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Oxidative Stress Responses of Perca fluviatilis Across Turkish Lakes and Dams

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Abstract

This study aimed to investigate the genetic diversity, phylogenetic relationships, and oxidative stress responses of *Perca fluviatilis* populations collected from 12 lakes and dams across different regions of Turkey. Oxidative stress markers, including superoxide dismutase (SOD), catalase (CAT), glutathione (GSH), glutathione peroxidase (GSH-Px), and malondialdehyde (MDA), exhibited significant differences among populations, reflecting habitat-specific stress conditions. The highest antioxidant enzyme activities and MDA levels were observed in populations from Samsun, Konya, and Adana, suggesting higher environmental stress, whereas populations from İzmir and Amasya displayed lower levels, indicating more stable habitats. Integrating molecular and biochemical data highlights the interaction between genetic structure and physiological responses to environmental pressures. These findings suggest that environmental factors such as water quality, pollution, and habitat characteristics influence both oxidative stress and adaptive capacity in *P. fluviatilis*. Overall, this study provides comprehensive insights into the genetic and physiological diversity of *P. fluviatilis* populations in Turkey and emphasizes the importance of combined molecular and biochemical approaches for sustainable management and conservation of perch fish populations.

Keywords: Antioxidant; Environmental Adaptation; Enzyme; Perch

1. Introduction

The European perch (*Perca fluviatilis* L.) is a medium-sized freshwater fish belonging to the family Percidae (McDowall 1996). The species was first described from Swedish lakes by Peter Artedi in 1730 and was subsequently classified by Carl Linnaeus in 1758 based on Artedi's work (Thorpe 1977; Pimakhin et al. 2015). The family Percidae comprises 10 genera and 195 species (Berra 2001). Fossil evidence suggests that the genus Perca originated approximately 19.8 million years ago during the early Miocene epoch (Stepien et al. 2015).

Extensive literature has been developed on the European perch (*Perca fluviatilis*) due to its wide distribution and importance in recreational fisheries and aquaculture (Pimakhin et al. 2015). Nevertheless, comprehensive studies focusing specifically on the biology and ecology of the species remain limited. Such research is essential to strengthen our overall understanding of the species, identify knowledge gaps and limitations, and evaluate the ecological drivers underlying its broad global distribution.

Fish are frequently exposed to a variety of environmental stressors such as temperature fluctuations, hypoxia, pollution, and changes in salinity, which can disrupt cellular homeostasis and induce oxidative stress (Schulte, 2014). Under such conditions, reactive oxygen species (ROS) levels increase, leading to potential damage to proteins, lipids, and nucleic acids (Juan et al. 2021). To counteract these effects, fish rely on an antioxidant defense system that includes key enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), and glutathione reductase (GR)

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(Ighodaro et al. 2018). Alterations in the activities of these enzymes are widely recognized as biomarkers of oxidative stress and environmental stress responses in aquatic organisms (Valavanidis et al. 2006; Regoli and Giuliani, 2014). For example, exposure to pollutants or hypoxia has been reported to significantly modify antioxidant enzyme activity in several freshwater and marine fish species, reflecting their adaptive physiological responses to stressful environments (Birnie-Gauvin et al. 2017; Abdel-Tawwab et al. 2019). Thus, monitoring antioxidant enzyme dynamics provides valuable insights into the health status of fish populations and their capacity to cope with environmental challenges (Mukherjee et al. 2017).

The present study aims to investigate the antioxidant enzyme activities (SOD, CAT, GSH, GSH-Px) and lipid peroxidation levels (MDA) are measured to evaluate the oxidative stress status and adaptive physiological responses of fish in relation to environmental conditions.

