been considered a valid method. Genomic data provide reliable support for determining the taxonomic position of the same species, especially in different geographical regions and in different hosts, and for understanding similarities or differences between populations (Moravec and Justine, 2017).

This study presents the first record of *Eustrongylides excisus* from *Gambusia holbrooki* and its 18S rRNA sequence. The 18S rDNA locus of *E. excisus* was determined to be 941 bases long and registered to the NCBI data system with accession number PP333225. The taxonomic position of the present isolates and other *Eustrongylides* isolates registered in NCBI was evaluated through a phylogenetic analysis using the Maximum Likelihood method. It was determined that the isolates in this study had similar sequences to the *Eustrongylides* samples previously reported from Türkiye (Ozturk and Ozturk, 2023; Pekmezci and Bolukbas, 2021). The sequence of the present study was found to close similarity to *Eustrongylides* isolates from countries geographically close to Türkiye, such as Iran and Italy, while the similarity rate with *Eustrongylides* isolates from countries such as China, Brazil and India were found to be low (Guardone et al., 2021; Franceschini et al., 2022; Mazzone et al., 2019; Kuraiem et al., 2019; Shamsi et al., 2023; Xiong et al., 2013; Youssefi et al., 2020). The phylogram results show that the sequence variation among the isolates of different populations of the same species increases gradually with distance. These results supported the effect of the allopatric isolation mechanism in the formation of variations among populations. There was also a small evidence showing the effect of the isolation mechanism on the evolution of taxa.

Classical, traditional anthelmintic drugs have poor efficacy against *Eustrongylides* species, because these types of drugs suppress parasites that mostly live in the gastrointestinal tract. *Eustrongylides* species are located in the body cavity outside the stomach, in the internal organs and even in the muscle tissues of fish. Parasites in this group can only be removed from fish surgically, which is practically impossible. In order to completely stop the life cycle of this parasite and to eradicate the parasite occurrence, it is necessary to destroy all fish infected with the parasite(Coyner 2002). The parasitic *E. excisus* species was found to be a second intermediate host in various fish species in Lake Eğirdir and to cause infection in the host fishes (Akcimen et al., 2014; Akcimen et al., 2018; Innal et al., 2019; Metin et al., 2014; Ozmen et al., 2021; Ozturk and Ozturk, 2023). Lake Eğirdir is rich in both zooplankton such as *Tubifex* sp, which are the first intermediate hosts for *E. excisus*, and many aquatic birds species which are the final hosts for *E. excisus* (Apaydın-Yagcı et al., 2014; Apaydın-Yagcı et al., 2018; Kosks, 2024). So, *E. excisus* can easily continue its existence and life cycle in Lake Eğirdir. *E. excisus* is known to be an important zoonotic agent for humans (Guardone et al., 2021; Ljubojevic et al., 2015; Mazzone et al., 2019). Therefore, fish species infected with this parasite in Lake Eğirdir pose a significant zoonotic source risk for the local human population. As a preventive measure, the internal organs of fish caught in Lake Eğirdir should be removed, examined for *E. excisus* under purple light, and eaten after cooking at high temperatures, and never consumed raw. In addition, when cage fishing is planned in Lake Eğirdir in the future, it should be taken into consideration that *E. excisus* infection may have negative effects on the growth and meat quality of cultured fish.

5. CONCLUSION

As a result, *E. excisus* was identified for the first time in this study from *Gambusia holbrooki*. Thus, a new fish species was added to the host fish diversity of *E. excisus*. Also, it was noted that the parasite species may be a zoonotic threat to the local people. In addition, the sequences belonging to the 18S rDNA locus of *E. excisus* sample in the host fish was identified and contributed to the studies on determining the genetic characteristics of the parasite species.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

HE, CB and VY planned and sampled the fieldwork. HE and MMS carried out parasite detection and molecular studies. MOO contributed to the interpretation of the results and led the writing of the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

ETHICAL STATEMENT

Since the fish used in the study were obtained dead from nature, the Local Ethics Committee for Experimental Animals certificate is not required.

DATA AVAILABILITY STATEMENT

The data used in the present study are available upon request from the corresponding author. Data is not available to the public due to privacy or ethical restrictions.

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Research Article | **Araştırma Makalesi**

Effect of Microalgae Growth Promoting Bacteria on Biomass Production of *Scenedesmus* Isolates in Co-Culture Systems

Mikroalg Büyümesini Destekleyen Bakterilerin Eş Kültür Sistemlerinde *Scenedesmus* İzolatlarının Biyokütle Üretimi Üzerindeki Etkisi

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Abstract: Microalgae are biotechnologically important microorganisms with the potential to address the challenges posed by rapid population growth and dwindling food resources through their metabolic products. This study focused on the isolation and identification of *Scenedesmus* and microalgae growth-promoting bacteria (MGPB) from wetlands in Erzurum, Türkiye, and investigated the impact of MGPB isolates on the growth performance of *Scenedesmus* species in a co-culture medium. *Scenedesmus* and MGPB isolates were collected from Palandoken Teke Creek Pond and Tortum Lake, respectively, followed by species identification. Co-culture experiments were conducted using 20 MGPB isolates from the same area, with *Scenedesmus flavescens* (from Palandoken Teke Creek Pond) and *Scenedesmus armatus* (from Tortum Lake) serving as test species. The experiment spanned seven days, with daily measurements of cell counts and biomass, along with dry matter weight assessments at the start and end of the study. The results showed that *S. armatus* and *S. flavescens* achieved the highest biomass in co-culture with *Bacillus* sp. and *Pseudomonas* sp., the cell counts of *S. armatus co-culture* with *Pseudomonas* sp. (A5) were 306±16.21 cells/ml, and this group followed by A6 (251±13.37 cells/ml), A7 (260±17.6 cells/ml), and F8 (93±6.01 cells/ml) groups. In conclusion, 6% growth was detected in *S. flavescens* biomass and 7% in *S. armatus* biomass. MGPB bacteria enhanced the growth of microalgae, underscoring their potential for biotechnological applications.

Keywords
- Biomass
- Co-culture
- MGPB
- *S. armatus*
- *S. flavescens*

Özet: Mikroalgler, metabolik ürünleri aracılığıyla hızlı popülasyon artışı ve azalan besin kaynaklarının oluşturduğu zorluklarla başa çıkma potansiyeline sahip biyoteknolojik açıdan önemli mikroorganizmalardır. Bu çalışma, Türkiye, Erzurum'daki sulak alanlardan *Scenedesmus* ve mikroalg büyümesini teşvik eden bakterilerin (MBTB) izolasyonu ve tanımlanmasına odaklanmış ve MBTB izolatlarının eş kültür ortamında *Scenedesmus* türlerinin büyüme performansı üzerindeki etkisini araştırmıştır. *Scenedesmus* ve MBTB izolatları sırasıyla Palandöken Teke Deresi Göleti ve Tortum Gölü'nden toplanmış ve ardından tür tanımlaması yapılmıştır. Eş kültür deneyleri, aynı alandan alınan 20 MBTB izolatı kullanılarak yürütülmüş ve test türleri olarak *Scenedesmus flavescens* (Palandöken Teke Deresi Göleti'nden) ve *Scenedesmus armatus* (Tortum Gölü'nden) kullanılmıştır. Deney, hücre sayısı ve biyokütlenin günlük ölçümleri ile çalışmanın başında ve sonunda kuru madde ağırlığı değerlendirmeleri ile yedi gün sürmüş, ve *S. armatus* ve *S. flavescens*'in *Bacillus* sp. ve *Pseudomonas* sp. ile birlikte eş-kültürde en yüksek biyokütleye ulaştığını, *S. armatus*'un *Pseudomonas* sp. (A5) ile birlikte kültürüne ait hücre sayımlarının 306±16,21 hücre/ml olduğunu ve bu grubu A6 (251±13,37 hücre/ml), A7 (260±17,6 hücre/ml) ve F8 (93±6,01 hücre/ml) gruplarının takip ettiği tespit edilmiştir. Sonuç olarak, Bu çalışmada *S. flavescens* biyokütlesinde %6, *S. armatus* biyokütlesinde ise %7 oranında büyüme tespit edildi. MBTB bakterileri mikroalglerin büyümesini artırarak biyoteknolojik uygulamalar için potansiyellerini vurguladı.

Anahtar kelimeler
- Biyokütle
- Eş-kültür
- MBTB
- *S. armatus*
- *S. flavescens*

1. INTRODUCTION

Microalgae are simple, single-celled, or colonial microorganisms ranging in size from 1 μm to 1 cm, capable of photosynthesis and thriving under autotrophic or heterotrophic conditions. They contain chlorophyll within the cells (Lee, 2008). Chemically, their structure is expressed as C106H181O45N16P1, whereas their biochemical composition includes carbohydrates, proteins, pigments, and lipids (Sajjadi et al., 2018).

Microalgae production conditions vary depending on the species, although all species require light, appropriate temperature, pH, and medium components (e.g., N, P, and K) to grow effectively. While medium composition varies across species, nitrogen and phosphorus make up 10-20% of the algal biomass and serve as primary nutrients, supplemented by macronutrients (Mg, Na, K, Ca), micronutrients, and vitamins (Andersen, 2005).

Microalgae have found applications in various sectors including biodiesel, food, and pharmaceuticals. However, different microalgae species are suited to specific sectors and their products are influenced by abiotic factors. For instance, Gouveia & Oliveira (2009) identified *Nannochloropsis oleoabundans* (a freshwater species) and *Nannochloropsis* sp. (a marine species) as promising candidates for biofuel production because of their high lipid contents (29.0% and 28.7%, respectively). Modifications in culture conditions, such as adjusting day-night cycles, light intensity, pH levels, and nutrient limitations (nitrogen or phosphorus) can significantly affect lipid and protein production. Ongoing research, for determining ideal culture conditions to optimize biomass yield and metabolic output, continues to evolve (Darki et al., 2017; An et al., 2020).

Although the concept of co-culturing microalgae with bacteria may appear novel in the current literature, its origins have been traced back to the 1930s (Waksman et al., 1937). Interest in beneficial interactions between microalgae and bacteria gained momentum in the 1970s and has continued to expand (Delucca & McCracken, 1977). While these bacteria share mechanisms with "plant growth-promoting bacteria," such as nitrogen fixation, phytohormone production, and phosphate solubilisation, they are now recognized as a distinct category called "microalgae growth-promoting bacteria" (MGPB). This classification reflects their unique capabilities, such as vitamin and CO_2 production, which are essential for microalgae cultivation (Palacios et al., 2022).

To qualify as MGPB, bacteria must exhibit at least two growth-promoting mechanisms for microalgae, beyond basic CO_2 supplementation via natural carbon catabolism. For example, the use of *Azospirillum* spp. in association with higher plant roots has been widely studied. Similarly, co-culture studies involving *Azospirillum* and *Chlorella vulgaris* have demonstrated the potential for advancing sustainable microalgal production technologies (De Bashan et al., 2002; Hernandez et al., 2009; Do Nascimento et al., 2013; Liu et al., 2020; Gonzalez-Gonzalez et al., 2021).

In this study, we investigated the co-cultivation of *Scenedesmus* species and MGPB isolates obtained from wetlands in the Erzurum Province, and aimed to assess the effects of MGPB isolates on the growth performance of *Scenedesmus* species.

2. MATERIAL and METHOD

2.1. Study of Microalgae and MGPB Sampling

In this study, microalgae samples were collected from Palandoken Teke Creek Pond and Lake Tortum within Erzurum using a plankton net with a mesh size of 10 μm. The samples were transferred to the laboratory in polyethylene sampling containers using a cold chain protocol. Bacteria were sampled simultaneously from the same stations as those used for the microalgae sampling. Water samples for bacterial sampling were taken with a Ruttner, and sediment samples were collected with an Ekman grab. Collected samples were transferred to sterile sample containers and transferred to the laboratory using the cold chain protocol, in which aseptic conditions were maintained (Wetzel and Likens, 2000).

2.2. Isolation and Identification of *Scenedesmus* Isolate

First, the collected samples were examined under a binocular microscope and selected for the isolation stage of the *Scenedesmus* isolate. *Scenedesmus* was isolated from selected samples using the micropipette method under an inverted microscope with a camera attachment (Zeiss Binocular Microscope). For the conventional identification of *Scenedesmus* isolates, binocular microscope examinations were matched with literature data (Prescott, 1973; Lind & Brook, 1980; Komarek & Fott 1983; John et al., 2002).

Bacteria used for MGPB research were isolated by preparing dilution series from 10^{-1} to 10^{-6} using phosphate buffered saline from each water and sediment sample and spreading each dilution onto Luria–Bertani (LB) agar and nutrient agar (NA) media. Cultures were grown at 28 °C for 24-48 hours and each of the bacteria showing discrimination in terms of colony morphology was subjected to repeated cultivation until pure colonies were obtained using the 3-phase streak method (Figure 1) (Vaikuntapu et al., 2014; Alaylar et al., 2019; Liu et al., 2020).

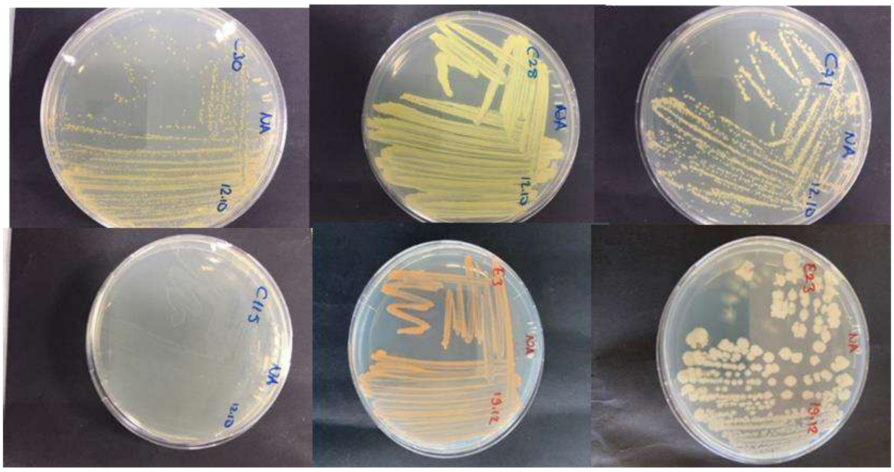


Figure 1. Sample images of solid cultures of MGPB isolates.

2.2.1. Selection of MGPB isolates

Nitrogen fixation, phosphate solubilization, and IAA (Indole-3-Acetic Acid) production criteria suggested in the literature were used for the selection of MGPB isolates for use in co-culture studies with *Scenedesmus* (Liu et al., 2020; Palacios et al., 2022).

2.2.2. Selection of nitrogen-fixing MGPB isolates

The content of selective media, recommended in the literature for the selection of bacterial isolates with nitrogen-fixing ability, used in the present study was as follows: Ashby's [for 1 L: 20 g mannitol, 0.2 g K_2HPO_4, 0.2 g $MgSO_4$, 0.2 g NaCl, 0.1 g K_2SO_4, 5 g $CaCO_3$ and 15 g agar], Jansen's medium [for 1 L: 20 g sucrose, 1 g K_2HPO_4, 0.5 g $MgSO_4$, 0.5 g NaCl, 0.1 g $FeSO_4$, 0.005 g Na_2MoO_4, 2 g $CaCO_3$ and 15 g agar], Jansen's medium [for 1 L: 10 g glucose, 1 g K_2HPO_4, 0.2 g $MgSO_4$, 0.2 g NaCl, 0.1 g $FeSO_4$, 0.005 g Na_2MoO_4, 1 g $CaCO_3$ and 15 g agar] (Liu et al., 2020).

2.2.3. Selection of phosphate-solubilizing MGPB isolates

Pikovskaya's agar [for 1 L: 10 g glucose, 5 g $Ca_3(PO_4)_2$, 0.5 g $(NH_4)2SO_4$, 0.2 g NaCl, 0.1 g $MgSO_4$ $7H_2O$, 0.2 g KCl, 0.002 g $MnSO_4$ $7H_2O$, 0.002 g $FeSO_4$ $7H_2O$, 0.5 g yeast extract, and 15 g agar] medium recommended by the literature was used for the selection of isolates with the potential to solubilize phosphate compounds (Alaylar et al., 2019; Liu et al., 2020).

2.2.4. Selection of indole-3-acetic acid (IAA)-producing MGPB isolates

For the selection of IAA-producing MGPB isolates, each isolate was allowed to grow for 72 h at 28 °C in Luria–Bertani Broth medium supplemented with 1% tryptophan. Then cells were sedimented by centrifugation (12000 rpm for 10 min), 4 ml of Salkowski's reagent was added to 1 ml of supernatant, and the mixture was incubated at 37 °C in the dark for 30 min. At the end of the study period, IAA concentrations of the samples were determined by colorimetric measurement at 530 nm (Liu et al., 2020).

2.3. Cultivation Studies

Scenedesmus isolates were inoculated into a 3N-BBM+V solid medium using the streak method under aseptic conditions (sterile cabinet). After waiting for 10 days in the incubation cabinet, the cells were placed in a 10 ml liquid medium and developed in an incubator for 7-8 days. Then, 10 ml tubes were transferred to liquid 3N-BBM+V medium in 250 ml conical flasks and cultured at 25 ºC, 43.15 $\mu mol/m^2s$ illumination and 110 rpm in an incubator (JRS Lab 32 brand) with a 16:8 hour day-night photoperiod.

In the experiment, 3N-BBM+V nutrient medium was used, which contained: 25 g/l

$NaNO_3$, 2.5 g/l $CaCl_2.2H_2O$, 7.5 g/l K_2HPO_4, 7.5 g/l $MgSO_4.7H_2O$, 0.75 g/l Na_2EDTA, 17.5 g/l $KH_2PO_3.3H_2O$, 2.5 g/l NaCl and supply of essential micronutrients ($FeCl_3.6H_2O$, $MnCl_2.4H_2O$, $ZnCl_2$, $CoCl_2.6H_2O$ and $Na_2MoO_4.2H_2O$) (Andersen, 2005).

2.4. Co-Culture Studies

The experimental co-culture setup for each sample used 20 MGPB and *Scenedesmus* isolates with the highest activity. For each co-culture experiment, the cell count of *Scenedesmus* isolates was taken into the nutrient medium at 2000-4000 cells/mL, and the experiment was established as 50/1 *Scenedesmus*/MGPB by adding the test MGPB isolate at a concentration of $1x10^5$-$2x10^5$ cells/ml. Each experiment was designed to have 3 replications.

The prepared co-cultures were developed for 7 days in the Algae Unit of Atatürk University Faculty of Fisheries at 25 ºC and 43.15 µmol/m^{2}s lighting conditions with a 16:8-hour day-night photoperiod.

2.5. Microalgae cell counts and biomass calculations

Samples from the homogeneous co-culture experimental medium were taken from a 3 ml sample and Lugol solution was dropped into the counting chamber and kept overnight. Cell counts were performed daily using a Zeiss Primo Vert model inverted microscope (Utermohl, 1958; Anonymous, 2003).

Phytoplankton count (cell/ml) = C × At/As × S × V

Here, C = Number of organisms counted (number), At = Counting cell bottom area (mm^2), As = Field of view (mm^2), S = Number of fields of view counted (number), and V = Precipitated sample volume (mL).

For the measurement of biomass of *Scenedesmus* isolates, 15 ml samples were taken after the trial cultures were mixed homogeneously every day and centrifuged for 5 minutes at 13400 rpm and 4°C and read at 680 nm wavelength in a spectrophotometer. The biomass formula for *Scenedesmus* isolates was calculated using the following equation (Li et al., 2021).

Biomass concentration (g/L) = 0.4818 x (A1-A0)

Here, A1 is the absorbance value of the algal sample and A0 is the absorbance value of the culture medium.

2.5.1. Dry cell weight

In this study, 50 ml culture samples were filtered at the beginning and end of the trial using Whatman GF/C filter papers (0.45 µ mesh size). After the filtration process, they were weighed on a 0.001 g sensitive scale, and their wet weights were determined. After the filtered samples were kept in an oven fixed at 100 °C for 1 h, they were placed in a desiccator, cooled to room temperature, and weighed on a 0.001 g sensitive scale (Vonshak, 1997).

2.6. Research Data Evaluation

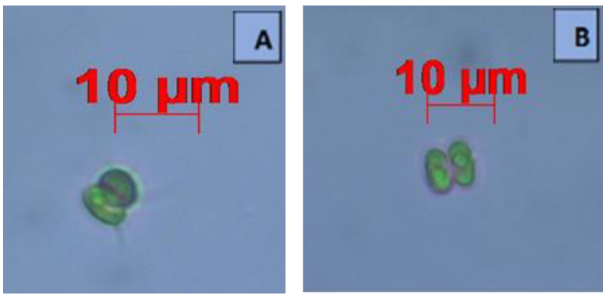
IBM SPSS 20 software was used to evaluate the statistical significance of the findings obtained from all analyses. Cell counting, biomass, and dry matter values were subjected to One-Way ANOVA, and a DUNCAN test was applied to evaluate the differences between them that were significant. In addition, linear correlation among the groups was determined by the Pearson Correlation test.

3. RESULTS

3.1. Identification of *Scenedesmus* and MBTB Isolate

In this study, *Scenedesmus armatus* from Tortum Lake and *Scenedesmus flavescens* from Palandoken Teke Creek Pond were identified (Figure 2).

Group: Chlorophyta
Order: Chlorophyceae
Family: Scenedesmaceae
Genus: *Scenedesmus*
Species: *Scenedesmus armatus*
(*Desmodesmus armatus* (Chodat) E.H.Hegewald
Scenedesmus flavescens
(*Desmodesmus flavescens* (Chodat) E.Hegewald)



Figures 2. *S. armatus* (A) ve *S. flavescens* (B)

Information on the bacterial species isolatedfrom Tortum Lake and the properties of MGPBare given in Table 1. The properties of the bacteria isolated from Palandoken Teke Creek Pond are listed in Table 2.

Table 1. Bacteria isolated from Tortum Lake and their MGPB characteristics.

