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RESEARCH ARTICLE ARAŞTIRMA MAKALESİ

Seasonal changes in oxidant and antioxidant biomarkers in liver and muscle of common carp (*Cyprinus carpio*) in Atatürk Dam Lake

Atatürk Baraj Gölü'nde yaşayan sazan balığı (*Cyprinus carpio*)'nın karaciğer ve kas dokusunda oksidan ve antioksidan biyobelirteçlerin mevsimsel değişimi

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Abstract: Seasonal investigations were conducted on 640 *Cyprinus carpio* specimens obtained through commercial fishing at four different stations (Gerger, Sitilce, Hosirge, and Samsat) in the Atatürk Dam Lake. MDA (malondialdehyde) levels were measured in the liver and muscle tissues of male and female fish; the results revealed a significant increase in MDA levels at stations exposed to point-source discharge. This indicates that pollution-induced oxidative stress in fish varies significantly across seasonal and regional scales. Among the stations compared, the lowest MDA values were detected in fish tissues from the Gerger station, while the highest values were recorded at the Sitilce and Hosirge stations. Analysis of SOD, GSH-Px, and GSH values across all stations showed that these parameters fluctuated in correlation with MDA levels thereby maintaining the oxidant-antioxidant balance. This study investigated seasonal and spatial variations in oxidative stress biomarkers in common carp (*Cyprinus carpio*) collected from four stations in Atatürk Dam Lake. A total of 640 specimens were analyzed for malondialdehyde (MDA), superoxide dismutase (SOD), glutathione peroxidase (GSH-Px), and reduced glutathione (GSH) levels in liver and muscle tissues. Results showed that MDA levels were significantly higher in fish collected from Sitilce and Hosirge stations, indicating elevated lipid peroxidation associated with point-source pollution. In contrast, the lowest MDA levels were observed at the reference station, Gerger. Antioxidant enzyme activities (SOD, GSH-Px, and GSH) exhibited tissue-, season-, and site-dependent variations, suggesting adaptive responses to oxidative stress. Overall, the findings demonstrate that anthropogenic pressures in Atatürk Dam Lake significantly alter the oxidant–antioxidant balance in fish, highlighting the usefulness of these biomarkers for environmental monitoring.

Keywords: Atatürk Dam Lake, *Cyprinus carpio*, oxidative stress, MDA, antioxidant enzymes, seasonal variation

Öz: Atatürk Baraj Gölü'nde dört farklı istasyondan (Gerger, Sitilce, Hosirge ve Samsat) ticari balıkçılık yoluyla elde edilen 640 adet sazan (*Cyprinus carpio*) örneği üzerinde mevsimsel araştırmalar gerçekleştirilmiştir. Çalışmada, erkek ve dişi bireylerin karaciğer ve kas dokularında malondialdehit (MDA) düzeyleri ölçülmüş; nokta kaynaklı deşarja maruz kalan istasyonlarda MDA düzeylerinde anlamlı bir artış tespit edilmiştir. Bu bulgu, balıklarda kirliliğe bağlı oksidatif stresin mevsimsel ve bölgesel ölçekte önemli farklılıklar gösterdiğini ortaya koymaktadır. İstasyonlar karşılaştırıldığında, en düşük MDA değerleri referans istasyon olan Gerger'de, en yüksek değerler ise Sitilce ve Hosirge istasyonlarında belirlenmiştir. Tüm istasyonlarda süperoksit dismutaz (SOD), glutatyon peroksidaz (GSH-Px) ve glutatyon (GSH) düzeylerinin MDA ile ilişkili biçimde dalgalanarak oksidan-antioksidan dengesinin korunmasına katkıda bulunduğu belirlenmiştir. Antioksidan enzim aktiviteleri (SOD, GSH-Px ve GSH), dokuya, mevsime ve istasyona bağlı farklılıklar göstererek oksidatif strese karşı adaptif bir yanıt sergilemiştir. Sonuç olarak elde edilen bulgular, Atatürk Baraj Gölü'ndeki antropojenik baskıların balıklarda oksidan-antioksidan dengesini önemli ölçüde değiştirdiğini ve bu biyobelirteçlerin çevresel izleme çalışmalarında kullanışlı araçlar olduğunu göstermektedir.