2. Materials and methods

2.1. Materials

Fish samples were collected from twelve different perch bodies in Türkiye, including Darıderesi Dam (Isparta), Yedikır Dam Lake (Amasya), Ürkmez Dam (İzmir), Tahtalı Dam (İzmir), Seyhan Dam (Adana), Şeyitler Dam (Afyon), Denizli Pond (Kocaeli), Karaağaç Pond (Uşak), Hirfanlı Dam (Kırşehir), Çamlıdere Dam (Ankara), Altınapa Dam (Konya), and Ladik Lake (Samsun). Sampling was carried out using gill nets with a mesh size of 4 mm. From each location, 25 individuals were obtained, resulting in a total of 300 specimens used in the study.

2.2. Methods

2.2.1. Malondialdehyde (MDA) and Antioxidant Enzyme Assays

To evaluate the stress status of fish from the sampled reservoirs and lakes, muscle tissues were collected and analyzed for oxidative stress biomarkers. Specifically, malondialdehyde (MDA) levels (Uchiyama and Mihara 1978), together with the activities of glutathione peroxidase (GSH-Px) (Tamura et al. 1982), catalase (CAT) (Aebi 1983; Li and Schellhorn 2007), reduced glutathione (GSH) (Cribb et al. 1989), and superoxide dismutase (SOD) (Wang et al. 2005), were determined.

3. Results and Discussion

The results of the antioxidant enzyme activities (SOD, CAT, GSH, GSH-Px) and malondialdehyde (MDA) levels in muscle tissues of fish are presented in Figure 1.

MDA is not an enzyme but a biomarker of oxidative stress, representing the end product of lipid peroxidation. It is a three-carbon aldehyde formed through the oxidation of polyunsaturated fatty acids when excessive reactive oxygen species (ROS) are generated, leading to lipid peroxidation in cell membranes. Environmental stressors such as poor water quality, temperature fluctuations, hypoxia, heavy metal exposure, toxic chemicals, or intensive rearing conditions can induce oxidative stress in fish. MDA levels serve as a biochemical indicator of such stress, with elevated concentrations in tissues such as liver, muscle, and gills reflecting the extent of oxidative damage (Korkmaz 2018). Statistical analysis revealed significant differences in MDA levels among fish from different locations. MDA analyses of fish sampled from various dams and lakes across Türkiye highlighted the impact of environmental conditions on lipid peroxidation. The highest MDA concentration (36.11 nmol/g) was observed in fish from Ladik Lake (Samsun), suggesting that these populations are exposed to elevated oxidative stress, potentially due to water quality deterioration, pollution, agricultural runoff, oxygen deficiency, or other environmental stressors. Moderate MDA levels were detected in fish from Altınapa Dam (Konya, 29.27 nmol/g), Çamlıdere Dam (Ankara, 21.46 nmol/g), and Hirfanlı Dam (Kırşehir, 20.14 nmol/g), indicating intermediate stress conditions. In contrast, the lowest MDA values (5.94–7.40 nmol/g) were recorded in fish from Ürkmez Dam (İzmir), Yedikır Dam Lake (Amasya), Darıderesi Dam (Isparta), and Tahtalı Dam (İzmir), suggesting more stable aquatic environments with lower oxidative stress. These location-specific differences indicate that oxidative stress levels vary considerably among water bodies, reflecting the influence of physicochemical conditions, pollution levels, and ecological balance on lipid peroxidation in fish.

GSH-Px is one of the key antioxidant enzymes involved in combating oxidative stress in fish. It plays a central role in maintaining cellular redox balance, neutralizing free radicals, and protecting cell membranes from oxidative damage. Together with superoxide dismutase (SOD) and catalase (CAT), GSH-Px constitutes a fundamental component of the antioxidant defense system in fish. Environmental stressors such as deteriorated water quality, temperature increases, ammonia accumulation, heavy metals, pesticides, or oxygen deficiency can alter GSH-Px activity (Kaymak 2011). In fish sampled from various dams and lakes across Türkiye, GSH-Px activity (µmol/g) was measured, revealing statistically significant differences among locations. GSH-Px, as a primary enzyme in reactive oxygen species (ROS) neutralization, provides a critical biochemical indicator of the oxidative stress level in the aquatic environment. The highest GSH-Px activity (49.45 µmol/g) was observed in fish from Ladik Lake (Samsun), significantly higher than other groups, indicating that these fish are exposed to elevated oxidative stress and have activated their antioxidant defense system in response. Other locations with high GSH-Px activities included Çamlıdere Dam (Ankara, 40.59 µmol/g), Hirfanlı Dam (Kırşehir, 40.21 µmol/g), and Altınapa Dam (Konya, 39.79 µmol/g). Conversely, the lowest activities were recorded in Yedikır Dam Lake (Amasya, 16.94 µmol/g) and Darıderesi Dam (Isparta, 17.37 µmol/g), suggesting reduced oxidative stress, limited environmental pressures, or differences in metabolic adaptation. The observed variation in GSH-Px activity among locations reflects the influence of environmental quality, water composition, pollution levels, dissolved oxygen availability, and potential toxic exposures on the oxidative status of fish populations.