Code	Bacteria Code	Species	Nitrogen Fixation	Phosphate Dissolution	IAA
A1	D22	*Bacillus* sp.	1.2	+	Negatif
A2	D91	*Bacillus* sp.	1.4	+ +	Negatif
A3	D108	*Bacillus* sp.	1.1	+ + + +	Negatif
A4	D144	*Bacillus* sp.	0.9	+ + +	Negatif
A5	D173	*Pseudomonas* sp.	0.9	+	Negatif
A6	D188	*Pseudomonas* sp.	1.3	+ +	Negatif
A7	D243	*Pseudomonas* sp.	0.8	+	Negatif
A8	D275	*Bacillus* sp.	0.4	+ +	Negatif
A9	D290	*Bacillus* sp.	0.6	+	Negatif
A10	D291	*Bacillus* sp.	0.4	+	Negatif

Table 2. Bacteria Isolated from Palandoken Teke Creek Pond and their MGPB characteristics.

Code	Bacteria Code	Species	Nitrogen Fixation	Phosphate Dissolution	IAA
F1	B163	*Pseudomonas* sp.	Negatif	+ + +	0.161
F2	B134	*Bacillus* sp..	Negatif	+ +	0.057
F3	B115	*Bacillus* sp.	Zayıf	+	0.126
F4	B105	*Pseudomonas* sp.	Negatif	+ +	0.602
F5	B98	*Pseudomonas* sp.	Negatif	+ +	0.069
F6	B100	*Pseudomonas* sp.	Negatif	+	0.048
F7	B76	*Pseudomonas* sp.	Negatif	+ +	0.007
F8	B93	*Bacillus* sp.	Negatif	+	0.164
F9	B94	*Pseudomonas* sp.	Negatif	+	0.127
F10	B96	*Pseudomonas* sp.	1.2	+	0.064

3.2. *S. armatus and S. flavescens* Cell Counting and Biomass

In this study, *S. armatus* and *S.flavescens* species isolated from both lakes were prepared as the control group and a co-culture environment inoculated with 20 MGPB each. The experimental groups were designated as control, A1-A10 for *S. armatus,* and F1-F10 for *S. flavescens*. Both the biomass value and cell numbers for both species were found to be statistically significant depending on the day and groups (p<0.05). It was determined that there was a correlation between *S. armatus* and *S. flavescens* biomass (Table 3).

Table 3. Correlation between *S. armatus* and *S. flavescens* biomass.

		Tortum Lake	Palandoken Teke Creek Pond
Tortum Lake	Pearson Correlation	1	1.0**
	Sig. (2-tailed)		0.0
	N	33	33
Palandoken Teke Creek Pond	Pearson Correlation	1.0**	1
	Sig. (2-tailed)	0.0	
	N	33	33

** The correlation significance level is 0.01

In the co-culture experiment with *S. armatus* and MGPB, the difference between the groups and the change depending on the day were found to be statistically significant (p<0.05). When the increase in biomass depending on the days throughout the experiment was compared with the control group, the highest biomass was found in the co-culture experiments with *Bacillus* sp. (0.34±0.05 mg/L) followed by *Pseudomonas* sp. (0.32±0.05 mg/L); the lowest biomass was found in the co-culture study with *Pseudomonas* sp. (Table 4). Throughout the study, an increase was detected in all groups except A10 and A9 until the 7th day (Figure 3).

Table 4. Changes in *S. armatus* biomass depending on days and groups (mg L^{-1}, Mean±SD, n=3).

Groups	Days						
	1	2	3	4	5	6	7
Control	0.16±0.0^{Bc}*	0.16±0.0^{Dc}	0.16±0.0^{Ec}	0.18±0.0^{Ec}	0.20±0.0^{Db}	0.25±0.0^{Fa}	0.25±0.01^{Ca}
A1	0.16±0.0^{Be}	0.24±0.0^{Cd}	0.27±0.0^{Cc}	0.27±0.0^{Dc}	0.29±0.0^{Cc}	0.42±0.0^{Aa}	0.37±0.01^{Bb}
A2	0.15±0.0^{Cd}	0.17±0.0^{Dc}	0.18±0.0^{Dc}	0.17±0.01^{Fc}	0.19±0.0^{Dc}	0.28±0.01^{Ea}	0.25±0.0^{Cb}
A3	0.17±0.0^{Bc}	0.18±0.0^{Dc}	0.19±0.0^{Dc}	0.17±0.0^{Fc}	0.18±0.0^{Ec}	0.32±0.1^{Da}	0.22±0.0^{Cb}
A4	0.24±0.01^{Ad}	0.29±0.01^{Ac}	0.37±0.01^{Ab}	0.37±0.01^{Ab}	0.39±0.01^{Aa}	0.36±0.01^{Cb}	0.35±0.0^{Bb}
A5	0.24±0.01^{Ae}	0.30±0.0^{Ac}	0.28±0.0^{Cd}	0.33±0.0^{Bb}	0.34±0.0^{Bb}	0.39±0.0^{Ba}	0.39±0.0^{Aa}
A6	0.25±0.0^{Ad}	0.28±0.0^{Bc}	0.30±0.0^{Bb}	0.30±0.0^{Cb}	0.33±0.01^{Bb}	0.40±0.01^{Ba}	0.39±0.0^{Aa}
A7	0.24±0.0^{Ad}	0.28±0.0^{Bc}	0.30±0.0^{Bb}	0.31±0.0^{Cb}	0.31±0.0^{Bb}	0.40±0.0^{Ba}	0.39±0.0^{Aa}
A8	0.15±0.0^{Cc}	0.28±0.0^{Ba}	0.16±0.0^{Ec}	0.16±0.0^{Fc}	0.22±0.0^{Db}	0.21±0.0^{Gb}	0.16±0.0^{Dc}
A9	0.14±0.0^{Dc}	0.17±0.0^{Db}	0.15±0.0^{Ec}	0.19±0.01^{Ea}	0.13±0.0^{Fc}	0.19±0.0^{Ga}	0.16±0.0^{Db}
A10	0.14±0.01^{Dc}	0.16±0.01^{Db}	0.16±0.01^{Eb}	0.13±0.01^{Gc}	0.14±0.01^{Fc}	0.23±0.01^{Ga}	0.18±0.01^{Db}

*A, B.. Capital letters indicate the difference between groups on the same day, and the difference between groups with different capital letters in the same column was statistically significant (p<0.05).
a, b,…: Lower-case letters indicate the difference between days in the same group, and the difference between days with different lower-case letters in the same row was statistically significant (p<0.05).

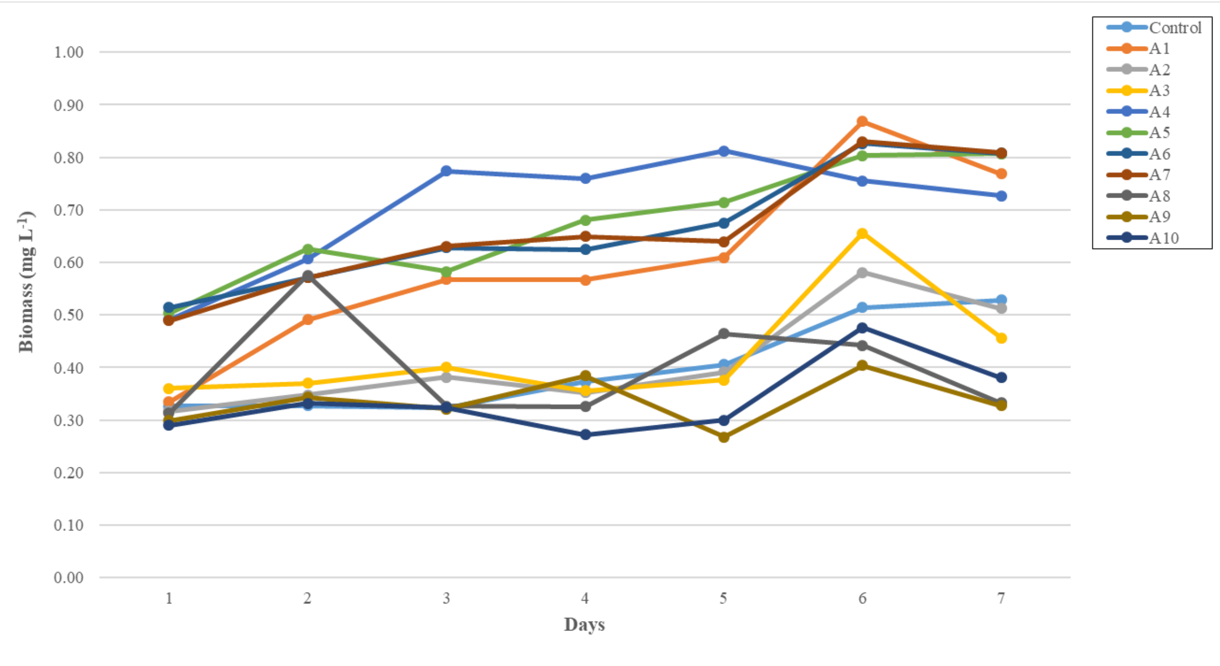


Figure 3. Biomass changes of *S. armatus* and MGPB co-culture groups depending on the day.

In the co-culture experiment with *S. flavescens* and MGPB, the change depending on the experimental groups and days was statistically significant (*p*<0.05). Throughout the experiment, the highest biomass was determined to be *Bacillus* sp. (0.10±0.01 mg L^{-1}) in the co-culture experiment. According to the average biomass value, the effects of *Pseudomonas* sp. were found to be similar to the control group (0.06±0.03 mg/L) (Table 5). In this study, a decrease was detected in all groups, except the F7 group after the 2nd day (Figure 4).

Table 5. Changes in *S. flavescens* biomass depending on days and groups (mg L^{-1}, Mean±SD, n=3).

Groups	Days						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Control	0.10±0.01^{Aa*}	0.09±0.0^{Aa}	0.10±0.0^{Aa}	0.04±0.01^{Bb}	0.04±0.01^{Bb}	0.03±0.01^{Db}	0.02±0.01^{Cb}
F1	0.07±0.0^{Bb}	0.09±0.01^{Aa}	0.07±0.01^{Cb}	0.05±0.0^{Bc}	0.04±0.0^{Bc}	0.03±0.0^{Dd}	0.02±0.0^{Cd}
F2	0.09±0.01^{Aa}	0.08±0.01^{Aa}	0.09±0.01^{Ba}	0.05±0.01^{Bb}	0.04±0.0^{Bb}	0.04±0.0^{Cb}	0.02±0.0^{Cc}
F3	0.10±0.01^{Aa}	0.09±0.0^{Aa}	0.10±0.0^{Aa}	0.05±0.0^{Bb}	0.04±0.0^{Bb}	0.04±0.0^{Cb}	0.02±0.0^{Cc}
F4	0.09±0.0^{Aa}	0.09±0.0^{Aa}	0.09±0.0^{Ba}	0.05±0.0^{Bb}	0.04±0.0^{Bb}	0.04±0.0^{Cb}	0.04±0.0^{Bb}
F5	0.09±0.01^{Aa}	0.09±0.0^{Aa}	0.09±0.01^{Ba}	0.04±0.0^{Bb}	0.04±0.01^{Bb}	0.05±0.01^{Cb}	0.04±0.01^{Bb}
F6	0.09±0.0^{Aa}	0.09±0.0^{Aa}	0.09±0.01^{Ba}	0.05±0.01^{Bb}	0.05±0.0^{Bb}	0.05±0.01^{Cb}	0.05±0.01^{Bb}
F7	0.08±0.0^{Ab}	0.08±0.0^{Ab}	0.08±0.0^{Bb}	0.04±0.0^{Bc}	0.04±0.01^{Bc}	0.18±0.0^{Aa}	0.03±0.01^{Cc}
F8	0.11±0.0^{Aa}	0.10±0.0^{Ab}	0.11±0.0^{Aa}	0.09±0.0^{A}	0.09±0.01^{Ab}	0.12±0.01^{Ba}	0.11±0.01^{Aa}
F9	0.07±0.0^{Bb}	0.09±0.01^{Aa}	0.07±0.01^{Cb}	0.05±0.01^{Bc}	0.04±0.01^{Bc}	0.05±0.0^{Cc}	0.04±0.01^{Bc}
F10	0.06±0.0^{Bb}	0.13±0.01^{Aa}	0.06±0.0^{Cb}	0.04±0.0^{Bc}	0.03±0.0^{Cc}	0.02±0.0^{Dd}	0.01±0.0^{Cd}

*A, B.. Capital letters indicate the difference between groups on the same day, and the difference between groups with different capital letters in the same column was statistically significant (p<0.05).
a, b,…: Lower-case letters indicate the difference between days in the same group, and the difference between days with different lower-case letters in the same row was statistically significant (p<0.05).

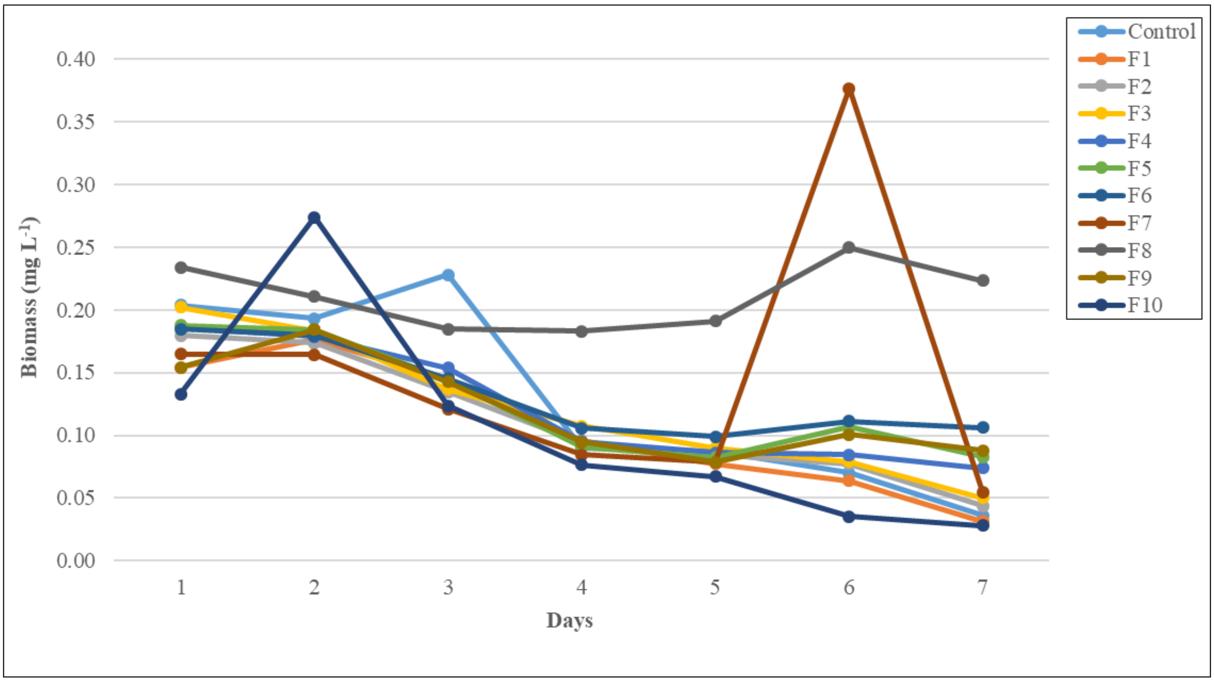


Figure 4. Biomass changes of *S. flavescens* and MGPB co-culture groups depending on days.

In the co-culture study with MGPB isolated from Tortum Lake and *S. armatus*, the change in cell count depending on the day and groups was found to be statistically significant ($p<0.05$). In this study, the highest cell count in the co-culture groups was determined in the experiment with *Bacillus* sp., with an average of 306±16.21 cells/ml. This was followed by the co-culture experiments with *Pseudomonas* sp. with a cell count of 251±13.37 cells/ml and *Pseudomonas* sp. with a cell count of 260±17.6 cells/ml. The cell count in the control group was calculated as an average of 107±45.03 cells/ml (Table 6).

Table 6. Change in *S. armatus* cell number depending on days and groups (cell/ml, Mean±SD, n=3).

Groups	**Days**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Control	80±22.63^{Ad*}	32±11.31^{Ee}	80±3.30^{Fd}	96±4.50^{Gc}	144±90.05^{Iab}	160±22.67^{Ha}	160±67.88^{Ia}
A1	64±11.3^{Bf}	64±33.06^{Df}	80±3.30^{Fe}	128±56.56^{Fd}	160±33.94^{Hc}	192±0.1^{Fb}	240±67.88^{Da}
A2	16±0.6^{De}	16±10.1^{Fe}	208±56.68^{Cd}	208±56.56^{Cd}	224±56.67^{Fc}	256±0.1^{Db}	288±67.88^{Ca}
A3	16±0.5^{De}	80±9.06^{Cd}	224±22.62^{Ba}	160±13.57^{Ec}	176±33.94^{Gb}	170±4.95^{Gb}	170±67.88^{Gb}
A4	10±0.1^{Ff}	96±11.3^{Be}	160±0.90^{Ed}	208±68.7^{Cc}	304±56.67^{Da}	224±60.78^{Eb}	208±67.88^{Ec}
A5	64±0.1^{Bf}	80±11.3^{Ce}	288±15.23^{Ad}	368±67.8^{Ac}	416±56.67^{Bb}	528±60.78^{Aa}	400±67.88^{Ab}
A6	80±45.25^{Ae}	80±0.1^{Ce}	160±24.36^{Ed}	320±56.56^{Bc}	448±56.67^{Aa}	352±60.78^{Cb}	320±67.88^{Bc}
A7	16±0.1^{Fe}	10±0.5^{Ge}	208±67.8^{Cd}	368±67.8^{Ac}	368±56.67^{Cc}	480±69.8^{Ba}	384±67.88^{Ab}
A8	32±11.31^{Cf}	144±33.9^{Ad}	192±22.62^{Da}	176±12.57^{Db}	160±33.94^{Hc}	80±5.90^{Ke}	32±67.88^{Kf}
A9	16±9.06^{De}	16±0.7^{Fe}	160±11.03^{Ed}	208±56.56^{Cb}	256±56.67^{Ea}	190±5.90^{Ic}	192±22.63^{Fc}
A10	16±9.06^{De}	16±0.7^{Fe}	160±11.03^{Ed}	208±56.56^{Cb}	256±56.67^{Ea}	190±5.90^{Ic}	192±22.63^{Fc}

*A, B.. Capital letters indicate the difference between groups on the same day, and the difference between groups with different capital letters in the same column was statistically significant (p<0.05).
a, b,…: Lower-case letters indicate the difference between days in the same group, and the difference between days with different lower-case letters in the same row was statistically significant (p<0.05).

In the co-culture study of MGPB with *S. flavescens* isolated from the Palandoken Teke Stream, the change in cell count depending on the groups and days was found to be statistically significant (p<0.05). The cell count was calculated to be 93±6.01 cells/ml in the co-culture medium with the highest *Bacillus* sp. added throughout the experiment. This value was determined as an average of 74±6.30 cells/ml and 71±3.01 cells/ml in the co-culture experiments with *Pseudomonas* sp. and *Bacillus* sp. (Table 7).

Table 7. Change in *S. flavescens* cell number depending on days and groups (cell/ml, Mean±SD, n=3).

Groups	**Days**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Control	80±45.25^{Ba*}	32±11.31^{Ec}	16±11.31^{Dd}	10±0.1^{Fe}	64±56.67^{Fa}	16±11.31^{Ed}	16±11.31^{Dd}
F1	64±11.31^{Cb}	64±56.67^{Db}	10±0.1^{Ed}	32±11.31^{Dc}	80±45.25^{Ea}	10±0.1^{Fd}	10±0.1^{Ed}
F2	80±45.25^{Ba}	32±11.31^{Ec}	16±11.31^{Dd}	48±22.62^{Cb}	80±45.25^{Ea}	10±0.1^{Fe}	10±0.1^{Ee}
F3	16±11.31^{Ef}	80±45.25^{Cd}	64±0.1^{Be}	160±67.88b^{B}	176±67.88^{Aa}	16±11.31^{Ef}	16±11.31^{Df}
F4	48±22.62^{Fb}	16±11.31^{Fc}	10±0.1^{Ed}	48±22.62^{Cb}	64±46.67^{Fa}	64±46.67^{Ba}	16±11.31^{Dc}
F5	64±56.67^{Cd}	32±11.31^{Ef}	128±0.1^{Aa}	48±22.62^{Ce}	96±45.25^{Db}	48±22.62^{Ce}	80±45.25^{Ac}
F6	176±67.88^{Aa}	80±45.25^{Cb}	16±11.31^{De}	16±11.31^{E}	48±22.62^{Gc}	48±22.62^{Cc}	32±11.31^{Cd}
F7	80±45.25^{Bb}	128±67.88^{Ba}	16±11.31^{Dd}	16±11.31^{Ed}	128±67.88^{Ca}	10±0.1^{Fe}	64±46.67^{Bc}
F8	32±11.31^{De}	144±67.88^{Ac}	32±11.31^{Ce}	176±67.88^{Aa}	160±67.88^{Bb}	80±45.25^{Ad}	32±11.31^{Ce}
F9	16±11.31^{Ed}	16±11.31^{Fd}	16±11.31^{Dd}	48±22.62^{Cb}	96±45.25^{Da}	32±11.31^{Dc}	32±11.31^{Cc}
F10	16±11.31^{Eb}	16±11.31^{Fb}	10±0.1^{Ec}	16±11.31^{Eb}	80±45.25^{Ea}	10±0.1^{Fc}	10±0.1^{Ec}

*A, B.. Capital letters indicate the difference between groups on the same day, and the difference between groups with different capital letters in the same column was statistically significant (p<0.05).
a, b,…: Lower-case letters indicate the difference between days in the same group, and the difference between days with different lower-case letters in the same row was statistically significant (p<0.05).