Anahtar kelimeler: Atatürk Baraj Gölü, *Cyprinus carpio*, oksidatif stres, MDA, antioksidan enzimler, mevsimsel değişim

INTRODUCTION

Atatürk Dam Lake, with a surface area of 817 km² and a water volume of approximately 48.7 km³, is the largest reservoir in Türkiye and holds a strategic position for regional inland fisheries and aquaculture Atatürk Dam Lake is the largest reservoir in Türkiye and plays a critical role in inland fisheries and aquaculture. However, increasing agricultural activities and anthropogenic inputs, including domestic and industrial discharges, pose significant risks to aquatic ecosystems. (DSİ,

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2024; EÜAŞ, 2025; Karadağ et al. 2014; Fırat et al. 2025). However, increasing agricultural irrigation activities and anthropogenic pressures from surrounding settlements—including point and non-point pollution sources—pose significant environmental risks that may impact fish populations in the reservoir (Karadede and Ünlü, 2000). In aquatic ecosystems, common carp (*Cyprinus carpio*) is a widely distributed species with high economic importance in both natural stocks and aquaculture. Due to its biological resilience and adaptability, it serves as an ideal model species for the biological monitoring of environmental conditions in large-scale reservoirs (FAO, 2009; Froese and Pauly, 2025).

Exposure to anthropogenic stressors such as agricultural drainage, industrial discharges, and urban wastes can increase the production of reactive oxygen species (ROS), leading to oxidative stress in fish. This process is further modulated by abiotic variables including temperature, dissolved oxygen, and salinity fluctuations (Lushchak, 2011; Valavanidis et al., 2006).

The antioxidant defense system, primarily comprising enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px), plays a vital role in neutralizing ROS and mitigating tissue damage (Valavanidis et al., 2006; Ayala et al., 2014). Monitoring these enzymes alongside malondialdehyde (MDA)—a key marker of lipid peroxidation—provides a robust ecotoxicological approach for assessing water quality and the biological impact of pollutants (Lushchak, 2011).

Despite its ecological and economic significance, comprehensive seasonal data on the oxidative status of *C. carpio* across different regions of Atatürk Dam Lake under varying discharge conditions are lacking. Therefore, this study aims to investigate the impacts of domestic and industrial discharges on the meat quality of common carp (*Cyprinus carpio*) in Atatürk Dam Lake, the largest reservoir on the Euphrates River and in Türkiye. By comparing reference sites with areas exposed to point-source discharges, this research evaluates a chain reaction—encompassing antioxidants and malondialdehyde (MDA)—that may lead to deterioration in meat quality. These parameters were analyzed in relation to seasonal variations, gender, and tissue types (liver and muscle) to determine the extent of oxidative stress and its implications for the regional aquatic ecosystem.

MATERIAL AND METHODS

Study area and fish sampling

The study was conducted at four stations (Gerger, Sitilce, Hosirge, and Samsat) in Atatürk Dam Lake. Fish were collected seasonally by the research team of our institution using gill nets. At each station, 40 individuals (20 females and 20 males) were sampled per season between January and December 2017, yielding a total of 640 common carp (*Cyprinus carpio*) across all stations and seasons. As fish were obtained as dead specimens immediately after capture, no anaesthesia was applied prior to tissue sampling. Sex was determined by macroscopic gonadal inspection. Following collection, liver and muscle tissues were immediately excised and stored at −80°C until biochemical analysis.

Biochemical analyses

Determination of lipid peroxidation (MDA analysis)

MDA levels were determined using the thiobarbituric acid (TBA) method (Placer et al., 1966). In this method, the absorbance of the pink-colored complex formed by the reaction between malondialdehyde (MDA)—a major end-product of lipid peroxidation—and thiobarbituric acid (TBA) was measured spectrophotometrically at 532 nm.

Analysis of antioxidant parameters

To determine the antioxidant status in fish tissues, three different biochemical methods were used:

Glutathione Peroxidase (GSH-Px): GSH-Px activity was determined according to the method of Beutler (1975). This assay is based on measuring the change in absorbance at 340 nm resulting from NADPH oxidation during the conversion of reduced glutathione (GSH) to oxidized glutathione (GSSG).