CAT is a key antioxidant enzyme involved in combating oxidative stress in fish. Although free radical production is a natural metabolic process, excessive accumulation can damage cellular structures. CAT plays a critical role in detoxification by converting reactive oxygen species (ROS), particularly hydrogen peroxide (H_2O_2), into harmless products, breaking it down into water (H_2O) and oxygen (O_2), thereby reducing oxidative stress in the organism. In fish, CAT is primarily found in metabolically active tissues such as the liver, kidney, muscle, and gills. Enzyme activity is highly sensitive to the physicochemical conditions of the aquatic environment, with stressors such as heavy metal pollution, temperature fluctuations, dissolved oxygen levels, and toxic substances capable of altering CAT activity (Kaymak, 2011). In fish sampled from various dams and lakes, CAT activity showed statistically significant differences ($p<0.05$). The highest activity (56.46 U/mg protein) was observed in samples from Ladik Lake (Samsun), which was significantly higher than all other groups. This was followed by Altınapa Dam (Konya, 46.69 U/mg protein) and Çamlıdere Dam (Ankara, 44.68 U/mg protein). Conversely, the lowest CAT activities were recorded in Ürkmez Dam (İzmir, 10.14 U/mg protein), Yedikır Dam Lake (Amasya, 10.41 U/mg protein), and Darıderesi Dam (Isparta, 11.06 U/mg protein). These findings indicate that the environmental conditions of the dams and lakes, including water quality, oxidative stress levels, and pollutant presence, significantly influence the antioxidant defense system in fish, with higher CAT activity observed in regions experiencing elevated oxidative stress.

GSH serves as a crucial antioxidant defense component in fish, contributing to the maintenance of cellular integrity by neutralizing harmful molecules such as reactive oxygen species (ROS). This function is particularly important in preventing oxidative damage processes, including lipid peroxidation. GSH also plays a key role in detoxification processes, primarily in the liver and other organs, working in conjunction with glutathione-S-transferase (GST) to convert xenobiotics and toxic compounds into water-soluble forms. As a central regulator of intracellular redox balance, GSH is oxidized to glutathione disulfide (GSSG) under oxidative stress conditions, with the ratio reflecting the level of stress experienced by the organism. Additionally, GSH protects against ROS-induced DNA mutations and protein degradation, supporting vital functions such as immunity, growth, and reproduction. GSH levels are influenced by various environmental and biological factors, including pollutants (e.g., heavy metals, pesticides), temperature fluctuations, oxygen availability (hypoxia), pH, nutrient content, seasonal variations, and fish age (Korkmaz 2018).