3.3. Dry Matter of *S. armatus* and *S. flavescens*

In this study, dry matter quantity was measured on the first and last days of the co-culture trial conducted with *S. armatus*, *S. flavescens* and MGPB isolates. In the trials conducted with *S. armatus*, the dry matter quantity was obtained from the co-culture trials conducted with *Pseudomonas* sp. compared to the control group (Figure 5). In the co-culture trial conducted with *S. flavescens* and MGPB species, the dry matter quantity was the same in all groups on the 7th day (Figure 6).

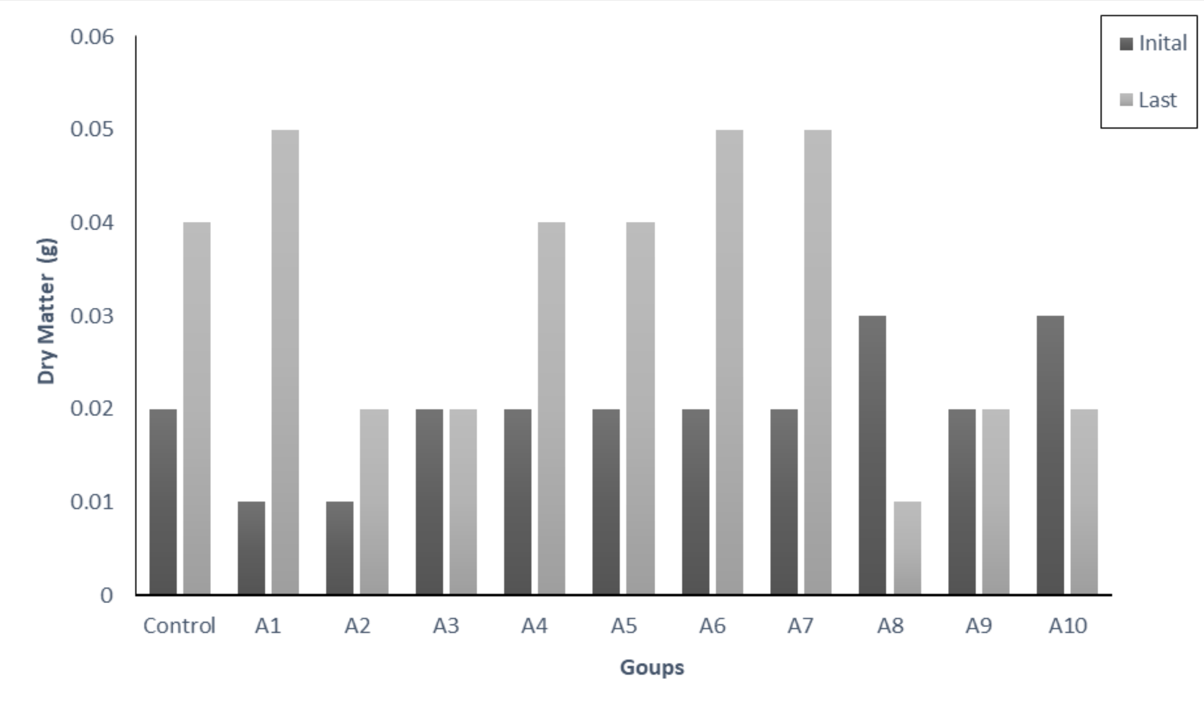


Figure 5. Change in dry matter value of *S. armatus* depends on groups.

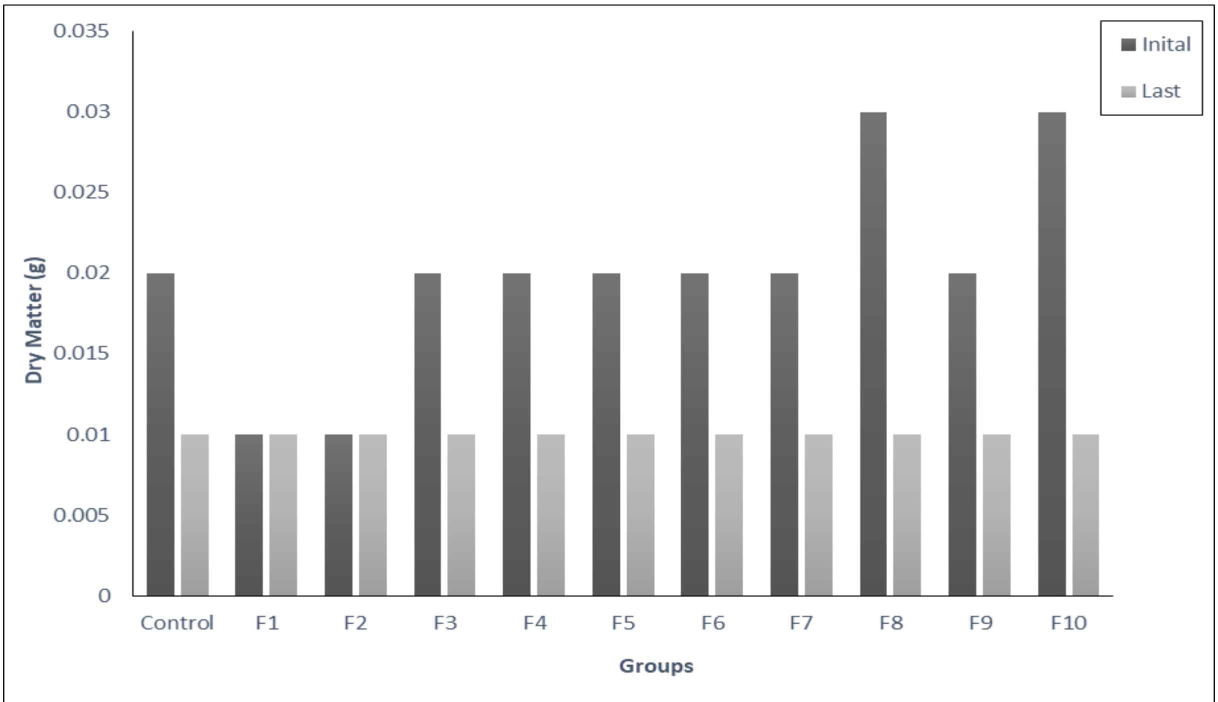


Figure 6. Change in dry matter value of *S. flavescens* depends on groups.

4. DISCUSSION

In this study, the changes in biomass and cell numbers in the co-culture medium of *S. armatus* and *S .flavescens* species isolated from the Palandoken Teke Stream and Tortum Lake, and MBTB species collected from the same locations were examined. MBTB species with nitrogen fixation and phosphorus retention properties were preferred by both species. While an increase in biomass and cell numbers was detected in *S. armatus* and MBTB co-culture experiments, almost the same biomass and cell numbers were calculated in the group with only 3N-BBM+V (control) medium in *S. flavescens* and MBTB co-culture experiments. However, higher biomass and cell numbers were detected in the co-culture medium of *S. armatus* and *S. flavescens*.

Many studies have investigated the optimal conditions of environmental factors (light, temperature, pH, etc.) to increase cell growth and biomass in microalgae cultures, as well as set up experiments by changing the concentrations of the nutrient medium (N and/or P stress) (Hızarcı, 2004; Şahin, 2010; Uslu et al., 2011; Ağırman, 2015; Bedil, 2015; Öztürk, 2016; Yılmaz, 2016; Akın, 2017; Aygün, 2017; Acar & Fakıoğlu, 2018; Öztürk, 2018; Kaplan Çoban, 2018; Aladağ, 2019; Çoban, 2019; Kurusakız, 2020; Özalın, 2020; Andeden, 2021; Şahin, 2021). In these studies, waste products and glucose galactose were applied as nutrient media for microalgae (Abreu et al., 2012; Aydoğdu and Fakıoğlu, 2022). In this study, the development of MBTB and Scenedesmus species by taking them in the same culture system was tested for the first time in our country. While the biomass of *S. armatus* and *S. flavescens* cultured in the co-culture medium was calculated as 0.25 mg/L and 0.07 mg/L on average, the biomass of *S. armatus* and *S. flavescens* only in the 3N-BBM+V medium was determined as 0.19 mg/L and 0.06 mg/L.

Nitrogen and phosphorus ratios, which are the main sources in the nutrient medium, vary depending on the microalgal species (Richmond, 2004). In this study, cell growth was observed with *S. armatus, which has the highest nitrogen fixation value and lowest phosphorus solubilization value among* MBTB species, while no cell growth was observed in *S. flavescens, which has a* “negative” nitrogen fixation value and high phosphorus retention value. In studies conducted with multiple limiting nutrients, the growth rate varied depending on the intracellular concentration of only the most limiting nutrient in microalgae (Klausmeier et al., 2004).

Pseudomonas asplenii has been reported to secrete heat-stable inorganic substances that have a growth-promoting effect on the microalgae *Chattonella marina* and increase its ability to grow in phosphate-limited environments (Palacios et al., 2022). In this study, *S. armatus* showed good growth in an environment with non-phosphate-limiting bacteria, whereas *S. flavescens* grew in an environment with phosphate-limiting bacteria.

Hernandez et al. (2009) investigated the effect of MBTB *Azospirillum brasilense* on nitrogen uptake by *Chlorella vulgaris* and reported that *Bacillus pumilus* can fix atmospheric nitrogen and produce ammonium to increase the growth of the microalgae *Chlorella vulgaris*. In this study, *Bacillus* sp. promoted the growth of *S. armatus*.

In this study, *Pseudomonas* sp., which can produce IAA, promoted an increase in *S. flavescens* biomass. It has been reported that the interaction between *Euglena gracilis* and five bacterial species capable of producing IAA (Pseudomonas sp. DSM 25356 and *Pseudomonas* sp. DSM25842, *Vibrio natriegens* KCTC 12726, *Paenibacillus yonginensis* KCTC 33428, and *Sphingomonas panaciterrae* KCTC 42646), and IAA-producing *Vibrio natriegens* had the capacity to increase growth (Kim et al., 2019).

Rhizobium sp. isolated from an open pond was cultured in open ponds in a co-culture medium with *Chlorella sorokiniana* and an increase in mass of 13.76% was achieved (Zhou et al., 2021). In this study, 6% growth was detected in *S. flavescens* biomass and 7% in *S. armatus* biomass.

5. CONCLUSION

This study is the first to use both bacteria and *Scenedesmus* isolates obtained from natural sources and monitor their development in a co-culture. MBTB stimulated the growth of *S. armatus* and *S. flavescens*. In this study, *Bacillus* sp. and *Pseudomonas* sp., which have nitrogen fixation, IAA production, and phosphorus retention capabilities, were thought to stimulate the growth of *S. armatus* and *S. flavescens*, respectively. Future co-culture studies are needed.

1. It is recommended to conduct research to determine the intracellular mechanism supporting the development of these species,
2. In addition to biomass increase, it is recommended to investigate the amounts of fat and protein, which are involved in intracellular metabolism, amino acid, and fatty acid compositions.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

AUTHOR CONTRIBUTIONS

Funding: Ö.F.; Literature: Ö.F.; Methodology: Ö. F., M. K.; Data analysis: Ö.F., Z.A.; Manuscript writing: Ö.F., Z. A. ; Performing the experiment: Ö.F. and Z.A. All authors approved the final draft.

ETHICAL APPROVAL STATEMENTS

Approval from the local ethics committee was not obtained because the experimental animals were not used in this study.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Research Article | Araştırma Makalesi

Characterization of Fishing Around Lake Madarounfa (Maradi/Niger) and its Impact on the Ecosystem

Madarounfa Gölü (Marradi/Nijer) Çevresinde Balıkçılığın Karakterizasyonu ve Bunun Ekosistem Üzerindeki Etkisi

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Abstract: This study aimed to characterize fishing and its effect on the functioning of Lake Madarounfa. Surveys were conducted to identify the fishing practices, used gears, the fish stock, and the impacts of fishing activities on the ecosystem. The fish fauna was studied through the catches of artisanal fishermen at four stations from June to December 2023. Twenty-two species belonging to twelve families and nineteen genera were identified. The Cichlidae family, with 4 genera and 4 species, was the most prevalent. Of the 5 fishing gear identified, the gillnet was the most used. A total of 35 tons of fresh fish were produced during the present study. This result showed that the greatest catch per unit effort (CPUE) was found with the cast net (9.72 kg/h). The analysis of the size structures showed a dominance of small individuals. More than 73.97% of individuals were smaller than 18.11±9.25 cm, corresponding to the mean total length of all fish individuals measured during this study. This level of fishing pressure on juveniles could affect the normal recruitment of fish stocks and lead to biodiversity erosion. Due to the intensity of uncontrolled fishing all year, agricultural activities and climate change, the functioning of the ecosystem is greatly disrupted. This constitutes a threat to the sustainability of the ecosystemic services provided by the lake. The findings of this work suggests that to ensure a sustainable fishery management of the lake, it is necessary to establish continuous monitoring and strengthen the enforcement of laws concerning ecosystem protection around this water body.

Keywords
- Anthropogenic activities
- Wetland
- Ramsar Site
- Fishing
- Maradi

Özet: Bu çalışma, Madarounfa Gölü balıkçılığını ve ekosisteme etkisini karakterize etmeyi amaçlamıştır. Balıkçılık uygulamalarını, kullanılan av araçlarını belirlemek, balık stoğunu ve balıkçılık faaliyetlerinin ekosistem üzerindeki etkilerini değerlendirmek için anketler yapılmıştır. Balık faunası zanaatkâr balıkçıların 4 istasyondan yakaladıkları av üzerinden Haziran-Aralık 2023 tarihleri arasında incelenmiştir. 12 familya ve 19 cinse ait 22 tür tespit edilmiştir. Cichlidae familyası 4 cins ve 4 tür ile en fazla temsil edilen familyadır. Belirlenen 5 av aracı arasında en çok kullanılanı uzatma ağıydı. Bu çalışma sırasında toplam taze balık üretimi 35 tondur. Bu sonuç, birim çaba başına en büyük avın (CPUE) dökme ağda (9,72 kg/saat) bulunduğunu gösterdi. Boy yapılarının analizi, küçük bireylerin baskınlığını gösterdi. Bireylerin %73,97'sinden fazlasının boyu 18,11±9,25 cm'den küçüktü. Gençler

Anahtar kelimeler
- Antropojenik faaliyetler
- Sulak alan
- Ramsar Alanı
- Balık tutma
- Maradi

üzerindeki bu seviyede balıkçılık baskısı, balık stoklarının normal şekilde kullanılmasını etkileyebilir ve biyolojik çeşitlilik erozyonuna yol açabilir. Madarounfa Gölü'nün küçüklüğü ve yıl boyunca kontrolsüz balıkçılığın yoğunluğu göz önüne alındığında ekosistemin işleyişi büyük ölçüde bozulmaktadır. Bu durum, gölün ekosisteme sağladığı katkıların sürdürülebilirliğine tehdit oluşturmaktadır. Gölde sürdürülebilir bir balıkçılık yönetimi sağlamak için, bu su kütlesinin çevresinde sürekli bir izleme sisteminin kurulması ve ekosistemin korunmasına ilişkin yasaların uygulanmasının güçlendirilmesi gerekmektedir.

1. INTRODUCTION

Fishing is one of the human activities that impacts aquatic ecosystems through uncontrolled fishing and unconventional fishing practices and gears. It is an activity that affects the dynamics of stocks and populations of aquatic living organisms (Lévêque & Paugy, 1999; Albaret et al., 2003; Ouattara et al., 2006). The effects on ecosystems are both direct, through the increase in mortality coefficient of target and non-target species or modifications of the biotope caused by fishing gear (Jennings and Kaiser 1998; Hall et al., 2000). The important role of this activity in the socio-economic development of populations has been confirmed by several studies (Lae, 1997; Ouattara et al., 2006).

Today, fishermen in developing countries no longer talk about the profitability of their activities, but rather about a simple livelihood (Montcho, 2011; Yacouba, 2019). Thus, fishery resources management is becoming more and more of a challenge biologically and economically (Montchowui et al., 2008; Tsikliras et al., 2015; Yacouba, 2019). To deal with this situation, Niger Republic has adopted a fishing development and responsible aquaculture strategy since 2007 for the conservation, management, and development of fishery resources respecting ecosystems and biodiversity, to deal with food insecurity and poverty.

Lake Madarounfa with a maximum depth varying between 1.5 and 5 meters according to the seasons and a surface area that varies between 4000 ha during the high-water period and 800 ha during the low-water period, is the largest permanent surface water body in the Maradi region (Niger) (Assane & Issiaka, 2021). This is protected by both national and international legal status. Indeed, the lake has been designated as a wetland of international importance according to the Ramsar Convention in 2021 (Ramsar, 2021). Today, fishing in Lake Madarounfa is an important activity among many other activities that provide several socio-economic benefits to local populations. Previous studies have been conducted on the ichthyological diversity of this lake (Ramsar, 2021, Assane & Issiaka, 2021). This study, the first attempt of its kind in the region, aimed to characterize fishing and its effect on the functioning of the lake Madarounfa.

2. MATERIALS and METHODS

2.1. Working schedule

This study was conducted from June to December 2023.

2.2. Study area

Lake Madarounfa is located in the district of Madarounfa which occupies the southern part of the Maradi region (Niger) between 13° and 15° north latitude and between 6° and 8° east longitude and covers a surface area of 3.500 km^2 which represents 9% of the Region. (Figure1).

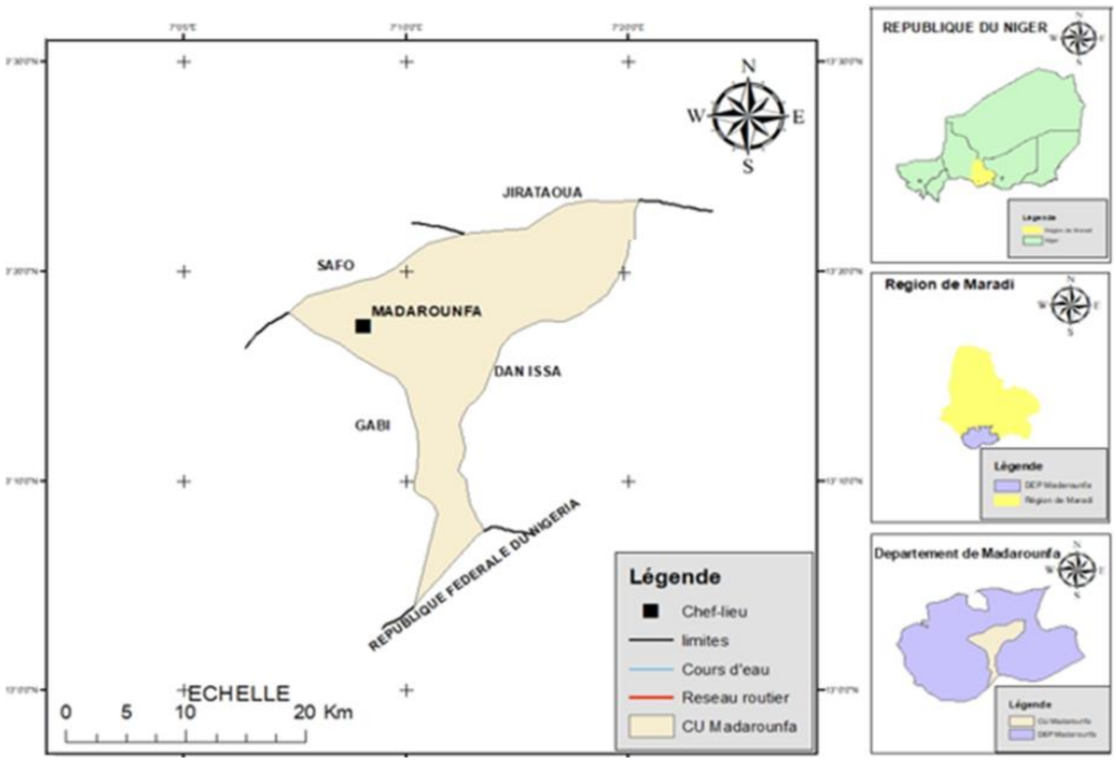

Figure 1. Location of the study area.

2.2. Determination of water physicochemical parameters

During this study, some physicochemical parameters were determined in situ. Measurements were carried out between 7 a.m. and 10 a.m. once a month during six (6) months from June to December 2023. The parameters measured were water temperature (°C), pH, total dissolved solids ((TDS) mg L^{-1}) and conductivity (µS cm^{-1}) using a multiparameter, the water depth (cm), and the water transparency (cm) using a Secchi disc. The data collected were processed and analyzed after testing their normality. The mean and standard deviation of each parameter were calculated and then, the Kruskal Wallis test was used to compare the averages among stations and months.

2.3. Diversity, morphometric characteristics and fish stock

To meet many fishermen, four (4) stations were chosen (Dantoudou, Madarounfa, Gamji, and Saoulaoua). Each station was visited 2 days per month during six months from June to December 2023 between 7 a.m. and 11 a.m. At each station, fish catches from artisanal fishing are sampled to characterize the fish population in the lake.

The fish diversity was studied using Shannon-Wiener Index (H') and the regularity or fairness of Piélou ((Eq) based on equations 1 and respectively.

$$H' = -\sum_{k=0}^{n} \quad (Pi * log2(Pi)) \qquad (1)$$

Pi = ni / N; ni is the number of individuals representing species i and N = total number of individuals.

$$Eq = \frac{H'}{log2*S} \qquad (2)$$

Where S = total number of species. The index varies from 0 to 1.

After identification using the key of Paugy et al. (2003), the morphometric characteristics of fish individuals were measured especially the total length (Lt), the standard length (Ls), and the total weight (Pt) of each individual using an ichthyometer and an electronic scale. Then, a Kruskal-Wallis test was performed to determine the change in species number from one month to another.