Glutathione (GSH) Level: The amount of GSH was measured using the method described by Chavan et al. (2005). In this analysis, the absorbance of the yellow-colored complex, formed by the reaction of sulfhydryl groups with 5,5'-dithiobis-2-nitrobenzoic acid (DTNB), was determined spectrophotometrically at 412 nm.

Superoxide Dismutase (SOD): SOD activity was measured using the method of Sun and Oberley (1988). The principle of this method is based on the reduction of nitroblue tetrazolium (NBT) by superoxide radicals generated by the xanthine-xanthine oxidase system. The resulting blue-colored formazan was measured at an absorbance of 560 nm.

Statistical analysis

Data were analyzed using SPSS version 25.0. Normality (Shapiro–Wilk) and homogeneity (Levene's test) were tested prior to analysis. Differences among groups were evaluated using one-way ANOVA followed by Tukey's HSD test. Significance was set at $P < 0.05$.

RESULTS

Biochemical analyses performed on the liver and muscle tissues of common carp (*Cyprinus carpio*) caught from four different stations in Atatürk Dam Lake—Gerger (reference), Sitilce, Hosirge, and Samsat (exposed to point-source discharge) revealed significant differences in oxidant–antioxidant parameters based on both season and station.

Lipid peroxidation (MDA)

MDA levels were significantly higher in individuals from the Sitilce and Hosirge stations, which are exposed to point-source discharges. The highest liver MDA values were recorded at the Sitilce, Hosirge, and Samsat stations for males in spring; at the

Samsat station for females in summer; at both Sitilce and at Hosirge for both sexes in autumn; and at Sitilce for males and Hosirge for females in winter.

For muscle tissue, the highest MDA values were observed at the Sitilce and Hosirge stations for females during the spring and summer. For males, the highest values were found at the Samsat station in the spring, and at the Sitilce and Hosirge stations in the autumn. Overall, MDA levels showed a continuous upward trend in areas exposed to point-source discharge, serving as a robust indicator of oxidative stress in the fish (Table 1).

MDA levels were consistently higher in fish from Sitilce and Hosirge stations compared to the reference station (Gerger). Seasonal variation was evident, with higher values generally observed during spring and autumn. These results indicate increased oxidative stress in areas exposed to pollution.

Superoxide dismutase (SOD)

SOD activities were found to be considerably higher in muscle tissue compared to liver tissue. Specifically, muscle SOD levels peaked at the Samsat station during the summer and autumn seasons for both males and females, and at the Hosirge station during the winter season. In liver tissue, the highest values were recorded at the Samsat station in summer and at the Gerger station in winter for both sexes. These results indicate that SOD plays a vital role as the first line of defense against environmental stress factors (Table 2).

Table 1. Comparison of lipid peroxidation (MDA, nmol/g tissue) levels in the liver (L) and muscle (M) tissues of C. carpio caught in reference (Gerger) and point-source discharge (Sitilce, Hosirge, and Samsat) areas of Atatürk Dam Lake during spring (S), summer (S), autumn (A), and winter (W) seasons, by sex (S) and stations.