In fish sampled from various dams and lakes across Türkiye, GSH levels exhibited statistically significant differences ($p<0.05$). The highest GSH concentration (79.56 µmol/g protein) was observed in fish from Ladik Lake (Samsun), significantly higher than all other groups. This was followed by Altınapa Dam (Konya, 69.36 µmol/g protein) and Hirfanlı Dam (Kırşehir, 68.67 µmol/g protein), suggesting that elevated GSH levels in these populations may reflect a robust antioxidant defense response to potential environmental stressors. Conversely, lower GSH levels were detected in fish from Denizli Pond (Kocaeli, 43.71 µmol/g protein), Şeyitler Dam (Afyon, 26.36 µmol/g protein), and Ürkmez Dam (İzmir, 25.56 µmol/g protein). The lowest values were recorded in Darıderesi Dam (Isparta, 13.97 µmol/g protein), Tahtalı Dam (İzmir, 19.08 µmol/g protein), and Yedikır Dam Lake (Amasya, 21.98 µmol/g protein). These results indicate that glutathione levels vary according to the ecological conditions of different dams and lakes and are likely associated with oxidative stress. Elevated GSH levels in Samsun, Konya, and Kırşehir populations may reflect adaptive responses to environmental stressors.

SOD is a key antioxidant enzyme that plays a central role in defending fish against oxidative stress. It functions primarily to neutralize the toxic effects of superoxide anions (O_2^-) generated during cellular metabolism, particularly in the mitochondrial respiratory chain. SOD converts these radicals into the less harmful hydrogen peroxide (H_2O_2), thereby protecting cellular components from oxidative damage. Major SOD isoforms identified in fish include cytosolic Cu/Zn-SOD, mitochondrial Mn-SOD, and, in some species, Fe-SOD. The expression levels of these enzymes can increase in response to environmental stressors such as temperature fluctuations, hypoxia, toxic compounds, and pathogens.

Consequently, SOD activity serves as a biochemical indicator of fish adaptive responses to environmental stress and overall health status (Kayhan et al. 2014).

In this study, SOD activities in European perch sampled from various water bodies across Türkiye are presented in Figure 1. The results suggest that environmental conditions and habitat characteristics influence oxidative stress levels in these populations. The highest SOD activity (34.41 U/mg protein) was recorded in fish from Ladik Lake (Samsun), indicating either greater exposure to oxidative stress or enhanced enzymatic defense mechanisms in this population. This was followed by Çamlıdere Dam (Ankara, 28.24 U/mg protein), Hirfanlı Dam (Kırşehir, 27.98 U/mg protein), and Altınapa Dam (Konya, 27.69 U/mg protein), where activities were statistically similar and relatively high, suggesting comparable environmental stress factors such as water temperature, dissolved oxygen, or pollution. Conversely, the lowest SOD activities were observed in Yedikır Dam Lake (Amasya, 11.79 U/mg protein) and Darıderesi Dam (Isparta, 12.08 U/mg protein), reflecting lower oxidative stress or reduced metabolic activity in these environments. Overall, regional differences in SOD activity indicate that environmental variability strongly influences metabolic stress and antioxidant responses in fish, likely mediated by factors such as water quality, pollution, temperature, dissolved oxygen, and habitat characteristics.