A survey was conducted among active fishermen and agents of the Madarounfa departmental environment directorate to determine the fish stock per season. The quantity of fish caught during the period of this study was then deducted and analyzed. Ideally, abundance indices should be derived from scientific studies independent of commercial fishing, such as those carried out by research groups. However, in many cases, due to cost or other logistical issues, fisheries independent surveys are just not feasible and so fisheries dependent, catch-rate data (CPUE) must be used to create an abundance index for stock assessments (Candy, 2004; Ducharme-Barth, 2021). Therefore, determining an abundance index from commercial data is a common procedure in fishing characterization. To analyze fishing catches around the lake, catch per unit of effort (CPUE) in kilogram per hour (kg/h) was calculated from fresh fish quantity recorded during the study period using equation 3.

$$CPUE = \frac{Total\ catch}{Fishing\ time\ x\ number\ of\ fishing\ gears\ x\ number\ of\ fishermen\ per\ fishing\ gear} \quad (3)$$

2.4. Weight-length relationships of abundant species in fish catches

The length-weight equation (Equation 4) was used to estimate the relationship between the weight (g) of the fish and its total length (cm). The length-weight was estimated as (Ricker, 1975):

$$Pt = aLt^b \quad (4)$$

Pt and Lt represent fish individuals' total weight and length, respectively while a and b are characteristic of environmental factors and species respectively.

To determine whether the relationships between selected morphological variables exhibit isometric or allometric change, a linear regression and t-tests were performed using IBM SPSS Statistics 23.

2.5. Condition factor of abundant species

The condition factor k is calculated for abundant species in fish catches using the following equation 5.

$$K = 100 * (\frac{Pt}{Lt^b}) \quad (5)$$

Pt is the total weight, Lt is the total length of the fish, and b is the allometry coefficient of the weight-length relationship. The condition factor is an important parameter in fisheries biology and is used to assess the fish's corpulence and overweight. Good growth condition of the fish is deduced when $Kn \geq 1$, while the organism is in poor growth condition compared to an average individual with the same length when $Kn < 1$ (Jisr et al., 2018).

2.7. Identification of fishing gears and their selectivity

The different fishing gear types used by fishermen were identified in situ and their selectivity was determined through the number of fish individuals caught by each gear. Then, a canonical correspondence analysis was carried out using the Past 4.03 software to examine the selectivity of fishing gear according to the specific diversity of catches. This permitted the identification of the common species cached by each fishing gear (George and Nédélec, 1991 ; Camille et al., 2016) used by fishermen around Lake Madarounfa.

3. RESULTS

3.1. Physicochemical parameters of the water

The physico-chemical characteristics of the water are presented in Table 1. It appears from the analysis of this table that the conductivity and transparency of water had high standard deviations (15.13 and 4.51, respectively), while the lowest standard deviation (0.11) was observed for TDS. The mean depth of the lake was 0.51±0.11 while the coefficient of variation varied between 0.3 and 0.69 for temperature and TDS respectively. The water temperature ranged from 20.3°C to 22.6°C with an average of 21.50±0.73°C. Statistical analysis showed no significant difference in water temperature between stations (P>0.05). However, there was a significant difference between months ($P < 0.05$).

Table 1. Summary of physicochemical parameters of the water during the study period.

	Temperature	pH	Conductivity (µS/cm)	TDS (ppm)	Transparency (cm)	Depth (m)
Mean	21.50±0.73	6.51±0.40	85.07±15.13	0.15±0.11	25.75±4.51	0.51±0.11
SD	0.73	0.40	15.13	0.11	4.51	0.11
Min	20.3	6.3	69	0.08	20.5	0.37
Max	22.6	7.3	118	0.42	40	0.97
CV	0.33	0.62	0.17	0.69	0.17	0.21

SD: Standard Deviation. Mini: minimum. Max: maximum. CV: coefficient of variation. TDS: total dissolved solids.

3.2. Species abundance

A total of 22 species were identified around the lake (Table 2). The Cichlidae constituted the most represented (44.83%) family with 4 species and 4 genera, followed by the Mormuridae family (14.88%) with 3 species and 3 genera and the Clariidae family (13.73%). The other families are each represented by a single species. The most abundant species in number are Oreochromis niloticus (22.28%), *Sarotherodon galilaeus* (15.33%), and *Bagrus bajad* (7.31%) (Table 2).

Table 2. List of identified fish species.

Families	Genera	Species	% values
Anabantidae	Ctenopoma	*Ctenopoma kingsleyae* (Günther, 1896)	0.67
Bagridae	Bagrus	*Bagrus bajad (Forskål, 1775)*	7.31
Characidae	Alestes	*Alestes macrophthalmus* (Günther, 1867)	0.71
	Brycinus	*Brycinus leuciscus* (Günther, 1867)	2.63
Cichlidae	Hemichromis	*Hemichromis bimaculatus (Gill 1862)*	1.16
	Oreochromis	*Oreochromis niloticus* (Linnaeus, 1758)	22.28
	Sarotherodon	*Sarotherodon galilaeus* (Linnaeus, 1758)	15.33
	Tilapia	*Tilapia zillii* (Gervais, 1848)	6.06
Clariidae	Clarias	*Clarias anguillaris* (Linnaeus,1758)	4.55
		Clarias gariepinus (Burchell, 1822)	5.88
	Heterobranchus	*Heterobranchus bidorsalis* (Geoffroy SaintHilaire, 1809)	3.30
Claroteidae	Chrysichthys	*Chrysichthys auratus* (Geoffroy Saint-Hilaire, 1808)	0.18
Latidae	Lates	*Lates niloticus* (Linnaeus,1758)	4.10
Mochokidae	Synodontis	*Synodontis courteti* (Pellegrin, 1906)	0.18
		Synodontis schall (Bloch et Schneider, 1801)	1.07
Mormyridae	Hyperopisus	*Hyperopisus bebe occidentalis* (Lacepède, 1803)	6.69
	Petrocephalus	*Petrocephalus bovei* (Valenciennes,1847)	3.48
	Pollimyrus	*Pollimyrus isidori* (Valenciennes, 1846)	4.72
Polypteridae	Polypterus	*Polypterus senegalus* (Cuvier, 1829)	0.62
Protopteridae	Protopterus	*Protopterus annectens* (Owen, 1839)	0.80
Schilbeidae	Schilbe	*Schilbe intermedius* (Rüppell, 1832)	4.63
		Schilbe mystus (Linnaeus,1758)	4.01

3.3. Spatial and temporal variations of diversity indices

Species diversity changed from one station to another during the study period. Thus, 21 species were identified at Dantoudou, 18 at Madarounfa, 10 at Gamji, and 14 at Saoulaoua (Table 3). The analysis of this table indicated that the Shannon diversity index changed from 1.96 to 3.88. On another hand, high Piélou fairness (0.8≤ Eq≤1) was observed at Dantoudou, Madarounfa, and Saoulaoua stations. The situation indicated a non-dominance in communities of these three stations contrary to the station of Gamji with low fairness (0≤ Eq ≤ 0.6) which indicated a dominance of one species in the community.

Table 3. Spatial variation of diversity indices.

Stations	Shannon diversity index (H')	Piélou fairness (Eq)	Species number
Dantoudou	3.88 ±0.18	0.88	21
Gamji	1.96 ±0.19	0.59	10
Madarounfa	3.48 ±0.19	0.83	18
Saoulaoua	3.17 ±0.22	0.83	14

The distribution of fish diversity based on the Shannon diversity index and Piélou fairness during the six months of the study period is represented in Table 4. It appears from the analysis of this table that the diversity index changed according to the months, but indicated a non-dominance of one species contrary to the Piélou fairness which indicated a dominance of one species during the 6 months.

Table 4. Temporal variation of diversity indices.

Months	Shannon diversity index (H')	Piélou fairness (Eq)	Species number
June	3.43±0.20	0.84	17
July	3.23±0.20	0.80	16
August	3.41±0.17	0.80	19
October	3.13±0.26	0.87	12
November	3.35±0.23	0.87	14
December	2.79±0.27	0.84	10

The result of the Kruskal-Wallis test (p = 0.33) showed that the number of species does not vary from one month to another (Table 5).

Table 5. Summary of the Kruskal-Wallis Test.

Null Hypothesis	Test	Sig.	Decision
The distribution of species is the same across categories of group.	Independent-Samples Kruskal-Wallis Test	0.33	Reject the null hypothesis

Asymptotic significance is displayed. The significance level is 0.05.

3.4. Morphometric variables of species

In total, 1122 fish individuals were measured during the 6 months of the study period. The individual number per species, minimum, average, and maximum values of total length, standard length, and total total weight are presented in Table 6. The total length changed from 5.5 cm (*Pollimyrus isidori*) to 60 cm (*Clarias anguillaris*), while the standard length varied between 5.2 cm (*Tilapia zillii*) to 60 cm (*Clarias anguillaris*). Species weight varied from 2 g (*Brycinus leuciscus*, *Pollimyrus isidori* and *Hemichromis bimaculatus*) to 2600 g (*Clarias anguillaris* and *Lates niloticus*).

The analysis of the extreme sizes in the captured fish by fishing gear showed that the individual with the largest maximum size (60.6 cm) was recorded in the gillnet catches while the creel and the cast net captured individuals having the smallest minimum size (5.5 cm).

Table 6. Morphometric parameters of fish species.

Species	N	Lt (cm)			Ls (cm)			Pt (g)		
		Lt max	Lt mean	Lt min	Ls max	Ls mean	Ls min	Pt max	Pt mean	Pt min
Alestes macrophthalmus	8	24	15.59±5.91	6.7	19	12.65±4.72	5.5	59	34.88±1.62	3
Bagrus bajad	82	49	27.38±9.61	8.7	42	23.30±8.48	7	926	197.01±10.04	3
Brycinus leuciscus	30	13.1	9.20±2	6.1	10.5	7.61±1.51	5	10	5.10±1.55	2
Chrysichthys auratus	2	26	26±0.23	26	24.8	24.80±0.56	24.8	97	97±3.56	9.7
Clarias anguillaris	51	65	25.41±10.18	10.5	60	22.54±9.41	9.3	2600	188.06±8.44	8
Clarias gariepinus	66	52.2	27.03±11.19	11.3	47	23.86±9.90	10	897	183.08±6.74	7
Ctenopoma kingsleyae	3	12.6	12.07±0.76	11.2	11	10.18±0.85	9.3	28	21.67±4.03	16
Hemichromis bimaculatus	13	13.5	8.48±2.15	6	11.5	7.15±1.75	5.3	38	9.54±1.14	2
Heterobranchus bidorsalis	37	54	26.36±9.30	15	48	23.14±8.04	13.7	1196	170.78±6.57	18
Hyperopisus bebe occidentalis	75	51.5	24.68±8.67	7	47	22.70±7.96	6	973	132.13±7.10	3
Lates niloticus	46	60.6	24.13±12.73	7.5	51	21.25±5.52	6.3	2600	323.24±7.06	5
Oreochromis niloticus	250	46	16.93±0.06	6.2	39	14.03±5.25	5.3	735	100.38±5.78	4
Petrocephalus bovei	39	12.2	10.82±1.25	7.2	11	9.33±1.14	6	19	11.72±3.85	3
Pollimyrus isidori	53	12.7	8.93±1.57	5.5	11.1	7.72±1.48	4.5	20	6.83±1.11	2
Polypterus senegalus	7	35	19.06±4.43	9.5	30.5	16.79±3.76	9	139	43.57±7.22	4
Protopterus annectens	9	46	34.72±8.23	20	42	30.59±8.09	19.3	428	197.33±5.31	57
Sarotherodon galilaeus	172	30.9	15.22±5.02	5.5	25.5	12.57±4.26	4.6	504	75.05±8.93	4
Schilbe intermedius	45	11.34	14.09±0.14	8.5	14.5	10.25±1.89	7.5	29	9.80±3.98	3
Schilbe mystus	52	19.2	13.71±3.04	8.5	16.8	12.08±2.68	6.3	51	18.42±4.19	4
synodontis courteti	12	15.6	11.48±2.17	8	12	9.42±1.61	6.5	26	16.58±6.64	7
Synodontis schall	2	21.5	18.45±4.31	15.4	16.3	14.15±3.04	12	96	59.00±4.33	22
Tilapia zillii	68	26.3	12.55±3.65	6.5	20	10.23±2.87	5.2	230	35.68±6.61	5

N= species number, Lt= total length, Ls= standard length, Pt= total weight, max= maximum, min = minimum

3.5. Weight-length relationship for dominant species and their condition factor

The analysis of the weight-length relationship of *Oreochromis niloticus, Sarotherodon galilaeus, Bagrus bajad,* and *Hyperopisus bebe occidentalis* which were dominant species in terms of numerical abundance during this study is shown in Table 7 and Figure 2. It appears from this analysis that the value of b is around 3 for *Sarotherodon galilaeus* showing an isometric growth (I, t-test, $P < 0.05$) which is statistically significant, $b > 3$ for *Bagrus bajad* which indicating a positive allometry (A+, t-test, $P > 0.05$) and a negative allometry (A-, t-test, $P > 0.05$) with $b < 3$ for *Oreochromis niloticus* and *Hyperopisus bebe occidentalis* indicating an insignificant variation. Also, there was a variation in the K factor values from one species to another with higher values for *Oreochromis niloticus* and lower for *Hyperopisus bebe occidentalis*. The high regression coefficients (R^2) obtained indicated that for all the species, the weight of the fish was highly correlated with the total length.

Table 7. Result of the morphometric variables analysis. The values given are from the equation $Pt = aLt^b$ and t-tests.

Species	a	b	R^2	K	Growth Type	P
Oreochromis niloticus	0.0184	2.9174	0.9308	2.73±0.010	A-	0.306
Sarotherodon galilaeus	0.0133	3.0351	0.9394	1.89±0.011	I	0.002
Bagrus bajad	0.0043	3.1292	0.9613	0.38±0.004	A+	0.726
Hyperopisus bebe occidentalis	0.0062	2.973	0.9429	0.3±0.004	A-	0.590

a is intercept and b is slope value of regression ; R^2 is the regression coefficient; I, A- and A+ indicating isometric, negative and positive allometric growth type, respectively. P is the t-tests P-values.

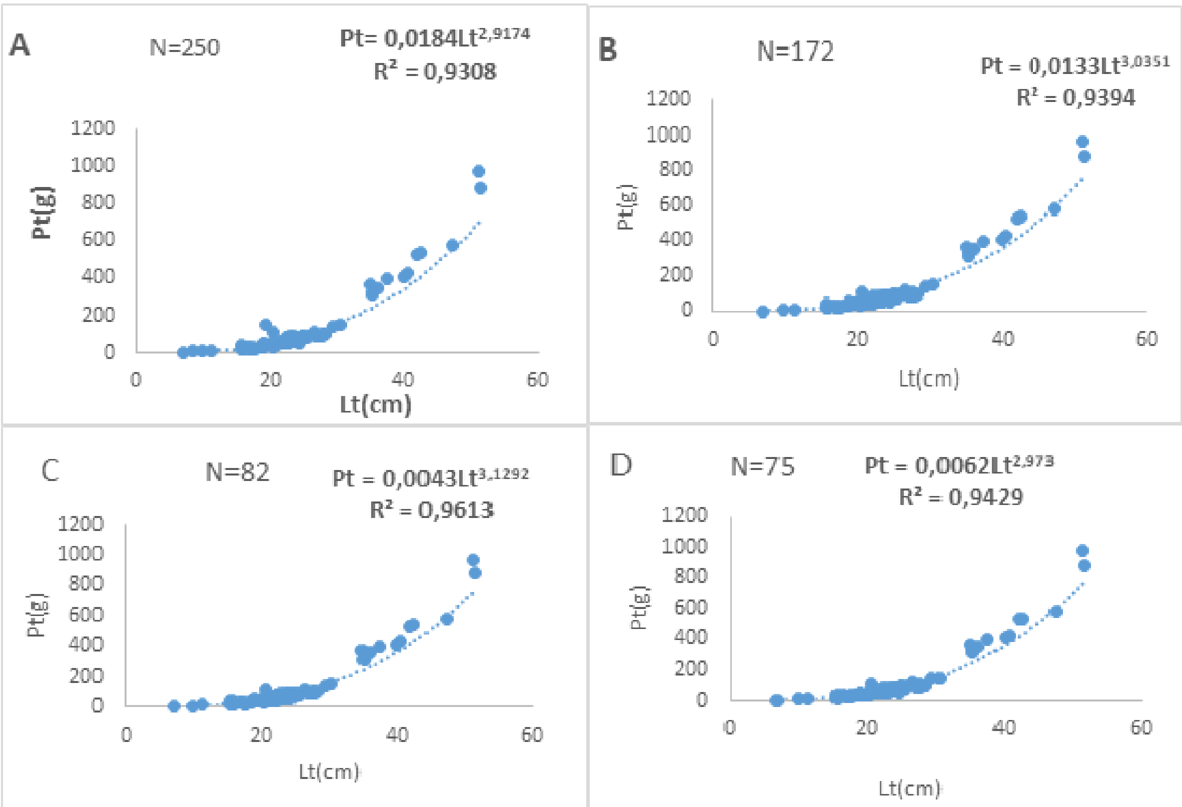

Figure 2. Weight-length relationship for dominant species : Lt= total length, Pt= total weight, A= *Oreochromis niloticus* ; B= *Sarotherodon galilaeus* ; C= *Bagrus bajad* ; D= *Hyperopisus bebe occidentalis*.

3.6. Typology of fishing gear and their selectivities

Madarounfa fishermen mainly used traditional equipment and most of the techniques used were widely used in artisanal fisheries in West Africa (Figure 4). The most widely used gear was the gillnet, which is a long, rectangular, single-walled net anchored to the seabed. It catches fish when they come into contact with it. This was used by 30% of fishermen. Traps were also widely used. These are stationary structures of many shapes and sizes into which fish are guided or pushed by the current. They can also be drawn into the gear by bait or other attractants. Cast nets are constructed from a series of tailored netting sections joined together to produce a cone-shaped net with weights and a drawstring attached to the perimeter, and are cast by fishermen to catch fish. Set longlines are longline gears that are anchored or otherwise fixed to the seabed at either end of the mainline. Butterfly nets are not specified. These are butterfly-shaped gillnets. The net, stretched over its supports, is held by a fisherman who moves through the water. As a result of this movement, the fish become entangled in the net.

Figure 3. Used fishing gears : a) Traps, b) Cast net, c) set gillnet, d) set longline, e) butterfly net.

The analysis of numerical abundance by fishing gear showed that the set gillnet was the most selective gear (45.01%) followed by the traps (35.65%), the set longline (13.57%), the cast net (3.39%) and then the butterfly net (2.67%). On the other hand, the selectivity of the gear according to weight abundance showed that 42.83% of the biomass was recorded for set longline followed by the set gillnet (39.62%), the traps (15.84%), the cast net (1.01%) and then the butterfly net (0.70%). To understand the selectivity of fishing gears related to the specific diversity in the catches around Lake Madarounfa, a canonical correspondence analysis (CCA), a multivariate analysis was carried out. From this analysis, it appears that the first two axes (1 and 2) concentrated 98.41% of the information (Table 8). Thus, *Bagrus bajad*, *Clarias gariepinus*, *Lates niloticus*, *Hyperopisus bebe occidentalis*, *Heterobranchus bidorsalis* and *Chrysichthys auratus* were the most captured by longlines, while *Oreochromis niloticus*, *Sarotherodon galilaeus*, *Polypterus senegalus* and *Protopterus annectens* were best represented in the catches of butterfly net. The trap catches contained more individuals of *Pollimyrus isidori*, *Ctenopoma kingsleyae,* and *Tilapia zillii* while those of the cast net contained more representatives of *Synodontis schall* and *Petrocephalus bovei*. The gillnet captured more individuals of *Protopterus annectens*, *Schilbe mystus,* and *Alestes macrophthalmus* (Figure 5).

Table 8. Summary of canonical correspondence analysis (CCA) of fishing gears and species selectivity.

Axis	Eigenvalue	%
Axis 1	0.25551	58.42
Axis 2	0.17489	39.99
Axis 3	0.0065013	1.487
Axis 4	0.0043215	009882

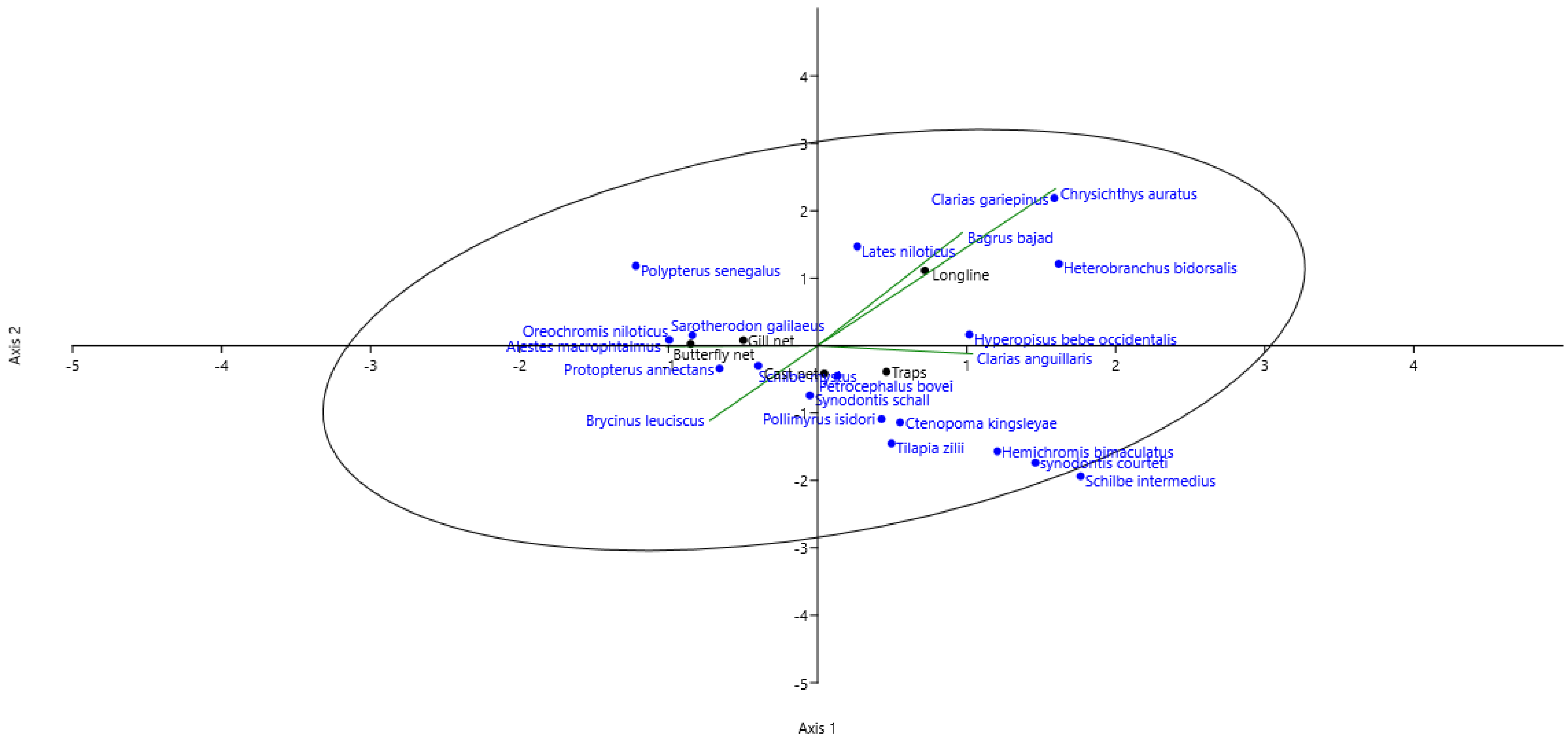

Figure. 4. Canonical correspondence analysis (CCA) plot of fishing gears and species selectivity.