Season	Tissue	Sex	Gerger	Sitilce	Hosirge	Samsat	P_i
S	L	♂	198.40±23.41^{c}	513.09±40.68^{b}	527.87±29.70^{ab}	632.97±35.20^{a}	***
		♀	272.41±22.96	322.50±20.90	377.36±33.11	436.57±74.73	-
		p	-	*	**	-	
	M	♂	44.26±5.69^{b}	41.87±4.40^{b}	43.79±6.17^{b}	79.79±2.99^{a}	**
		♀	52.34±1.34^{b}	159.88±11.12^{a}	155.82±21.50^{a}	77.98±3.30^{b}	***
		p	-	***	***	-	
S	L	♂	310.05±52.86	360.38±46.00	383.75±45.93	410.22±55.20	-
		♀	391.10±38.56^{b}	302.10±25.14^{b}	307.07±30.38^{b}	517.19±16.94^{a}	**
		p	-	-	-	-	
	M	♂	35.58±8.56	32.13±1.74	33.23±3.09	43.20±6.28	-
		♀	26.22±1.18^{c}	46.34±0.53^{a}	40.35±6.55^{ab}	30.26±1.98^{bc}	*
		p	**	**	-	-	
A	L	♂	177.92±14.56^{b}	343.18±22.66^{a}	371.38±10.61^{a}	110.03±6.26^{c}	***
		♀	139.25±24.35^{b}	408.78±5.68^{a}	370.93±62.38^{a}	147.25±5.85^{b}	**
		p	-	*	-	*	
	M	♂	35.13±3.45^{b}	68.67±5.42^{a}	74.54±4.05^{a}	41.56±3.82^{b}	***
		♀	41.06±8.72	55.59±4.25	48.89±7.20	44.44±4.80	-
		p	-	-	*	-	
W	L	♂	297.59±42.50^{ab}	434.17±56.19^{a}	311.05±60.00^{ab}	199.17±25.35^{b}	*
		♀	430.49±49.46^{ab}	400.28±48.53^{ab}	514.20±24.92^{a}	318.70±17.52^{b}	-
		p	-	-	*	*	
	M	♂	51.35±10.87	44.37±4.95	62.31±2.49	63.53±3.49	-
		♀	66.72±6.29^{a}	22.17±2.15^{b}	24.25±3.57^{b}	34.42±8.79^{b}	**
		p	-	*	**	*	

Note: ♂: Male, ♀: Female; p: Comparison between sexes within the same station and tissue (independent samples t-test); Pi: Comparison between stations within the same row; different letters (a, b, c) in the same row indicate significant differences between stations (Duncan's multiple range test); -: P > 0.05 (non-significant), *: p < 0.05, **: p < 0.01, ***: p < 0.001.

Table 2. Comparison of superoxide dismutase (SOD-U/g protein) levels in the liver (L) and muscle (M) tissues of C. carpio caught in reference (Gerger) and point-source discharge (Sitilce, Hosirge, and Samsat) areas of Atatürk Dam Lake during spring (S), summer (S), autumn (A), and winter (W) seasons, by sex (S) and stations.

Season	Tissue	Sex	Gerger	Sitilce	Hosirge	Samsat	P_i
S	L	♂	12.72±0.90	10.03±0.63	10.11±0.56	10.28±0.61	-
		♀	14.13±1.07^{a}	8.66±0.34^{b}	9.04±0.45^{b}	12.83±0.29^{a}	**
		p	-	-	-	-	
	M	♂	119.26±8.93^{ab}	93.73±4.13^{b}	85.61±14.53^{b}	131.62±11.00^{a}	*
		♀	152.17±19.88^{a}	76.87±11.75^{b}	73.07±15.72^{b}	132.14±12.66^{a}	*
		p	-	-	-	-	
S	L	♂	12.63±0.27^{b}	10.41±0.30^{c}	10.94±1.03^{bc}	19.34±0.56^{a}	***
		♀	12.78±1.04^{b}	10.95±0.44^{b}	10.79±0.85^{b}	18.26±0.83^{a}	**
		p	-	-	-	-	
	M	♂	244.51±11.07^{b}	140.78±20.49^{c}	137.23±12.18^{c}	319.88±10.05^{a}	***
		♀	120.85±2.53^{b}	142.52±21.34^{b}	145.38±19.85^{b}	306.66±43.88^{a}	**
		p	**	-	-	-	
A	L	♂	12.78±0.94^{b}	15.62±0.50^{a}	15.03±0.32^{ab}	12.78±0.95^{b}	*
		♀	13.31±0.60	12.32±1.06	13.16±0.65	12.93±1.87	-
		p	-	-	-	-	
	M	♂	115.92±12.75^{b}	141.87±5.21^{b}	132.21±9.67^{b}	280.19±19.79^{a}	***
		♀	57.94±9.94^{b}	162.55±6.32^{b}	168.70±7.26^{b}	269.96±17.72^{a}	***
		p	*	-	*	-	
W	L	♂	5.13±0.35^{a}	3.44±0.17^{bc}	4.11±0.30^{b}	2.54±0.24^{c}	***
		♀	4.63±0.66^{a}	3.16±0.10^{b}	2.62±0.22^{b}	2.95±0.39^{b}	*
		p	-	-	*	-	
	M	♂	114.18±9.56^{bc}	74.35±5.06^{c}	222.16±13.34^{a}	141.90±17.44^{b}	***
		♀	136.54±13.85^{b}	47.46±2.38^{c}	182.84±15.72^{a}	140.27±12.16^{b}	***
		p	-	**	-	-	