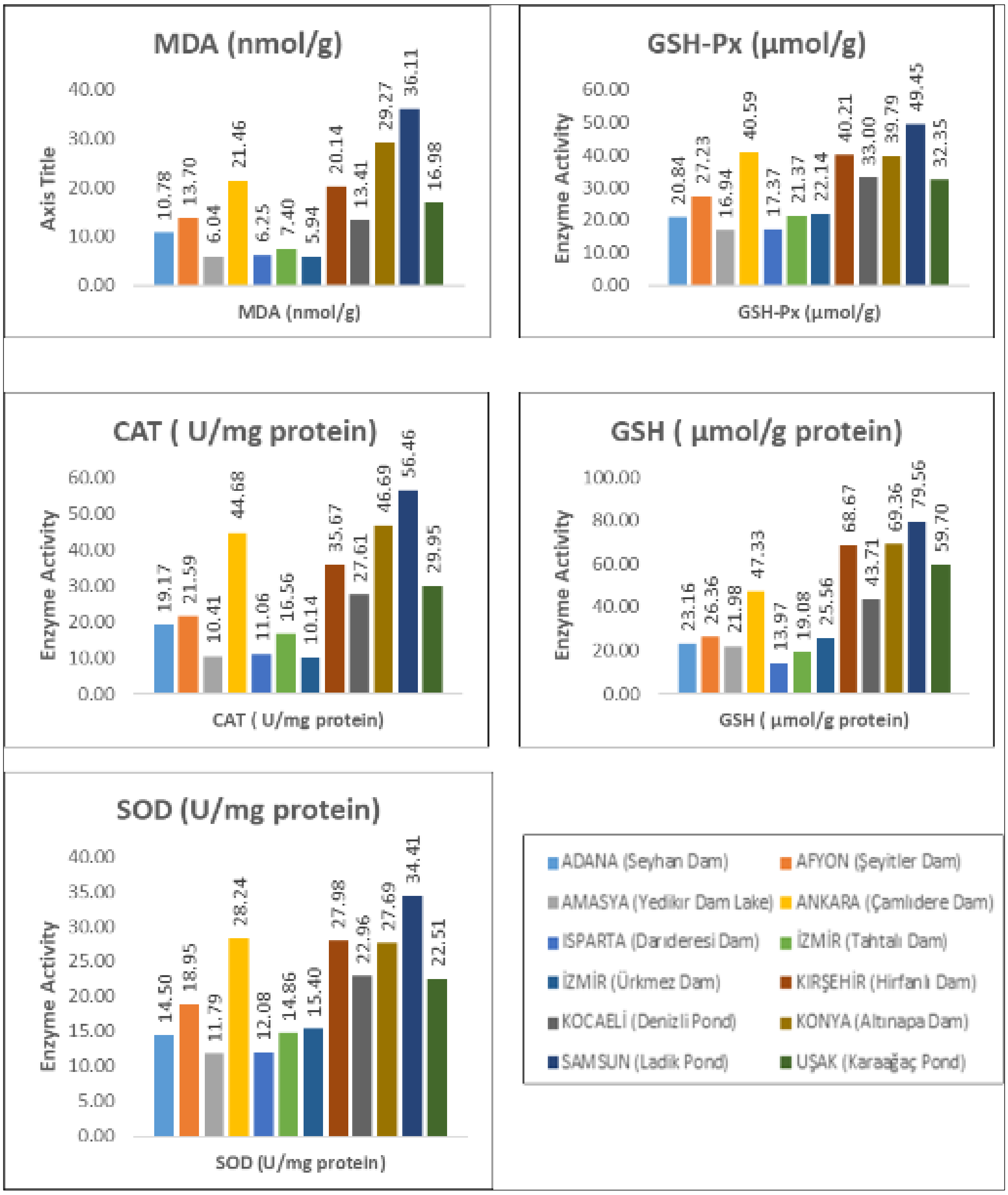

Figure 1 MDA levels and antioxidant enzymes activity

Environmental conditions and habitat variability exert significant physiological effects on the antioxidant enzyme systems in fish. Factors such as water temperature, dissolved oxygen, pollution levels, food availability, and seasonal changes can induce variations in the production of reactive oxygen species (ROS), leading to oxidative stress at the cellular level (Birnie-Gauvin et al. 2017). These conditions activate defense mechanisms in fish, resulting in changes in the activities of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), glutathione-S-transferase (GST), and glutathione peroxidase (GPx) (Bhagat and Ingole 2016). In the present study, fish exhibited habitat-dependent variations in the activity levels of antioxidant defense systems, namely SOD, CAT, GSH, GSH-Px, and MDA.

Previous studies have also reported similar patterns. Shahjahan et al. (2022) demonstrated that climate change and other environmental stressors significantly influence fish antioxidant enzyme systems, with marked increases in SOD, CAT, GPx, and GSH activities in response to temperature rise and environmental variability. Fadhlaoui and Couture (2016) investigated the effects of temperature (9°C and 28°C) and metal (nickel and cadmium) stress on *P. flavescens*, showing that SOD, CAT, GST, GPx, and GSH activities were effectively induced under these conditions, suppressing lipid peroxidation. Shaheen et al. (2014) reported that probiotic supplementation in *P. flavescens* led to lower GPx and SOD activities and *COI* gene expression compared to controls, indicating reduced ROS accumulation and mitigated oxidative stress. Similarly, Pascual et al. (2003) observed that starvation in Sparus aurata caused increases in MDA levels and oxidative damage, while SOD and CAT initially increased and then declined over prolonged stress, with glutathione-related enzymes (GPx and GR) showing a comparable trend.