3.7. Fish stock and catch per unit effort (CPUE)

The production of fresh fish recorded by the environmental services for the six months corresponding to the data collection period for this study was estimated at 35 tonnes. From this production, the catches per unit of effort (CPUE) by type of fishing gear were calculated in kilograms per hour (kg/h). Thus, the CPUE for gillnets, creels, longlines, butterfly nets, and cast nets were respectively 1.94 kg/h, 2.43 kg/h, 2.43 kg/h, 4.86 kg/h, and 9.72 kg/h. From this result, it appears that the greatest catch was made with the cast net (9.72 kg/h) while few fish were captured with gill net (1.94 kg/h) over the same fishing time interval.

3.8. Impacts of fishing on the lake

From the characterization of fishing activities around the lake, it appears that gillnet and creel were fishing gears that captured all size classes with a high proportion (>50%) of small individuals. Also, more than 73.97% of the catches had smaller lengths than the average size (18.11±9.25 cm). Moreover, high catch per unit of effort (CPUE) relative to the small size of the lake indicates pressure on fishery resources. This situation could lead to a reduction in abundance and a change in population dynamics.

Fishermen around Lake Madarounfa most often use unconventional methods and some have more than one fishing campaign per day. These practices are a threat to the lake ecosystem and could be a disturbance that could lead to the death of certain aquatic organisms, thus disrupting the natural balance of the environment. Indeed, it has been reported in the survey and observed in the field the destruction of spawning areas during the crossing of fishing boats and the trampling of fishermen.

4. DISCUSSION

The water temperatures measured during this study were different from those of the lake Marounfa reported by Ramsar (2021) and Ibrahim (2020), who reported a temperature variation between 29.6˚C and 30.3˚C. This could be due to the influence of the rain and cold seasons which coincided with our data collection period. The pH values obtained during this study were between 6,5 and 8,5 and differ slightly from those (5.5-7.4) reported by Ramsar (2021). The low conductivity could be due to low mineralization. The low transparency values observed during this study could be due to runoff which carries suspended matter and throws it into the lake. These high concentrations of suspended matter affect the transparency of water in the rainy season, which becomes low (Akpan, 2004).

The ichthyological fauna during the study was constituted of 22 species belonging to 21 genera and 12 families dominated by the Cichlidae. This result was different from that obtained by Assane and Issiaka (2021) who reported 40 species belonging to 30 genera and 14 families from 2013 to 2019 in the same lake. This difference could be explained by the duration of data collection and the disappearance of some species from the lake during the data collection period. The number of species identified is also lower than that (95 species) obtained by Yarombé et al. (2019) in Lake Séligué in Mali. This could probably be due to the small size of Lake Madarounfa comparatively to Lake Séligué, but also to the intensity of artisanal fishing activities all the year around Lake Madarounfa. Indeed, Montcho (2011) reported that increasing fishing efforts by multiplying the number of fishing campaigns in time and/or space increases the probability of catching more species.

The spatial and temporal distribution in terms of number and biomass showed a dominance of Oreochromis niloticus for 4 months. Indeed, this species is naturally distributed in several African watersheds such as the Nile and Congo basins, and several Ethiopian lakes. In West Africa, its natural distribution covers the Senegal, Gambia, Volta, Niger, and Chad basins (Assane & Issiaka, 2021). But its numerical and weight abundances changed according to months, habitats, and fishing techniques, Yacouba (2019).

Among the parameters used in fisheries biology, the study of weight-length relationships and the condition factor plays a very important role (Moutopoulos & Stergiou, 2002; Lederoun et al., 2016, 2022; Brahim et al., 2023). Weight-length relationships make it possible to determine the weight of fish by knowing their length, or vice versa, and to evaluate the overweight of fish to assess their growth, and the fishing pressure in the environment (Lalèyè, 2006; Lederoun et al., 2022; Brahim et al., 2023). The weight-length relationship of dominant species showed positive allometry for Sarotherodon galilaeus and Bagrus bajad indicating more individuals growing in weight than in length during this study. This is probably due to the high water period during which food is abundant for the fish and coincided with the reproduction period where the majority of mature females carry eggs increasing their weight to increase further while their growth in length becomes stable. According to Brahim et al. (2023), weight-length relationships can be used in fisheries management, to monitor the growth of organisms (overweight) and, consequently, to formulate recommendations for responsible exploitation of the stock. The condition factor (K) during the study for Oreochromus niloticus and Sarotherodon galilaeus showed that these species lived in better nutritional conditions. However, the K factor indicated an unfavorable ecological condition for Bagrus bajad and Hyperopisus bebe occidentalis which could be due to excessive use of some fishing gear and techniques which result in permanent stress for several species. According to Lévêque and Paugy (2006), the condition factor is an indicator of not only fish evolution state but also a better tool for comparing the overall physiological state of populations between basins presenting different ecological conditions. Moreover, it has been reported that the condition factor makes it possible to assess the health status or well-being of the fish (Froese, 2006, Lederoun et al., 2016), but also to evaluate the ecological status of the ecosystem in which the fish live (Anene, 2005; Lederoun et al., 2022).

Relatively to the size of the lake, fish production over the study period can be considered high. This situation resulted in high CPUEs indicating more pressure on fishery resources. However, according to Justin (2007), the CPUE is an excellent exploitation indicator whose value is inversely proportional to that of the fishing pressure.

It appears from this study that the gillnet and the creel were fishing gears that caught all size classes with a high proportion (>50%) of small individuals. This result is similar to the finding of Lévèque and Paugy (2006) who reported that among fixed gears, the most frequently used by scientists as well as by fishermen are gillnets because of their advantage of being easy to use. Fishing is one of the human activities that affects aquatic ecosystems through uncontrolled fishing efforts, and widespread use of non-regulatory fishing practices and gears (Adélie, 2018). There are several effects of fishing on ecosystems which range from direct effects, such as reduction in abundance and modification of size spectra, to indirect effects on trophic levels (Albaret & Laë 2003; Balirwa et al., 2003; Chapman et al., 2003; Laurans et al., 2004).

The analysis of the size classes around Lake Madarounfa showed a predominance of small individuals. This fishing pressure on juveniles could affect the normal recruitment of fish stock in the lake and lead to biodiversity erosion. Jeppe et al. (2017) reported that the pressure of overly selective fishing in certain arid areas of sub-Saharan Africa has reduced the stock of large fish species which have been replaced by small species.

Overexploitation can lead to biodiversity reduction, or in some cases, the extinction of species or groups of species. This situation occurs when the biological capacities of some species no longer allow them to cope with intense fishing pressure and ensure population renewal. In this case, only a small number of species manage to adapt to fishing pressure and end up dominating the population (Greenstreet et al., 1999). Also, the degradation level of the lake can increase due to the large number of boats, combined with the effect of trampling by fishermen which could lead to mortality and disturbance of fish life cycle.

Given the small size of Lake Madarounfa and the intensity of uncontrolled fishing all year round, has greatly disrupted the functioning of the ecosystem and threatens the sustainability of the ecosystemic services provided by the lake. This worrying situation, the consequences of which could be dramatic, should be analyzed to detect its impacts on the functioning of the lake ecosystem and on the dynamics of fish populations and species. This diagnosis is an essential requirement for the preservation and sustainable management of the lake. For sustainable exploitation of the lake fishery resources, respecting seasonal fishing closure periods is necessary as recommended by Ouattara et al. (2006). Indeed, fishing activities modify the substrate of exploited ecosystems and directly associated populations, in particular the benthos. The majority of mobile fishing gears scrapes the surface, or digs into the substrate of aquatic ecosystems could result in diversity reduction, especially in populations of fish that use these structures as habitat (Hall-Spencer & Moore, 2000; Piet et al., 2000; Kaiser et al., 2002; Justin, 2007). These fishing gears could also directly affect the physical properties of the substrate (Kaiser et al., 2002).

5. CONCLUSION

Lakes are wetlands that host significant biodiversity and are sources of numerous ecosystem services. These lake environments ensure food needs through the services provided and contribute to the development of local communities socio-economic activities. Lake Madarounfa is subject to several anthropogenic pressures including agricultural activities, fishing and domestic use. However, uncontrolled fishing activities constitute a threat to the sustainability of the ecosystem services provided by the lake. This worrying situation whose consequences could be dramatic, should be analyzed to detect its impacts on the functioning of the lake ecosystem and on the dynamic of fish populations and species. The main direct effect of fishing is the reduction in species abundance. It primarily affects large species which are becoming rare in fisherman catches and the functioning of the lake.

To ensure the sustainable management of the lake, continuous monitoring and the enforcement of ecosystem protection laws around the water body must be strengthened. The findings of this study showed that Lake Madarounfa is an excellent site for biodiversity conservation in general and fish resources in particular.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Fiction: AAT, IY; Literature: AAT; Methodology: AAT, IY; Data collection: HIM, AAT; Data analysis and manuscript writing: AAT, HIM; Supervision: IY.

ETHICAL STATEMENTS

Local Ethics Committee Approval was not obtained because experimental animals were not used in this study.

DATA AVAILABILITY STATEMENT

Data supporting the findings of the present study are available from the corresponding author upon reasonable request.

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Research Article **Araştırma Makalesi**

Capital-Labor-Output Nexus in Türkiye's Fisheries Sector: Panel ARDL Analysis

Türkiye Balıkçılık Sektöründe Sermaye-Emek-Üretim İlişkisi: Panel ARDL Analizi

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Abstract: This study analyzes the relationship between production, labor force and capital investments in the fisheries sector in the Marmara, Aegean, Mediterranean, Western Black Sea and Eastern Black Sea regions of Türkiye and examines their effects on sectoral growth and employment. In the study, total fish production, number of employees in the sector and capital investments (number of vessels) variables are used in the panel data analysis covering the period 2006-2023. According to the results of the analysis, the labor force has a positive and significant effect on production, but the effect of capital on production is negative. This shows that capital investments in the Turkish fisheries sector have not been able to provide the expected productivity growth. Moreover, capital investments are found to support employment by increasing labor demand. The long-run cointegration results reveal a strong equilibrium relationship between the variables. This study contributes to the existing research in the literature and provides strategic recommendations for the development of sustainable growth and productivity policies in Türkiye's fisheries sector. In particular, supporting aquaculture activities, modernizing capital investments and taking regional differences into account are critical for the long-term sustainability of the sector.

Keywords
- Fisheries sector
- Aquaculture
- Panel data
- Türkiye

Özet: Bu çalışma, Türkiye'nin Marmara, Ege, Akdeniz, Batı Karadeniz ve Doğu Karadeniz bölgelerinde balıkçılık sektöründe üretim, işgücü ve sermaye yatırımları arasındaki ilişkiyi analiz etmekte ve bunların sektörel büyüme ve istihdam üzerindeki etkilerini incelemektedir. Çalışmada 2006-2023 dönemini kapsayan panel veri analizinde toplam balık üretimi, sektörde çalışan sayısı ve sermaye yatırımları (tekne sayısı) değişkenleri kullanılmıştır. Analiz sonuçlarına göre, işgücünün üretim üzerinde pozitif ve anlamlı bir etkisi vardır, ancak sermayenin üretim üzerindeki etkisi negatiftir. Bu durum, Türk balıkçılık sektöründe sermaye yatırımlarının beklenen verimlilik artışını sağlayamadığını göstermektedir. Ayrıca, sermaye yatırımlarının işgücü talebini artırarak istihdamı desteklediği tespit edilmiştir. Uzun dönem eşbütünleşme sonuçları değişkenler arasında güçlü bir denge ilişkisi olduğunu ortaya koymaktadır. Bu çalışma, literatürdeki mevcut araştırmalara katkıda bulunmakta ve Türkiye'nin balıkçılık sektöründe sürdürülebilir büyüme ve verimlilik politikalarının geliştirilmesi için stratejik öneriler sunmaktadır. Özellikle su ürünleri yetiştiriciliği faaliyetlerinin desteklenmesi, sermaye yatırımlarının modernize edilmesi ve bölgesel farklılıkların dikkate alınması sektörün uzun vadeli sürdürülebilirliği için kritik önem taşımaktadır.

Anahtar kelimeler
- Balıkçılık sektörü
- Su ürünleri yetiştiriciliği
- Panel veri analizi
- Türkiye

1. INTRODUCTION

The fisheries sector plays a key role in ensuring food security and providing employment worldwide (FAO, 2020). However, in the context of Türkiye, the sector holds unique importance due to the country's rich marine resources and strategic geographical location. Surrounded by seas on three sides, Türkiye has access to diverse ecosystems including the Black Sea, the Aegean Sea, and the Mediterranean Sea.

These ecosystems support both national food supply and economic activity in coastal regions (TurkStat, 2024).

In Türkiye, the fisheries sector plays an important role in coastal economies by contributing to employment, regional development, and foreign trade. According to 2022 data, approximately 100 thousand people are directly employed in the fisheries sector, and related activities support broader economic growth (Ministry of Agriculture and Forestry, 2019). Türkiye produces various fish species for both domestic consumption and export markets, with trout and sea bass being particularly important for increasing international competitiveness (FAO, 2023).

Despite its potential, the sector faces significant structural and environmental challenges. Overfishing, marine pollution, climate change, and the decline of fish stocks threaten sustainability (Hekimoğlu and Altındeğer, 2012). These problems have made it clear that the limits of capture-based production have been reached, prompting a shift towards aquaculture as a more sustainable alternative (FAO, 2020). Aquaculture not only increases total production but also enhances employment opportunities in coastal areas.

Türkiye has made notable progress in aquaculture, particularly in the Aegean and Mediterranean regions, supported by government incentives and modern production technologies. The increasing share of aquaculture in total production reduces reliance on traditional fishing methods (TurkStat, 2024). This transformation is supported by technological investments aimed at boosting export capacity and international competitiveness. As a result, the fisheries sector remains central to Türkiye's efforts toward achieving sustainable economic and environmental development goals.

The aim of this study is to reveal the dynamics of sectoral growth and employment by analyzing the relationships between production, labor, and capital in the fisheries sector across the Marmara, Aegean, Mediterranean, Western Black Sea, and Eastern Black Sea regions. The analysis covers the 2006–2021 period and uses key variables such as fish production (catch and aquaculture), registered labor force, and capital investment (vessel count). Employing panel data methods, the study investigates both regional characteristics and national trends. Unlike most previous studies that focus on either production or capital, this paper offers a more comprehensive view by incorporating labor and its interaction with capital. The findings aim to guide sectoral policy formulation and support strategies for sustainable fisheries management.

In the literature, the fisheries sector is recognized for its multifaceted contributions to economic development, food security, and employment (FAO, 2020). Carlson et al. (2020) emphasized the role of capital investment and modern technology in enhancing production capacity. Similarly, Triezenberg et al. (2020) highlighted the productivity gains from adopting modern infrastructure. On the labor side, Teh and Sumaila (2011) explored how employment in the fisheries sector contributes to socio-economic sustainability. Garza-Gil (2017) examined how regional disparities influence employment, suggesting that infrastructure investments stimulate job creation.

Region-specific productivity differences are also widely acknowledged. Hekimoğlu and Altındeğer (2012) noted the relatively high productivity in the Black Sea Region but pointed to infrastructure shortcomings as a barrier to growth. In regions such as Marmara and the Aegean, tourism competes with fisheries, affecting sector performance (Samsun Directorate of Agriculture and Livestock, 2012).

Recent studies suggest that improving capital efficiency through innovative policies can positively affect both production and employment (Ainsworth et al., 2023). Liu et al. (2018) stressed the role of spatial management tools in balancing output and employment. Oyakhilomen and Zibah (2013), in their study on Nigeria, argued that inefficiencies and reliance on imports limited the sector's contribution to GDP — a challenge also seen in Türkiye, where fish consumption remains low and trade deficits persist (FAO, 2023).

Several Türkiye-specific studies have explored the links between infrastructure, energy costs, and regional production (Garza-Gil, 2017; Carlson et al., 2020). These findings underline the importance of region-sensitive and technology-driven investment strategies to improve sectoral performance. Arslan and Yıldız (2021) emphasized the sector's untapped potential due to low per capita consumption and insufficient infrastructure. Gün and Kızak (2019) supported this view with statistical evidence of declining capture fisheries and rapid growth in aquaculture. Sarıözkan (2016) found that despite this growth, the sector's share in GDP remains limited, calling for increased public support and effective marketing strategies. Similarly, Tolon (2019) provided a historical account of fisheries policy and its economic evolution, underscoring the role of strategic investment and sustainability planning.

Other scholars have examined financial, trade, and labor dimensions of the sector. Kekül (2024) used CBRT sectoral balance sheets in a panel data framework and concluded that financial leverage hampers profitability, whereas equity turnover enhances it. Ukav (2023) analyzed foreign trade data and found that aquaculture exports have quadrupled in the past decade, driven by rising demand from Europe. On the labor side, Öztürk and İbik (2023) identified mismanagement and declining profitability as major drivers behind the migration of Turkish fishermen to Mauritania. These studies provide critical insights into the sector's financial sustainability, export potential, and labor challenges, reinforcing the importance of region-specific strategies for long-term resilience and growth.

In summary, existing literature confirms the complex and regionally diverse interplay between production, capital, and employment in the fisheries sector. A detailed country-specific analysis of these dynamics is essential for effective policy design. This study contributes to the literature by jointly analyzing the impact of labor and capital on production, as well as how production and capital influence employment. By integrating a regional perspective focused on five key coastal regions of Türkiye, it addresses a significant gap in the empirical literature and offers valuable insights for both the academic community and policy-makers.

2. MATERIAL and METHODS

2.1. Fisheries sector in Türkiye

This study was conducted seasonally in 2016. Figure 1 provides a comparative annual comparison of the total catch and landings in the Marmara, Aegean, Mediterranean, Western Black Sea and Eastern Black Sea regions of Türkiye, as well as the total fish production in Türkiye as a whole. These are of great importance for understanding the structural and environmental changes in the fisheries sector over the years. Approximately 400,000 tons of fish caught in 2006 exceeded 500,000 tons in 2007 but showed a significant downward trend from 2008 onwards. This decline can be explained by factors such as overfishing, deterioration in marine ecosystems and depletion of fish stocks (Hekimoğlu and Altındeğer, 2012). This decline until 2014 shows that the sector faces serious structural problems in terms of sustainability. The period after 2014 reveals that despite short-term recoveries, the overall downward trend in the amount of fish caught has continued. This can be attributed to intense fishing pressure in the Black Sea and increasing pollution in the Marmara Sea (Samsun Directorate of Agriculture and Livestock, 2012).

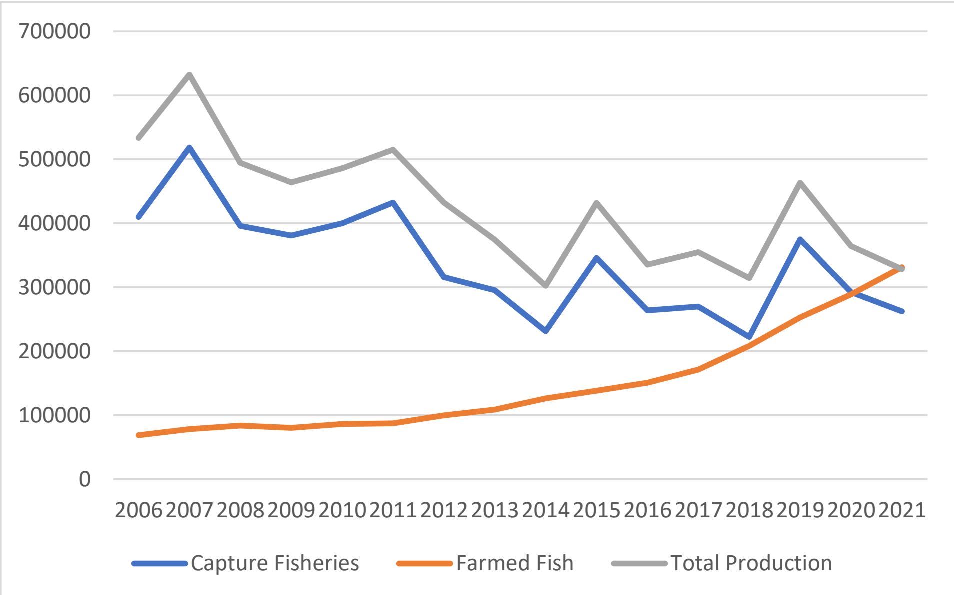

Figure 1. Capture, farmed and total fish production in Türkiye by years (2006-2021).

The increase in the amount of farmed fish has shown a remarkable trend. Approximately 70,000 tons of farmed fish production in 2006 exceeded 300,000 tons by 2021. This continuous increase is attributed to technological investments and government incentives in aquaculture (FAO, 2020). The spread of modern aquaculture facilities, especially in the Aegean and Mediterranean regions, has been one of the most important reasons for this increase (TEPGE, 2023). In addition, infrastructure improvements and modern production techniques supported by government policies have also accelerated the growth in the aquaculture sector.

The green line representing the total fish production in Türkiye followed a stable course between 2006 and 2010, and this balance was maintained thanks to the increase in the amount of farmed fish despite the decline in the amount of fish caught since 2011. However, in 2021, the sharp decline in the amount of fish caught led to a decline in total production. This suggests that the limits of capture-based production have been reached and aquaculture activities are becoming even more important for the sustainability of the sector. Liu et al. (2018) emphasized the contribution of aquaculture to economic and ecological sustainability and highlighted the benefits of investments in this area to regional economies.

This reveals that production dynamics in Türkiye's fisheries sector are shaped on two different bases: capture fisheries and aquaculture. While the decline in the amount of fish caught emphasizes the need for more effective policies to protect marine ecosystems, the growth in aquaculture offers great potential for the future development of the sector. FAO (2020) stated that aquaculture plays a critical role in meeting the growing demand for food worldwide, while Ainsworth et al. (2023) stated that this growth should be supported by capital efficiency and innovative policies. In this context, Türkiye needs to prioritize aquaculture investments to increase total fish production in a sustainable manner, while at the same time implementing effective management policies to protect marine resources.

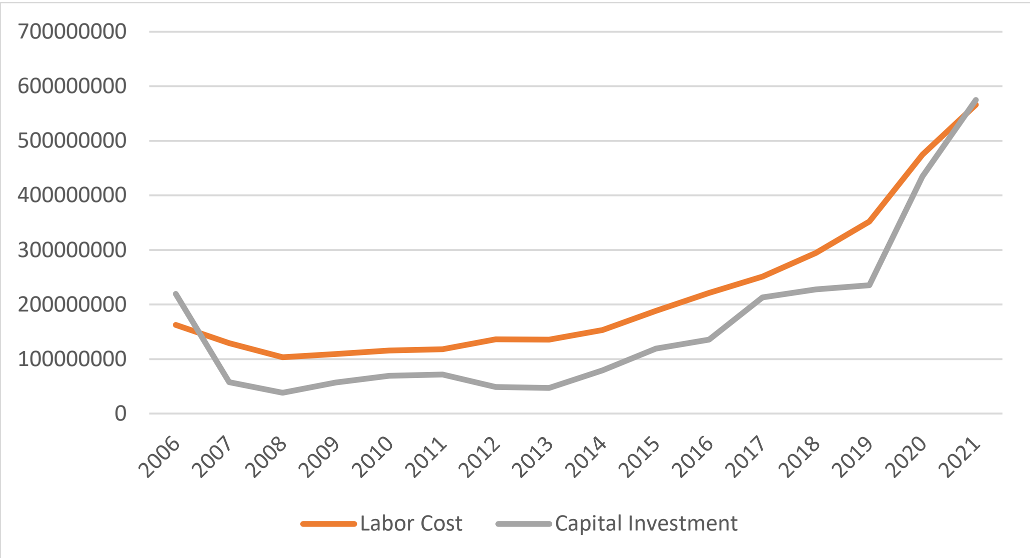

Figure 2. Labor cost and capital investment of the fisheries sector in Türkiye.

Figure 2 shows the annual changes in labor costs and capital investments in the Turkish fisheries sector between 2006 and 2021. The graph provides important information for understanding the growth dynamics of the sector and the evolution of the two key inputs over the years.

In 2006, capital investments started at a higher level than labor costs. However, in 2007, labor costs surpassed capital investments, and this difference became more pronounced in the following years. This reflects the labor-intensive production structure in the fisheries sector and the impact of the increase in labor costs on the sector, especially after 2010. In particular, as stated in the Samsun Directorate of Agriculture and Livestock (2012) report, high labor costs in fishing activities in regions such as the Black Sea and Marmara have increased pressures on sectoral productivity.

While labor costs remained flatter between 2010 and 2013, capital investments decreased during the same period. This reflects a period of decline in new vessel purchases and modernization investments in the fishing sector. This decline can be attributed to capital constraints following the global economic crisis (Garza-Gil, 2017). At the same time, the recession and decline in production in the sector during this period reduced the rate of return on capital investments, making it difficult to encourage new investments.

Since 2014, a significant increase in capital investments has been observed. A rapid increase is especially noticeable in 2018 and beyond. This increase can be explained by the adoption of modern fishing technologies and government incentive policies for the aquaculture sector (Triezenberg et al., 2020). This increase in capital investments indicates a growth trend in Türkiye's fisheries sector that is in line with investments in aquaculture.

Labor costs, on the other hand, have increased steadily in the post-2014 period, with a particularly sharp rise in 2020. This can be attributed to both inflationary pressures and increased labor demand in the sector. Moreover, this increase in labor costs was also affected by labor market regulations and wage increase policies (Teh and Sumaila, 2011).

Overall, the chart shows how the dynamics between capital investments and labor costs in the fisheries sector have changed over time. In 2020 and 2021, capital investments and labor costs approach the same level, indicating that a capital-intensive structure is developing in the sector. FAO (2020) emphasizes that capital-intensive production models provide higher productivity in the long run and contribute to a more sustainable structure, especially in aquaculture activities.

In conclusion, the graph clearly shows the increasing importance of labor costs in the Turkish fisheries sector and the impact of the growth in capital investments on production capacity in the sector. These trends call for a balanced focus of sectoral policies on both labor and capital investments. This presents important opportunities to optimize resource utilization at the regional and national levels.

The dynamics presented in figures 1 and 2 clearly demonstrate the accelerating shift from capture-based production to aquaculture in Türkiye's fisheries sector and the impact of labor and capital investments on the sustainability of the sector. While Figure 1 highlights the increasing role of aquaculture in total fish production, Figure 2 reflects the changing balance between capital investments and labor costs. The decline in landings and the growth of aquaculture indicate which components need to be focused on more for the sector's future growth and sustainability goals. The importance of capital-intensive activities in terms of long-term sustainability and productivity is a finding frequently emphasized in the literature (FAO, 2020; Ainsworth et al., 2023).

In this context, the importance of our study comes forward once again. In addition to analyzing the impact of the amount of fish caught and farmed in the Marmara, Aegean, Mediterranean, Western Black Sea and Eastern Black Sea regions of Türkiye on production, our analysis of the role of labor and capital on sectoral growth provides a strategic guide for sectoral policies. Considering the data in the graphs, our study will contribute not only to academic knowledge but also to the development of sustainable growth and productivity policies in Türkiye's fisheries sector. These findings provide a critical foundation for understanding regional dynamics and designing more effective policies on the national scale.

2.2. Data

The dataset used in this study is based on annual data on the fisheries sector covering the Marmara, Aegean, Mediterranean, Western Black Sea and Eastern Black Sea regions of Türkiye. These data, collected between 2006 and 2023, aim to examine fishing activities in each region in detail. The data set includes variables such as the total amount of saltwater fish produced (sum of the amount of fish caught (tons) and the amount of fish farmed (tons)), the number of vessels used in the fishing sector and the number of people working in the sector. This comprehensive dataset allows for the analysis of both the production and employment dimensions of the fisheries sector. It also allows for a detailed examination of the differences between regions. The dataset provides a solid basis for analyzing sectoral growth, productivity and sustainability by reflecting temporal and regional changes in production activities based on both traditional fishing methods and aquaculture. The wide time span and regional disaggregation make the dataset highly valuable for examining long-term trends and regional comparisons in the fisheries sector. The present study used this comprehensive dataset to conduct quantitative analyses on the production and employment dimensions of the sector.

The variables used in this study represent production and production inputs in the Turkish fisheries sector:
- lnQ is total production (in tons),
- lnL is the total number of employees employed in the sector, and
- lnK is capital investments (number of vessels).
In order to analyze the relationship between the variables and to obtain a more appropriate scale, the natural logarithms of all variables are taken. In this way, the wide range of values of the variables is homogenized and better represents a linear relationship in the analysis. The data were compiled from official statistics provided by the Turkish Statistical Institute (TurkStat) and harmonized with the dataset covering 2006-2023 used in the study.

Table 1. Descriptive statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max
lnQ	90	11.110	0.9547	9.1942	12.749
lnL	90	8.8594	0.3316	8.0536	9.4003
lnK	90	7.9509	0.3449	7.3746	8.6898

When the descriptive statistics are analyzed, it is seen that the average value of the lnQ variable (production) is 11.11. This value indicates that the average production in the Turkish fisheries sector is quite high. However, with a standard deviation value of 0.9547, it is understood that production values vary significantly across time and regions. lnL has a lower standard deviation (0.3316) compared to the production value with a mean of 8.8594. lnC has a mean of 7.9509 and a standard deviation of 0.3449, indicating that capital investments have a similar distribution to labor. The minimum and maximum values emphasize that there are significant differences in terms of production, labor force and capital in the analyzed period and regions. Overall, the descriptive statistics reflect the regional and temporal diversity of the Turkish fisheries sector in terms of production and inputs. This diversity provides an important basis for the study to provide a deeper understanding of sectoral dynamics.

Figure A1 shows in detail the yearly variation in the catch and landings in the Marmara, Aegean, Mediterranean, Western Black Sea and Eastern Black Sea regions of Türkiye. In general, the Aegean and Mediterranean regions present a picture where aquaculture activities are growing rapidly, while the Marmara and Black Sea regions are more dominated by capture-based production. The Aegean Region is noteworthy for its rapid increase in aquaculture activities, especially since 2010. This growth can be explained by the geographical advantages of the region and the spread of modern aquaculture facilities. While a similar increase is observed in the Mediterranean Region, it is observed that production based on fishing is relatively limited. This can be attributed to the limited fishing potential in the region and the growth of aquaculture to fill this gap.

The amount of fish caught in the Marmara and Western Black Sea regions follows a relatively fluctuating course, and it is observed that aquaculture is quite limited in these regions. While fishing activities in Marmara had stronger potential in the past, they have shown a slightly decreasing trend in recent years. The Western Black Sea presents a stable outlook in terms of catches despite periodic fluctuations. The Eastern Black Sea Region stands out with high levels of fish catches. However, it is noteworthy that aquaculture activities are also limited here. Increasing aquaculture capacity in these regions offers an important opportunity to ensure sustainable growth in the sector. Regional differences highlight the need to diversify Türkiye's fisheries policies and develop strategies tailored to the potential of each region.

2.3. Methodology

In this study, the panel ARDL (Autoregressive Distributed Lag) model was employed to analyze the long-run and short-run relationships between production, labor, and capital across different regions of Türkiye’s fisheries sector. This model is particularly suitable for datasets with a relatively small time dimension and larger cross-sections, which aligns with the structure of this study (2006–2021 across five regions). One of the main advantages of the panel ARDL approach is its flexibility in handling variables with mixed levels of integration (i.e., I(0) and I(1)), unlike traditional cointegration methods that require all variables to be integrated in the same order. Additionally, the model captures heterogeneous dynamics across cross-sectional units, allowing for region-specific short-run variations while imposing a common long-run structure. Compared to fixed or random effects models, panel ARDL provides a more robust framework for studying dynamic interactions and adjustment processes, making it ideal for sectoral analyses with regional focus. Furthermore, the inclusion of lags in both dependent and independent variables helps account for delayed effects, which are common in sectors such as fisheries where policy or investment changes influence outcomes over time.

2.3.1 Panel Unit Root Tests

In panel data analysis, testing whether the variables are stationary is critical for the accuracy of the methods to be applied. In this study, IPS (Im, Pesaran and Shin, 2003) and Breitung (2000) tests are used as panel unit root tests. While the IPS test assumes different autoregressive structures for each unit in heterogeneous panel data, it tests the first difference stationarity assumption. The flexibility provided by this test is important since Türkiye exhibits different economic and environmental structures in five different regions. The test statistic is expressed as follows:

$$t_{IPS} = \frac{1}{N}\sum_{i=1}^{N} t_i \quad (1)$$

Where t_i is the test statistic for the null hypothesis of stationarity of the autoregressive parameters for each cross-section. The Breitung test assumes that the series in the panel have a common autoregressive parameter, which leads to more robust results, especially in small samples. Moreover, it can more accurately detect the stationarity of the series under the assumption of a common autoregressive parameter. It is determined that the variables in our panel data set do not contain unit roots and should be stationary.

2.3.2. Panel Cointegration Tests

Panel cointegration tests were applied to examine the long-run relationships between the variables. Pedroni (1999) and Kao (1999) cointegration tests are used in this study. The Pedroni cointegration test is an approach that allows for heterogeneity across cross-sectional units and is based on multiple regression equations. The test was conducted within the framework of the following model:

$$y_{it} = \alpha_i + \delta_i t + \beta x_{it} + \epsilon_{it} \quad (2)$$

where y_{it} represents the dependent variable and x_{it} represents the independent variables. The Pedroni test tests for cointegration by checking whether the error term is stationary. According to the results of this test, which are analyzed with various statistics, it is determined that there is a long-run relationship between the variables (Pedroni, 1999).

The Kao test is applied under the assumption of homogeneous cross-section to verify whether there is cointegration between the series. The test is based on the stationarity analysis of the following error terms:

$$\epsilon_{it} = \rho\epsilon_{it-1} + u_{it} \quad (3)$$

A coefficient ρ less than one indicates the presence of cointegration. The Kao test assumes that all units in the panel have common autoregressive parameters. This test offers a simpler structure compared to the Pedroni method and is used as a supportive tool for cointegration results. The test results confirmed a strong cointegration relationship between the variables (Kao, 1999).

2.3.3. Panel ARDL Model

The econometric model constructed using the variables defined earlier is as follows:

$$lnQ_{it} = \beta_0 + \beta_1 lnL_{it} + \beta_2 lnK_{it} + u_{it} \quad (4a)$$

$$lnL_{it} = \beta_3 + \beta_4 lnQ_{it} + \beta_5 lnK_{it} + e_{it} \quad (4b)$$

The Pooled Mean Group (PMG) estimator developed by Pesaran et al. (1999) is used to estimate long-run and short-run coefficients. The panel autoregressive distributed lag (panel ARDL) model restricts the long-run coefficients to be the same but allows the short-run coefficients and error variances to differ across groups (Pesaran et al., 1999). In addition to dynamic identification, the ARDL approach also allows for testing cointegration. The cointegrated time series system can be estimated as an ARDL model with the advantage of being I(0) or I(1) without the need to specify which of the variables in the cointegration relationship are I(0) at level or I(1) at first difference. However, the variables should not be I(2) stationary in the second difference. At the same time, the ADRL model allows the estimation of both short-term and long-term relationships between the dependent and independent variables. Since the ARDL technique works well with small samples, it is highly recommended to use it with a small data sample. The specification form of the ARDL (p, q) approach with lag p for the dependent variable and lag q for the independent variables is as follows:

$$Y_t = \delta + \sum_{k=1}^{p} \theta Y_{t-k} + \sum_{j=1}^{q} \gamma W_{t-j} + e_t \quad (5)$$

In this equation, Y is the dependent variable, W is the explanatory variables, δ, θ and γ are the estimated coefficients of the model and e_t is the error term.

When equation (4a) is adapted to the ARDL model, it can be written as follows (Equation 6):

$$\Delta lnQ_{it} = a_0 + \emptyset_i \sum_{j=1}^{p} \Delta lnQ_{i,t-j} + \theta_i \sum_{j=1}^{q} \Delta lnL_{i,t-j} + \beta_i \sum_{j=1}^{q} \Delta lnL_{i,t-j} + \pi ECT_{t-1} + \varphi_1 lnQ_{i,t-1} + \varphi_2 lnL_{i,t-1} + \varphi_3 lnK_{i,t-1} + u_{it} \quad (6)$$

In this equation, Δ is the difference operator, $\emptyset_i$, θ_i and $\beta_i$are the short-run coefficients, ECT is the error correction term explained from the long-run equilibrium relationship, φ_i is the long-run coefficients and u_{it} is the error term.

3. RESULTS

Before applying the ARDL method, the variables should be tested for unit root tests. Table 2 analyzes the stationarity of the variables used in the study with IPS and Breitung unit root tests. These tests are an important method to determine whether the variables used in panel data analysis have a constant mean and variance over time (Baltagi, 2008). The results of whether the variables are stationary at I(0) and at first difference I(1) are reflected in the table. The IPS and Breitung panel unit root test results have been summarized. Although the level values of the series contain unit roots, they are stationary at a 1% significance level when the first differences are taken.

Table 2: Unit root tests.

Variables	IPS		Breitung	
	I(0)	I(1)	I(0)	I(1)
lnQ	-0.862 (0.194)	-4.086 (0.000)	-2.051 (0.020)	-2.898 (0.002)
lnL	0.179 (0.571)	-6.579 (0.000)	-0.582 (0.281)	-5.168 (0.000)
lnK	-0.475 (0.318)	-5.578 (0.000)	-1.557 (0.059)	-7.291 (0.000)

Note: The values in parentheses are probability values.

Table 3 presents the results of Pedroni and Kao cointegration tests. Pedroni and Kao tests are common methods used in panel data analysis to assess whether there is a long-run relationship between variables. In this context, the test results are critical to understand whether the hypotheses of the study are supported or not.

According to the Pedroni test results, the p-values for Panel PP, Panel ADF, Group PP and Group ADF statistics are less than 0.01. This indicates the existence of a long-run cointegration relationship between the variables. The consistent significance of both panel and group statistics of the Pedroni test strongly supports the existence of a long-run equilibrium relationship between the variables used. The results of the Pedroni test provide a reliable framework for assessing cointegration relationships, especially in heterogeneous panels.

The results of the Kao test indicate that the ADF statistic is -2.798 and the corresponding p-value is 0.0026. This result again supports the cointegration hypothesis at the 0.01 significance level. The Kao test is used for cointegration analysis, especially in less complex panels, as it offers a simpler structure. These results support the findings from the Pedroni test.

Table 3. Panel Cointegration Test.

Pedroni Test		
	Statistic	**Prob.**
Panel PP	-4.685	0.0000
Panel ADF	-5.211	0.0000
Group PP	-3.455	0.0003
Group ADF	-4.196	0.0000
Kao Test		
	t-stat	**Prob.**
ADF	-2.798	0.0026

In general, the results of both Pedroni and Kao tests reveal the existence of a long-run relationship between the analyzed variables. This finding suggests that the model provides a solid basis for making forecasts and developing policy recommendations based on long-run relationships. As noted in the literature (Pedroni, 1999; Kao, 1999), such cointegration tests are critical for understanding long-run dynamics in panel data models.

Table 4 presents the results of the panel ARDL model estimated separately for two dependent variables: lnQ (output) and lnL (labor). The analysis distinguishes between long-run equilibrium relationships and short-run dynamic adjustments. In the first model, where lnQ is the dependent variable, the ARDL (3,2,2) specification reveals that labor has a statistically significant and positive impact on output at the 1% level. Specifically, a 1% increase in the labor force leads to an approximate 1.8% increase in output, highlighting the labor-intensive nature of the fisheries sector in Türkiye. Conversely, capital investment exerts a negative long-run effect on output, also significant at the 1% level. This result suggests that capital accumulation, in its current form, may not be aligned with productivity-enhancing outcomes.

The negative impact of capital in both the short and long run can be attributed to several sector-specific inefficiencies. In Türkiye, capital investments in fisheries are often channeled into outdated or inefficient assets, such as aging vessels and insufficiently modernized infrastructure. These may fail to enhance production capacity and, in some cases, even generate cost burdens. Furthermore, regional mismatches in capital allocation, combined with weak strategic planning and limited technological integration, reduce the productivity of capital. The dominance of small-scale enterprises, coupled with restricted access to finance and expertise, may also hinder the transformation of capital into effective output. Environmental constraints—such as overfishing, marine pollution, and diminishing fish stocks—further suppress the marginal return on capital investments. Collectively, these factors underscore the need for coordinated, region-specific investment strategies to ensure capital contributes positively to production growth.

In the second model, where lnL is the dependent variable and the ARDL (1,2,2) specification is used, both output and capital are found to have positive and statistically significant effects on employment in the long run. This finding indicates that production growth fosters labor demand, while capital investments play a supportive role in job creation within the sector. Notably, the error correction term is negative and highly significant (-0.7885), indicating a strong and rapid adjustment toward long-run equilibrium following short-run deviations. While some short-run coefficients are not statistically significant in either model, the presence of a significant error correction mechanism suggests that sectoral imbalances are eventually corrected over time.

In summary, the ARDL analysis offers valuable insights into the dual dynamics of labor and capital in Türkiye’s fisheries sector. Labor emerges as a consistently productive input in terms of enhancing output, while capital contributes meaningfully to employment but not directly to production. These asymmetric impacts highlight the importance of restructuring capital investments and fostering labor efficiency as complementary strategies for sustainable sectoral development.