Seasonal and environmental influences were also documented by Morozov and Yurchenko (2018), who found significant seasonal variations in liver SOD, CAT, and GST activities in European perch, peaking during spawning and at higher water temperatures, highlighting the adaptive plasticity of antioxidant systems to both biological rhythms and environmental conditions. Kupprat et al. (2021) demonstrated that artificial night lighting increased oxidative stress markers and decreased immune function in perch. Our study similarly observed significant habitat-dependent differences in MDA, SOD, GSH, GSH-Px, and CAT activities, with higher MDA levels in fish from Adana, Konya, and Ankara, suggesting elevated environmental stress in these regions. Conversely, fish from Izmir exhibited generally lower antioxidant enzyme activities, consistent with Elçi and Karataş (2009), who reported limited pollutant transport to the Tahtalı Dam, potentially explaining the reduced oxidative stress in that region.

Domestication and environmental adaptation have also been shown to affect antioxidant responses. Palińska-Żarska et al. (2021) indicated that wild fish exhibit adaptive regulation of antioxidant systems, with SOD and GSH-Px levels increasing in response to habitat oxidative load. Grasset et al. (2016) demonstrated that both temperature and metal pollution influenced SOD activity and other antioxidant responses in *P. flavescens*, while Dumitru et al. (2018) observed interspecific variability in antioxidant enzyme activities and MDA levels among fish from the Prut River, reflecting differences in environmental stress exposure. Rusinek-Prystupa et al. (2022) reported significant redox parameter variations in fish from lakes with different trophic levels, largely linked to water quality, while El Nahas et al. (2017), and Santana et al. (2022) highlighted that antioxidant enzyme activity can vary in response to pollution from agricultural runoff and pesticide exposure.

Consistent with these studies, our results indicate that environmental conditions significantly influence oxidative stress biomarkers in European perch. Fish exposed to higher environmental stress exhibited elevated antioxidant enzyme activities, likely reflecting responses to pollutants and reduced water quality. Conversely, fish in more stable habitats experienced lower oxidative stress and correspondingly lower antioxidant enzyme activity. These findings suggest that adaptive regulation of antioxidant defenses in fish is closely tied to environmental conditions, with direct implications for ecosystem health and the conservation of fish populations. High MDA levels and antioxidant activities in locations such as Ladik Lake (Samsun), Altınapa Dam (Konya), and Hirfanlı Dam (Kırşehir) point to potential stressors from agricultural runoff, pesticide use, and fertilization (Farombi et al. 2007; Slaninova et al. 2009; Vinagre et al. 2012), whereas lower oxidative stress in Izmir's Ürkmez and Yedikır Dam lakes reflects more stable environmental conditions with reduced anthropogenic impact.

4. Conclusion

The integrated analysis of antioxidant enzyme activities (SOD, CAT, GSH, GSH-Px) and MDA levels reflected habitat-specific oxidative stress, with higher enzymatic activities and lipid peroxidation in populations exposed to potential environmental stressors. Collectively, these findings suggest that environmental pressures not only shape the physiological stress responses but may also interact with genetic structure, highlighting the adaptive mechanisms of *P. fluviatilis* populations. This integrative approach underscores the importance of combining molecular and biochemical assessments for the conservation, management, and ecological evaluation of perch populations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

Author contribution

KA and İD have obtained specimens. KA and İD performed the experiments and analysed the data. KA and İD drafted and revised the manuscript.

Data availability

The datasets generated during or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

The research was approved by the Local Ethics Committee for Aquatic Vertebrate Experiments of Isparta University of Applied Sciences with the decision number 003 dated 22 May 2025 and the number E-90006624-804 -18721.

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