Table 4. Panel ARDL Results.

lnQ dependent – ARDL (3,2,2)		**lnL dependent – ARDL (1,2,2)**	
Variables	**Coefficient**	**Variables**	**Coefficient**
Long Run Equation		**Long Run Equation**	
lnL	1.7989***	lnQ	0.2224***
lnK	-1.1838***	lnK	1.8125***
Short Run Equation		**Short Run Equation**	
COINTEQ01	-1.1902	COINTEQ01	-0.7885***
D(LNQ(-1))	0.6059	D(LNQ)	-0.2511*
D(LNQ(-2))	0.4986*	D(LNQ(-1))	-0.0993*
D(LNL)	-0.8549	D(LNK)	0.0962
D(LNL(-1))	-2.1406**	D(LNK(-1))	-0.0428
D(LNK)	2.0339	C	-6.2826***
D(LNK(-1))	2.3728*		
C	6.0587		

4. DISCUSSION

This study investigates the dynamic interactions between production, labor, and capital in Türkiye's fisheries sector, with a particular focus on their effects on output and employment. The results reveal both parallels and divergences from the international literature and highlight country-specific dynamics that warrant closer policy attention. Notably, the first model indicates a negative and statistically significant relationship between capital and output. While prior studies generally report a positive association between capital investments and production efficiency (Carlson et al., 2020; Triezenberg et al., 2020), the findings of this study align more closely with the Türkiye-specific challenges emphasized by Kekül (2024) and Gün and Kızak (2019). These challenges include inefficient capital allocation, the use of outdated technologies, and ecological degradation, all of which collectively reduce the productivity of capital.

One of the critical structural explanations for this outcome is the imbalance in capital distribution across regions. Particularly in the Marmara and Western Black Sea regions, declining fish stocks and industrial pollution have undermined the effectiveness of vessel-based investments. Instead of improving infrastructure or investing in sustainable production systems, capital expenditures in these areas have disproportionately targeted vessel numbers, which do not necessarily enhance output. While Ainsworth et al. (2023) emphasize that capital effectiveness depends on technological modernization and spatial planning, this study shows that such strategic planning remains limited in Türkiye's fisheries sector.

In contrast, the second model demonstrates that capital positively affects employment, indicating that investments—albeit structurally limited—still generate labor demand. This finding is consistent with studies that highlight the labor-intensive nature of modernized equipment used in fisheries (Teh & Sumaila, 2011; Öztürk & İbik, 2023). Moreover, the positive and significant impact of labor on output reinforces the observation that Türkiye's fisheries sector continues to rely on labor-driven production dynamics. These outcomes suggest that the transition to a capital-intensive model has not yet materialized, and that growth continues to be supported primarily by human capital.

From a policy perspective, these findings underline the importance of region-specific and functional capital planning. Policymakers should prioritize investments in sustainable infrastructure, such as cold chain systems, harbor modernization, eco-friendly aquaculture facilities, and fish processing centers. In underperforming regions, public funding should be directed toward upgrading logistics, energy efficiency, and ecosystem restoration, particularly where overfishing and pollution have reduced natural resource availability.

To implement regional incentive policies more effectively, differentiated support mechanisms should be developed based on local needs and resource capacities. For instance, in the Marmara region, where environmental degradation limits productivity, incentives should focus on pollution control infrastructure and transitioning to aquaculture. In contrast, in the Eastern Black Sea region, where labor remains highly productive, support should target training programs, cooperative formation, and improved vessel maintenance. National fisheries policy should be restructured to include a regional performance-based investment framework, where subsidies and credits are allocated in line with ecological carrying capacity, labor absorption potential, and technological innovation.

Moreover, policy design should involve multi-stakeholder platforms that include fishers' cooperatives, local authorities, universities, and NGOs to ensure that investment decisions reflect on-the-ground realities. Performance monitoring systems should be integrated into these programs to evaluate the long-term impact of public support on productivity, sustainability, and employment. The success of such policies will depend on administrative coordination, targeted financing, and clear long-term strategies that link sectoral investment to national development goals.

In summary, this study contributes to the literature by offering an empirical explanation for why capital investments in Türkiye's fisheries sector have failed to yield the expected production gains. It also confirms the continued relevance of labor as a growth driver and offers concrete, context-specific policy recommendations. These include restructuring capital allocation strategies, designing regionally differentiated incentives, and enhancing human capital development—all of which are crucial for achieving long-term sustainability and competitiveness in the sector.

5. CONCLUSION

In light of the findings of the study, a number of policy recommendations can be offered to support sustainable growth and increase the efficiency of capital investments in Türkiye's fisheries sector. First, capital investments should be directed towards more efficient and modernized equipment. Replacing outdated technologies with modern fishing equipment can both increase production capacity and reduce costs. Secondly, it is important to implement region-based incentive policies to address the imbalances in capital allocation across regions. Increasing infrastructure investments, especially in regions with low production capacity such as Marmara and the Western Black Sea, can increase productivity in the sector.

Thirdly, increasing incentives for aquaculture can offset the sustainability problems experienced in fisheries-based production. It is stated in the literature that aquaculture activities offer significant opportunities in terms of both production and employment in the fisheries sector (FAO, 2020). In this context, technology and infrastructure investments should be prioritized, especially in regions with high aquaculture potential such as the Aegean and Mediterranean. In addition, the implementation of sector-specific training and certification programs to increase the quality of the workforce can contribute to sustainable growth in production and employment. However, the feasibility of these policies is directly related to the effective use of financial resources and the development of solutions that are in line with local dynamics. It is critical that policymakers develop strategies that are sensitive to local needs, considering regional differences.

This study has several important limitations. First, the dataset used focuses only on Türkiye's fisheries sector and does not include international comparisons. This may limit the general validity of the results. Second, the variables used in the analysis focus only on the capital and labor dimensions of the effects on sectoral growth and employment. However, other important variables such as energy costs, environmental factors and government policies are not considered in this study. Future studies can provide a more comprehensive analysis by including these variables.

In addition, although regional disparities were analyzed in the study, the causes of these disparities were not examined in detail. By examining the causes of interregional disparities in more depth, future research can reveal how sectoral policies can be more effective at the regional level. Moreover, the use of different methods (e.g. structural equation models or spatial econometric analyses) may be useful to assess the relationships between variables in a broader framework. Further studies in line with these recommendations will provide a stronger and more comprehensive knowledge base for the sustainable growth of the fisheries sector.

CONFLICTS OF INTEREST

The authors affirm that there are no identifiable financial or personal conflicts that could impact the research.

ETHICS APPROVAL

The study did not require any specific ethical

approval.

DATA AVAILABILITY

For inquiries for datasets, please contact the corresponding author.

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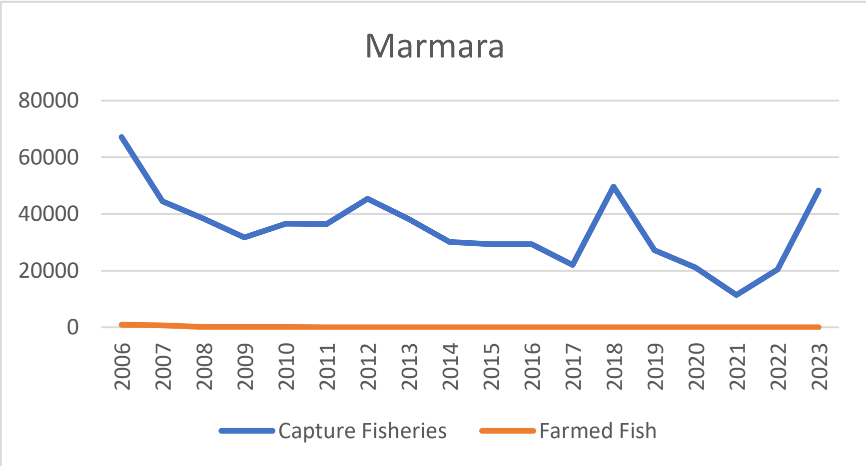
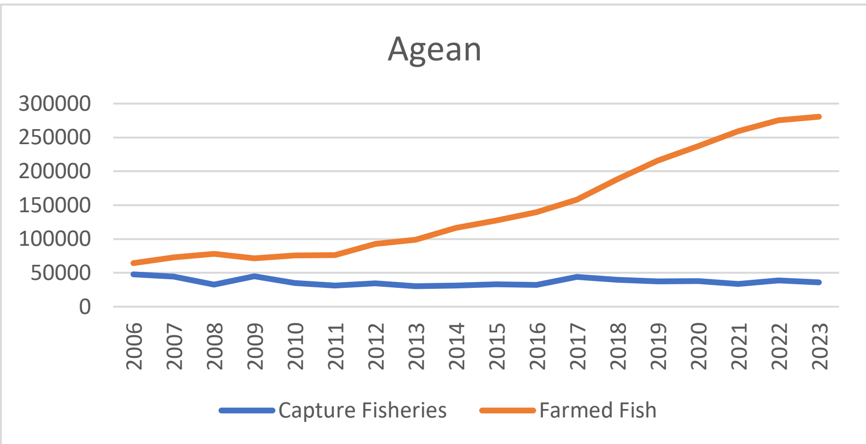
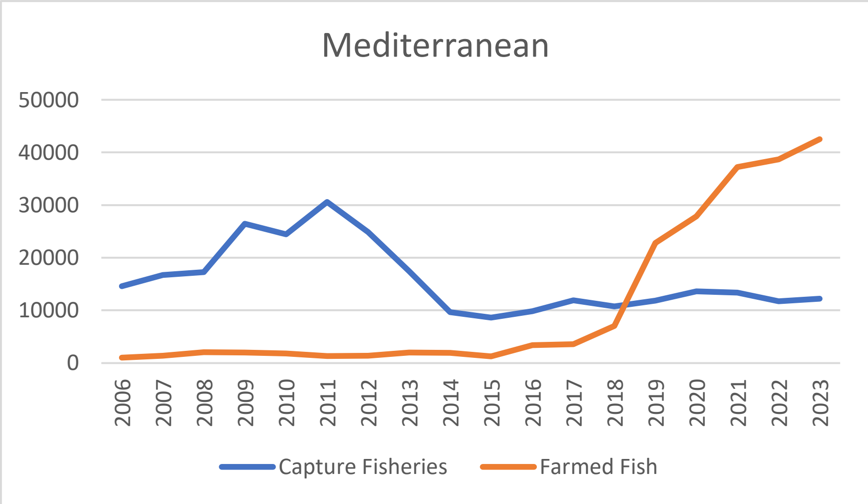
APPENDIX

Figure A1.



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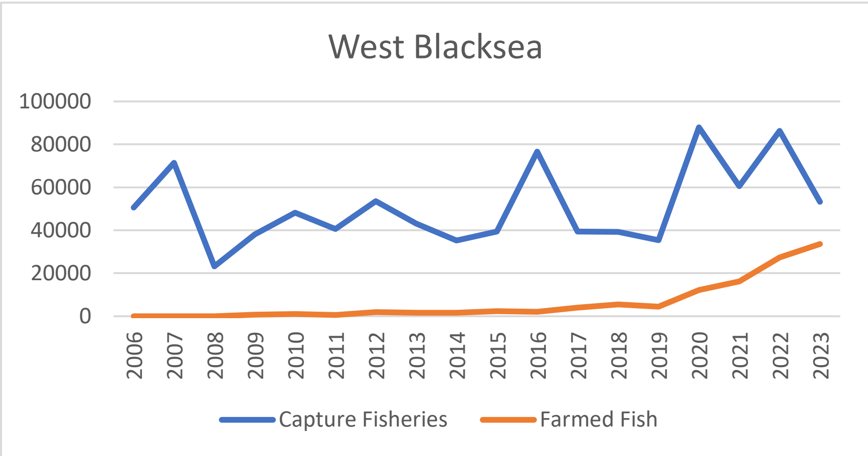
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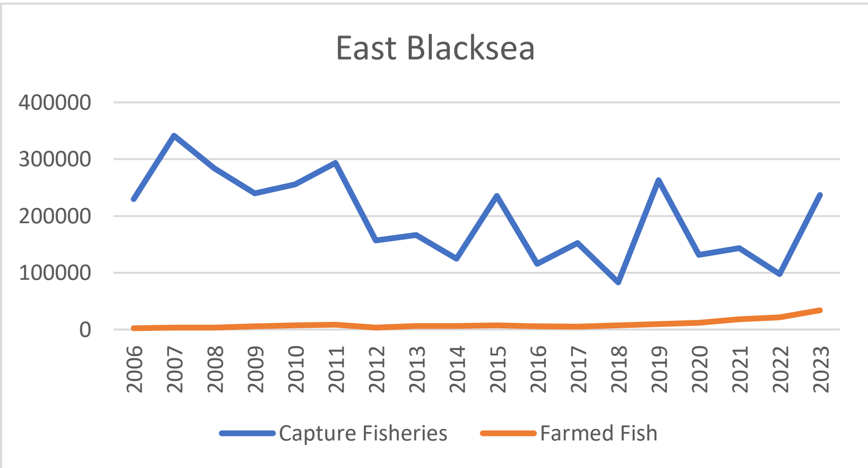
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Capture Fisheries
Farmed Fish

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Aquaculture in Africa: Challenges and Future Prospects

Afrika'da Su Ürünleri Yetiştiriciliği: Zorluklar ve Gelecek Perspektifleri

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Abstract: Aquaculture in Africa has shown gradual growth, though progress remains slow due to differences in water availability, economic conditions, and access to fisheries across countries. Therefore, this study examines the challenges and prospects of the fish farming sector in Africa. Evaluating aquaculture performance should consider factors beyond production levels or GDP contribution, such as its role in food supply, population size, and natural resource availability. Egypt leads in aquaculture contribution to national fish supply, followed by Lesotho, which focuses on exports. Ethiopia, Guinea-Bissau, and Sudan have significant per capita fish supply gaps. Egypt also dominates in total production, with 2018 output surpassing all other African countries combined. Countries like Rwanda, Burundi, Lesotho, and Benin have shown strong production growth over the past decade, while Lesotho, South Africa, and Mauritius excel in high-value aquaculture production. The combination of reaching maximum yields in marine and inland fisheries, expanding markets, urbanization, and opportunities for private-sector growth presents immense potential for aquaculture development in Africa.

Keywords
- Africa
- Aquaculture
- Challenges
- Future Prospects

Özet: Afrika'da su ürünleri yetiştiriciliği kademeli bir büyüme göstermiştir, ancak ülkeler arasında su bulunabilirliği, ekonomik koşullar ve balıkçılığa erişimdeki farklılıklar nedeniyle ilerleme yavaş kalmaktadır. Bu nedenle, bu çalışma Afrika'daki balık çiftçiliği sektörünün zorluklarını ve beklentilerini incelemektedir. Su ürünleri yetiştiriciliği performansını değerlendirirken, gıda tedariğindeki rolü, nüfus büyüklüğü ve doğal kaynak bulunabilirliği gibi üretim seviyeleri veya GSYİH katkısının ötesindeki faktörler dikkate alınmalıdır. Mısır, ulusal balık tedarikine su ürünleri yetiştiriciliği katkısında başı çekerken, onu ihracata odaklanan Lesotho takip etmektedir. Etiyopya, Gine-Bissau ve Sudan'da kişi başına düşen balık tedariğinde önemli açıklar bulunmaktadır. Mısır, 2018 yılı üretiminin diğer tüm Afrika ülkelerinin toplamından fazla olmasıyla toplam üretimde de lider konumdadır. Ruanda, Burundi, Lesotho ve Benin gibi ülkeler son on yılda güçlü bir üretim büyümesi gösterirken, Lesotho, Güney Afrika ve Mauritius yüksek değerli su ürünleri yetiştiriciliği üretiminde öne çıkmaktadır. Deniz ve iç su balıkçılığında maksimum verime ulaşma, genişleyen pazarlar, kentleşme ve özel sektör büyüme fırsatlarının birleşimi, Afrika'da su ürünleri yetiştiriciliğinin geliştirilmesi için muazzam bir potansiyel sunmaktadır.

Anahtar kelimeler
- Afrika
- Su Ürünleri Yetiştiriciliği
- Zorluklar
- Gelecek Perspektifleri

1. INTRODUCTION

Aquaculture was initially brought to various African nations in the early 20th century to support colonial recreational fishing (Heck et al., 2007). Kenya's success in cultivating tilapia led colonial governments to promote African aquaculture, enhancing nutrition, income, and employment through government-supported fish farming stations and production ponds (Adeleke et al., 2020). Since the 1960s, the FAO, in collaboration with governments, donor nations, research institutions, and nongovernmental organizations, has led efforts to promote aquaculture development in the region. These initiatives initially focused on basic research and practical techniques for cultivating various primarily indigenous species. The sector's growth accelerated thanks to financial and technical support from bilateral and multilateral donors, amounting to approximately US$500 million between the early 1970s and early 1990s. However, by the mid-1990s, funding for aquaculture in Africa declined significantly as donors shifted their priorities to address pressing issues like education, healthcare, and governance (Heck et al., 2007). Fish is a vital component of Africa's agri-food system with significant potential to address food and nutrition insecurity. It provides 19% of the animal protein consumed across the continent and offers essential micronutrients and long-chain polyunsaturated fatty acids, which are difficult to replace with other food sources. Small indigenous fish, such as Dagaa from Lake Victoria and Kapenta in southern Africa, are integral to traditional diets and serve as rich sources of micronutrients. Additionally, fish is highly efficient at converting feed into high-quality food (Bene et al., 2015).

Despite its immense potential in fisheries and aquaculture, Africa lags behind other regions in global fish production, consumption, and trade (FAO, 2018). The sector faces numerous challenges that hinder its growth and sustainability, including a lack of improved fish breeds, feeds, technical training, weak research capacity, inadequate human and financial resources, poor market infrastructure, and weak governance and regulation (Brummett et al., 2008). Additionally, fish post-harvest losses and waste are significant problems, with more than a quarter of the fish harvest being lost in Sub-Saharan Africa (Affognon et al., 2015). In Sub-Saharan Africa, deterioration from long-distance transportation, high temperatures, inadequate packaging, insufficient preservation techniques, erratic logistics, species preferences, and fishing gear constraints are the main causes of fish post-harvest losses (Abelti & Teka, 2024). The lack of developed cold chains is a key area for intervention to improve resource efficiency and increase profits in the value chain. Compared to Asia, where aquaculture is highly developed, Africa's aquaculture sector, mainly commercial aquaculture, remains in its early stages, with Egypt and Nigeria being notable exceptions. Overfishing and overcapacity have further stressed fishery resources, especially in Western Africa. Africa's declining per capita fish consumption severely impacts food and nutrition security, as fish provides essential micronutrients and protein to millions of malnourished people (FAO, 2018).

2. THE STATUS OF AQUACULTURE IN AFRICA

Africa’s contribution to global aquaculture production remains modest at approximately 1.9 % (FAO, 2024).However, it has grown significantly due to large-scale investments in Egypt, Nigeria, Uganda, and Ghana (Cai et al., 2017). Between 1995 and 2018, production increased twenty-fold, from 110,200 tons to 2,196,000 tons, with a Compound Annual Growth Rate (CAGR) of 15.55%. This growth has been driven by the rise of private sector-led small and medium enterprises (SMEs) and the establishment of large commercial ventures. These developments were supported by public backing, foreign direct investment, increased interest in aquaculture, and global awareness initiatives (Satia, 2011).

Most African aquaculture production (99%) comes from inland freshwater systems, primarily cultivating native and abundant species like tilapia and African catfish. In contrast, mariculture accounts for only 1% of total production, though it is a growing and promising subsector (FAO, 2018). Innovations in aquaculture include introducing new production systems, such as tanks and cages, alongside improvements to existing methods (Satia, 2017). The sector employs approximately 6.2 million people, with women playing a significant role, particularly in large-scale commercial farms. Women are predominantly involved in downstream activities such as postharvest processing and marketing within the aquaculture value chain (Satia, 2016). Given its scale and potential, aquaculture is well-positioned to enhance food security, reduce unemployment, and support Africa's economic development (Adeleke et al., 2020).

Many African governments recognize the importance of fostering a supportive business environment and implementing policy reforms to promote economic growth, positively impacting the aquaculture sector (Satia, 2011). Some nations have introduced aquaculture-focused policies and strategic frameworks to guide the sector's development. While a few governments have facilitated soft loans and incentives, significant barriers remain. Challenges such as limited access to affordable credit, inadequate availability of high-quality inputs, and land ownership issues continue to hinder aquaculture development and expansion (Moehl & Machena, 2000). Africa's aquaculture sector is diverse, with regions excelling in different production and value aspects. In North Africa, Egypt leads in production volumes and national fish supply. East Africa is dominated by Uganda, which ranks third in Africa and excels in critical indicators like national fish supply, GDP contribution, and renewable water use. In Southern Africa, Zambia leads in production and per capita production, while South Africa stands out for high-value marine species farming. Lesotho and Zimbabwe excel in relative contributions to national fish supply, GDP, and inland aquaculture. West Africa sees Nigeria dominate in output and value, with Ghana excelling in aquaculture’s contribution to GDP, production per capita, and value per capita. Central Africa remains underdeveloped, with the Democratic Republic of the Congo leading in production but ranking low in Africa overall. At the same time, high fish consumption is driven by abundant capture fisheries in countries like São Tomé and Príncipe, Gabon, and Congo. This regional breakdown illustrates Africa's growing aquaculture industry, with distinct strengths and challenges across the continent (table 1) (Hinrichsen et al., 2022).

Research efforts in the region have primarily concentrated on species characterization, selective breeding, and developing low-cost diets in select centers. On-farm participatory research using model farms and private enterprises has facilitated the rapid transfer of aquaculture technologies through farmer-to-farmer networks, particularly in countries targeted by SPADA. However, extension services remain weak, highlighting the need to strengthen connections between research and development initiatives (Cocker, 2014). In some countries, the private sector has increasingly taken the lead in producing and delivering essential aquaculture inputs, such as seed and feed (Wadah et al., 2022). In contrast, others host manufacturers and suppliers of aquaculture equipment (Koge et al., 2018). Aquaculture producer associations are active across many African nations, playing vital roles in information dissemination, knowledge exchange, and supporting aquaculture-related activities. Additionally, fish farmer clusters have emerged as effective mechanisms for improving service delivery, achieving economies of scale, lowering transaction costs, and enhancing competitiveness (Satia, 2017).

Despite the obstacles, such as inadequate infrastructure and a lack of facilities, emerging aquaculture marketing activities in some countries are gradually improving the value chain (Elsheikh et al., 2022). To meet consumer demand for ready-to-prepare products, artisanal fish processing subsectors are developing near farms and markets, utilizing simple techniques. Value-addition practices, including freezing, smoking, drying, and cold-smoking catfish fillets, have also enabled the export of processed products to European markets. The leading aquaculture producers in Africa include Egypt, Nigeria, Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi, and South Africa (Satia, 2017). These countries have achieved significant growth over the past decade, driven by capacity building, good governance, research and development, access to credit, and a strong emphasis on private sector-led aquaculture. Private sector involvement has spurred investments in effective management practices, advanced production systems, aqua-feed formulation, and the establishment of vibrant producer associations and service providers (Satia, 2011). As the aquaculture industry grows and activities intensify, several challenges are emerging in leading countries, including increasing demand for capital, insufficient quantities and quality of seed and feed, competition for resources (land, water, and feed), and the need to strengthen aquaculture management and overall governance of the sector (Satia, 2016). Despite these obstacles, the combination of peak marine and inland capture fisheries yields, expanding markets and services, urbanization, and private-sector development opportunities presents significant potential for aquaculture growth (Satia, 2017).

Around 2.5 million tonnes of aquaculture were produced in Africa in 2022, making up 1.9% of the world's total (FAO,2024), while in 2018, Africa's contribution to global aquaculture production was estimated at 2.196 million tons, accounting for a modest 2.67% of the total, with freshwater finfish production being the dominant sector (Halwart, 2020). The top producers—

Egypt, Nigeria, and Uganda—accounted for approximately 90% of the region’s total aquaculture output. Egypt’s aquaculture industry overgrew in 1998, driven by ongoing government interventions and increased private sector investment. As a result, Egypt’s production rose from 139,389 tons in 1998 to 1,561,457 tons in 2018, representing 71% of Africa’s total aquaculture production (Feidi, 2018). Nigeria, with a population exceeding 200 million (Pison et al., 2022), has the highest fish demand in Africa, leading to the swift development of peri-urban commercial aquaculture. Driven by market demand, aquaculture production in Nigeria grew from 20,458 tons in 1998 to 291,233 tons in 2018. The Nigerian government plays a crucial role in creating a supportive business environment, while the private sector leads the aquaculture value chain development. In Uganda, aquaculture development gained momentum in 2000 due to growing awareness of its potential to combat malnutrition, food insecurity, and unemployment. This sector received significant support through government initiatives and aid from development partners, increasing production from 2,360 tons in 2001 to 103,737 tons in 2018 (Adeleke et al., 2020).

Table 1: Top 10 aquaculture producers in Africa in 2018.

Country	Production (metric tons)
Egypt	1,561,457
Nigeria	291,233
Uganda	103,737
Ghana	76,630
Zambia	24,300
Tunisia	21,756
Kenya	15,124
Malawi	9014
Madagascar	7421
South Africa	6181

2.1 Aquaculture production systems in Africa

Aquaculture production in Africa is highly diverse, varying in terms of technologies, natural resources, and value chain structures. Most production (82%) occurs in inland waters (FAO, 2021), with ocean-based aquaculture mainly practiced in the Mediterranean and the Black Sea (70% of marine production) and the Indian Ocean (29%). The production systems can be categorized as extensive, semi-intensive, or intensive, with different approaches in various regions (Hinrichsen et al., 2022).

In Sub-Saharan Africa, common production systems include earthen ponds, cages, and basins. In North Africa, extensive systems are common, where juvenile fish are stocked in reservoirs, a method practiced in countries like Egypt, Morocco, Algeria, and Libya (El-Sayed, 2017). Semi-intensive aquaculture, typically practiced in earthen ponds with supplementary feeding, is most prevalent in Egypt, contributing up to 80% of the country's fish production (Soliman, 2017). Intensive systems in tanks and cages are also proliferating (Satia, 2017).

In Southern Africa, production systems are more varied, with raceways used for trout farming, ponds for extensive and semi-intensive production, and cages for grow-out. Additionally, longlines are used for mussel and oyster production, and recirculating aquaculture systems (RAS) are more common in South Africa. South Africa also employs land-based pumping systems for abalone farming using advanced hatchery technology. Cage fish farming is essential, with large companies operating on lakes such as Lake Kariba in Zambia, where two cage farms control 85% of the cages (Adeleke et al., 2020).

In East Africa, aquaculture is mainly extensively pond-based due to lower infrastructure costs and more straightforward techniques. However, some farmers have adopted more intensive methods like cage farming, which is profitable and requires less capital per unit of fish produced. Uganda has the highest number of inland cage farms in East Africa (18%), followed by Kenya, Tanzania, Rwanda, Zimbabwe, Zambia, and Malawi (Musinguzi et al., 2019). Lake Victoria has the highest number of caged aquaculture facilities among African inland waters (Musinguzi et al., 2019).

In West Africa, countries like Guinea, Côte d'Ivoire, and Cameroon use dam ponds created by closing valleys to form large ponds. Integrated agri-aquaculture systems are standard in Benin and Nigeria (Satia, 2017). Cage farming is prevalent among privately owned industrial farms, producing between 1,000 and 10,000 tons of fish annually (Hinrichsen et al., 2022).

2.2. Fish feed in Africa

The growth of aquaculture production in Africa has been accompanied by increased fish feed production. Before 2010, feed mills primarily produced feed for terrestrial animals and only supplied fish feed when requested explicitly by farmers. This was due to low demand, which made it challenging for manufacturers to invest in dedicated production lines for aquaculture feed (Agboola et al., 2019). However, the rise in aquaculture production, particularly in Egypt, can be attributed to a shift from extensive to semi-intensive and intensive production systems (Waite et al., 2014), which are feed-dependent (El-Sayed et al., 2015). This transition has spurred demand for more feed, prompting the development of local feed production capacity, including the establishment of new feed mills and increased feed imports.

In Egypt, feed mills grew from five in 1999, producing 20,000 tons annually, to 73 mills, producing approximately 1 million tons per year by 2017 (Shaalan et al., 2018). Nigeria, which has the highest number of feed mills in Sub-Saharan Africa, produces 60% of the local aqua feeds used (Adeleke et al., 2020). Despite this, the production capacity of these mills is relatively low, with output ranging from 0.5 to 3 tons of feed per hour. Large-scale aquaculture investors in countries like Nigeria, Uganda, Kenya, and Zambia still rely heavily on imported aquaculture feed and ingredients due to their higher quality, better value for money, and the competition for ingredients from other sectors of animal production (Adedeji & Okocha, 2011). Feed manufacturers in these countries have established regional feed mills or outlets to meet the growing demand. Despite these advancements, the fish feed industry and farmers face the challenge of rapidly increasing feed prices.

2.3 Fish hatchery in Africa

The availability and quality of juvenile fish for stocking have consistently been highlighted as significant obstacles to African aquaculture development (Shaalan et al., 2018). Most fish seeds are sourced from the wild (wild catch), production ponds, or both licensed and unlicensed hatcheries. However, collecting fish seeds from the wild is strongly discouraged due to biosecurity risks, unpredictability, and sustainability concerns (Hasimuna et al., 2019). While the number of hatcheries on the continent has grown significantly over the past two decades, primarily due to private sector investment, most hatcheries are small-scale. These hatcheries mainly produce fingerlings of Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). Standard hatchery systems include small open ponds, hapas (net enclosures), indoor tanks, and concrete tanks, with some hatcheries also using indoor flow-through tanks and recirculating raceways. In Egypt, for example, between 400 and 500 private hatcheries are producing sex-reversed tilapia, though only about 150 are licensed. . Farmers prioritize cost over quality, through selective breeding programs (Hebisha & Fathi, 2014).

There is a significant gap in the demand for high-quality juvenile fish in Africa (Adewumi, 2015), which stems from various factors, including poor genetic management and deteriorating genetic quality in parental populations. Furthermore, many hatcheries lack standardized practices and adequate quality control, and regulatory frameworks to ensure seed quality are often absent or poorly implemented. Biosecurity measures to prevent contamination are minimal or non-existent in many hatcheries. There is an urgent need to explore advanced breeding technologies to address these challenges and develop new and improved fish seed strains (Kajungiro et al., 2019).

3. CHALLENGES OF AQUACULTURE IN AFRICA

Aquaculture production in Africa faces several significant challenges that must be addressed for sustainable growth. Inadequate infrastructure is a crucial obstacle, limiting many producers’ access to larger markets and hindering the sector’s potential for growth. Additionally, government regulations are often poorly adapted or poorly enforced, which stifles local initiatives and slows the development of the industry. Small-scale farmers, who make up a significant portion of the sector, lack training and technical support, which hampers the adoption of modern, efficient aquaculture practices. To overcome these barriers, international cooperation and capacity-building programs can be pivotal in providing farmers with the necessary resources and training, particularly in rural areas (Adeleke et al., 2020). Another major challenge is the impact of climate change (Adeleke et al., 2020). Fluctuating temperatures, extreme weather events, and changes in water quality significantly affect fish farm productivity (Elsheikh, 2021). To mitigate these effects, an integrated approach that combines innovative technologies with sustainable resource management is essential for the sector's resilience (Elsheikh et al., 2024). Targeted initiatives to enhance their involvement in the sector will improve livelihoods and contribute to long-term, sustainable development in African aquaculture.

3.1 Climate change

Increasing aquaculture production can lead to resource constraints as competition for land and freshwater intensifies (Elsheikh et al., 2022, Bagdatli et al., 2023). According to Ahmed et al. (2019), the expansion of land-based aquaculture systems, such as ponds and tanks, may be limited by the need for agricultural land. Additionally, freshwater resources, vital for aquaculture in Africa, are also used for crop production and other purposes, making water limitations a concern (Elsheikh & Nasreldin, 2022). As freshwater aquaculture continues to grow, competition for water may increase, particularly for maintaining pond levels and replacing water lost through seepage and evaporation. To address these pressures, it is recommended that aquaculture production systems be intensified to increase efficiency and reduce the feed conversion ratio (Mungkung et al., 2014). However, switching to marine water systems may not fully resolve these challenges, as a large portion of the water used in aquaculture is indirectly related to aquafeed production (Mungkung et al., 2013). Other significant environmental issues are water pollution and eutrophication caused by expanded aquaculture. Using fertilizers, antibiotics, and wastewater discharges containing nutrients from feed and waste can lead to eutrophication, negatively affecting water quality. Over 90% of aquaculture production in Africa relies on fed systems, which contribute to high levels of phosphorus and nitrogen in wastewater, resulting in organic matter buildup (FAO, 2020). This buildup can deplete oxygen levels, cause algal blooms, and lead to disease outbreaks. Improvements in technology and management practices are needed to reduce aquaculture's impact on water pollution. These include using settling ponds before wastewater discharge, incorporating filtration systems, and adopting modern production systems like recirculating aquaculture systems and biofloc technology (Waite et al., 2014).

Aquaculture is more vulnerable to climate change than capture fisheries, as changing environmental conditions directly affect cultured organisms and infrastructure (Augustyn et al., 2017). Climate change poses significant threats to aquaculture production through global warming, ocean acidification, sea-level rise, and increasingly frequent extreme weather events like floods, droughts, and irregular rainfall patterns (Ahmed et al., 2019). While much research has focused on global impacts, fewer studies address the specific effects on African aquaculture. The impacts can be categorized into ecological changes (e.g., altered productivity, new diseases, algal blooms), physiological changes in organisms, operational shifts, resource limitations (freshwater and feed shortages), and socio-economic consequences, including increased poverty and food insecurity for farmers (Asiedu et al., 2017). Mitigation strategies like sustainable wastewater management and environmentally friendly technologies are essential to building resilience, alongside adaptation measures focused on enhancing the strength of aquaculture systems, such as diversifying species and optimizing water and feed use. The African aquaculture sector requires tailored climate strategies to ensure its sustainability and reduce the socio-economic impacts of climate change (Hinrichsen et al., 2022).

4. OPPORTUNITIES FOR GROWTH AND FUTURE DIRECTIONS:

Despite modest growth, aquaculture productivity in Africa has increased steadily over time. The macroeconomic environment, access to fisheries resources, water availability, and other variables vary widely across African countries (Hinrichsen et al., 2022). Aquaculture in Africa presents challenges and opportunities, with key nations such as Egypt, Nigeria, and Uganda emerging as leaders in various aspects compared to South Africa. Regarding market demand, these countries exhibit higher per capita fish consumption and more efficient value chains, spurring aquaculture growth. Egypt, for example, benefits from a well-established market system. At the same time, Nigeria has developed a robust catfish value chain, with Fish Farming Estates enhancing access to large markets and reducing post-harvest losses. Uganda’s Tilapia and niche catfish markets also show promising growth (Adeleke et al., 2020). In contrast, South Africa has lower fish consumption, with its aquaculture sector facing relatively low production levels and numerous challenges. Regarding infrastructure, Egypt, Nigeria, and Uganda boast more developed support systems, including active government involvement in hatcheries, research, training, and establishing fish farm estates. While South Africa has an infrastructure capable of supporting feed and fish seed production, governmental involvement is limited beyond policy-making, and firms are often far from fish farms. Environmental factors play a significant role. Egypt faces constraints from limited land and water availability due to its desert climate, while Nigeria and Uganda benefit from abundant arable land, water, and a warm tropical climate suitable for aquaculture. On the other hand, South Africa is limited by water scarcity in its inland areas and an unfavorable climate for traditional aquaculture (Hinrichsen et al., 2022). Regarding technology, Egypt has been a leader in adopting advanced production systems, including desert aquaculture and integrated systems. Nigeria and Uganda have also integrated efficient technologies into feed production, hatchery operations, and fish processing. South Africa, however, lags in technological adoption, which hampers the expansion of its aquaculture sector. On the commercialization front, Egypt, Nigeria, and Uganda have attracted private and government investments, particularly in feed and seed production. Nigeria's Fish Farming Estates model has significantly enhanced the aquaculture value chain, while Uganda's private sector-driven growth has been notable. South Africa's aquaculture sector relies primarily on private investment, with recent policy shifts aiming to adopt a value chain-driven approach. Lastly, regarding institutional support and skill development, Egypt, Nigeria, and Uganda benefit from well-established aquaculture research institutions and universities that support capacity building. South Africa has aligned its policies with regional development goals but lacks the level of institutional support and training facilities seen in other key aquaculture nations (Adeleke et al., 2020). The bottom line is that, while Egypt, Nigeria, and Uganda excel in various aspects of aquaculture development, South Africa's sector faces challenges in market demand, infrastructure, technology adoption, and institutional support, hindering its growth compared to these African leaders.

5. CONCLUSION

Aquaculture in Africa holds immense potential to drive economic growth, enhance food security, and foster rural development, but its progress remains uneven across the continent. While countries like Egypt, Lesotho, and Uganda have made significant strides in high-value aquaculture production, the sector faces challenges such as resource constraints, technological gaps, and fish supply per capita disparities. Addressing these issues requires a tailored approach prioritizing sustainable practices, effective resource management, and strategic capacity-building. Collaboration among governments, regional organizations, and international partners is essential to foster knowledge exchange, finance innovative technologies, and improve market access. Strengthening local aquaculture industries could reduce food insecurity, create new income opportunities, and support livelihoods. By leveraging its natural resources, enhancing policy frameworks, and promoting inclusive growth, Africa can unlock the full potential of aquaculture and build a resilient, sustainable, and equitable future for the sector.

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The author declares that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

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DATA AVAILABILITY STATEMENT

Data sharing does not apply to the present study as no new data was created or analyzed.

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Wagenaar, D. A., Hamilton, M. S., Huang, T., Kristan, W. B., & French, K. A. (2010). A hormone-activated central pattern generator for courtship. Current Biology, 20(6), 487-495. https://doi.org/10.1016/j.cub.2010.02.027

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Bu bölümde finansal destek dışında çalışmanın yürütülmesine katkı sunanlar belirtilir.

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VERİ KULLANILABİLİRLİK BEYANI
Bu bölümde makalede kullanılan verilerin anonim kullanılabilirliğine ilişkin beyanda bulunulmalıdır. Acta Aquatica Turcica dergisi, yazarları araştırma verilerini paylaşmaya teşvik etmektedir.

Örnek-1: Bu çalışmada kullanılan veriler Figshare platformunda ttps://doi.org/10.6084/m9.figshare.11815566.v1 DOI adresi ile erişime açıktır.

Örnek-2: Bu çalışmada kullanılan verilere ilgili yazardan talep üzerine erişilebilir. Veriler, gizlilik veya etik kısıtlamalar nedeniyle kamuya açık değildir.

Örnek-3: Bu çalışmada kullanılan veriler makul talep üzerine ilgili yazardan temin edilebilir.

Örnek-4: Bu çalışmada yeni veri oluşturulmadığı veya analiz edilmediği için veri paylaşımı bu makale için geçerli değildir.

Örnek-5: Araştırma verileri paylaşılmaz.

Örnek-6: Bu çalışmada kullanılan veriler bu makalenin ekinde mevcuttur.

ATIFLAR

Atıflar yıl sırasına göre ve aralarında noktalı virgül (;) olacak şekilde aşağıdaki formatlarda yazılır:

- Tek yazar:
(Yazar, yıl)
-- … olduğu düşünülmektedir (Küçük, 2008; Güçlü, 2018a; Güçlü, 2018b).
-- Küçük (2008)'e göre …

- İki yazar:
(Yazar-1 ve Yazar-2, yıl)
-- … önemli parametreler arasında yer almaktadır (Küçük ve Güçlü; 2001; Ekici ve Koca, 2021a; Ekici ve Koca, 2021b).
-- Ekici ve Koca (2021b)'a göre …

- Üç ve daha çok yazar:
(Yazar vd., yıl)
-- … dönemsel olarak tekrarlayabilmektedir (Yiğit vd., 2006a; Yiğit vd., 2006b; Boyacı vd., 2020)
-- Boyacı vd. (2020)'e göre …

KAYNAKLAR

Kaynaklar APA 7. versiyona göre yazılmalıdır. Tüm yazarların isimleri verilmelidir, ancak 10. yazardan sonra "vd." kısaltması da kabul edilmektedir. Özel kullanımlar hariç olmak üzere tüm eser türlerinde eser isminin sadece ilk harfi büyük, eserin yayınlandığı veya sunulduğu dergi, yayınevi, kongre isimlerinde geçen tüm kelimeler büyük harfle başlanarak yazılmalıdır.

1-Makale

Dergi ismi kısaltılmadan (italik), cilt (italik), sayı, sayfa numaraları ve aktif link içerecek şekilde DOI numarasına yer verilmelidir:

Petrauskienė, L., Utevska, O., & Utevsky, S. (2009). Can different species of medicinal leeches (Hirudo spp.) interbreed? Invertebrate Biology, 128(4), 324-331. https://doi.org/10.1111/j.1744-7410.2009.00180.x

Wagenaar, D. A., Hamilton, M. S., Huang, T., Kristan, W. B., & French, K. A. (2010). A hormone-activated central pattern generator for courtship. Current Biology, 20(6), 487-495. https://doi.org/10.1016/j.cub.2010.02.027

2-Kitap

Kitap başlığı italik olacak şekilde ve yayın kuruluş ismi olacak şekilde verilmelidir.

Nesemann, H., & Neubert, E. (1999). Annelida, Clitellata: Branchiobdellida, Acanthobdellea, Hirudinea. Spektrum Akademischer Verlag.

Sawyer, R. T. (1986). Leech biology and behavior. Oxford University Press.

3-Kitap bölümü

Bölüm başlığı normal, kitap başlığı italik olacak şekilde, editör(ler), bölümün sayfa numaraları, yayıncı kuruluş ve varsa aktif link içerek şekilde DOI numarasına yer verilmelidir:

Le Couteur, D., Kendig, H., Naganathan, V., & McLachlan, A. (2010). The ethics of prescribing medications to older people. In S. Koch, F. M. Gloth, & R. Nay (Eds.), Medication management in older adults (pp. 29-42). Springer. https://doi.org/10.1007/978-1-60327-457-9_3

McCormack, B., McCance, T., & Maben, J. (2013). Outcome evaluation in the development of person-centred practice. In B. McCormack, K. Manley, & A. Titchen (Eds.), Practice development in nursing and healthcare (pp. 190-211). John Wiley & Sons.

4-Web sitesi

Sayfa başlığı italik, websitesinin ismi ve sayfanın aktif linki olacak şekilde verilmelidir.

International Union for Conservation of Nature. (2010). Chondrostoma nasus. https://www.iucnredlist.org/species/4789/97800985

Wikipedia. (2021). Toxicology. https://en.wikipedia.org/wiki/Toxicology

5- Tezler

Tez başlığı italik olacak şekilde, tez türü (Doktora, Yüksek lisans, Tıpta Uzmanlık) ve üniversite ismi belirtilmelidir.

Filik, N. (2020). Kültür balıklarından izole edilen Aeromonas hydrophila suşlarında fenolik bileşenlerin çevreyi algılama sistemi üzerine inhibisyon etkisi ve suşlar arasındaki klonal ilişkinin pulsed field jel elektroforez yöntemiyle belirlenmesi [Doktora tezi, Isparta Uygulamalı Bilimler Üniversitesi].

Özdal, A. M. (2019). Effects on growth and coloration of red pepper suplementation as pigment sources to diets of jewel cichlid (Hemichromis guttatus) [Yüksek lisans tezi, Isparta Uygulamalı Bilimler Üniversitesi].

6- Konferans, sempozyum sunumları

Etkinlik tarihi, sunu başlığı (italik), sunum türü (Sözlü sunum, Poster sunum), etkinlik adı, şehir ve ülke verilmelidir.

Ceylan, M., Çetinkaya, O. (2017, Ekim 4 - 6). Assessment of population structure and size of medicinal leech Hirudo verbana, inhabiting some model wetlands of Turkey [Sözlü sunum]. International Symposium on Limnology and Freshwater Fisheries, Isparta, Türkiye.

Snoswell, C. (2016, Ekim 31 - Kasım 3). Models of care for store-and-forward teledermatology in Australia [Poster sunum]. 7th International Conference on Successes and Failures in Telehealth, Auckland, Yeni Zelanda.

NOT: Dergi yazım kurallarına uygun olarak hazırlanmayan makaleler değerlendirmeye alınmayacaktır.