Note: ♂: Male, ♀: Female; p: Comparison between sexes within the same station and tissue (independent samples T-test); Pi: Comparison between stations within the same row; different letters (a, b, c) in the same row indicate significant differences between stations (Duncan's multiple range test); -: P > 0.05 (Non-significant), *: p < 0.05, **: p < 0.01, ***: p <0.001.

Glutathione peroxidase (GSH-Px)

GSH-Px activities were also found to be higher in muscle tissue compared to liver tissue. In both males and females, the highest liver GSH-Px levels were observed at the Gerger station in spring and at the Samsat station in summer. In the autumn, the highest liver GSH-Px activity was recorded at the Gerger station for females and at the Samsat station for males.

In muscle tissue, high values were observed at the Gerger, Sitilce, and Hosirge stations in spring for both sexes. Specifically, high levels were recorded at Sitilce and Hosirge

for males in summer and autumn; at Gerger and Samsat for females in summer; and at Samsat for females in autumn. In winter, the highest values were found at the Hosirge station for males and at the Gerger, Sitilce, and Samsat stations for females. These results demonstrate that GSH-Px provides a differentiated adaptive response across tissues (Table 3).

Reduced glutathione (GSH)

GSH levels showed a narrower range of variation than the other parameters. In liver tissue, higher GSH values were recorded at the Samsat station for females in spring; at the Gerger station for males; and at the Gerger and Hosirge stations for females in summer. In autumn, the highest values were observed at the Sitilce and Samsat stations for males and at the Gerger station for females. In winter, higher GSH values were recorded at the Samsat station for both sexes. Notably, very high liver GSH levels were detected in female individuals at the Samsat station in winter (6.65±0.67 µmol/g tissue). This suggests that female individuals may exhibit a more robust reduced glutathione response to oxidative stress.

In muscle tissue, high values were observed at the Hosirge station for females in spring and for males in summer. During the winter, high levels were recorded at the Gerger, Sitilce, and Samsat stations for males, and at the Gerger station for females (Table 4).

When the data are evaluated as a whole, it is evident that point-source discharge pressure in Atatürk Dam Lake significantly affects oxidative stress parameters in common carp. The increase in MDA levels, the most critical indicator of lipid peroxidation, reveals the severity of oxidative stress. Antioxidant defense mechanisms such as SOD, GSH-Px, and GSH exhibit variability across seasons and stations. Fluctuations in antioxidant systems were observed in parallel with the increase in MDA, particularly at the Sitilce and Hosirge stations. Notably, significant increases in both SOD and GSH levels were observed at the Samsat station. These findings clearly demonstrate that anthropogenic pressures in Atatürk Dam Lake cause regional and seasonal disruptions in the oxidant–antioxidant balance, thereby impacting fish health.

Table 3. Comparison of glutathione peroxidase (GSH-Px, U/g protein) levels in the liver (L) and muscle (M) tissues of C. carpio caught in reference (Gerger) and point-source discharge (Sitilce, Hosirge, and Samsat) areas of Atatürk Dam Lake during spring (S), summer (S), autumn (A), and winter (W) seasons, by sex (S) and stations.

Season	Tissue	Sex	Gerger	Sitilce	Hosirge	Samsat	P_i
S	L	♂	1.23±0.16^{a}	0.36±0.04^{b}	0.36±0.07^{b}	0.49±0.01^{b}	***
		♀	1.04±0.07^{a}	0.57±0.04^{b}	0.54±0.05^{b}	0.71±0.05^{b}	**
		p	-	*	-	*	
	M	♂	24.97±1.26^{b}	23.75±0.86^{b}	26.03±0.41^{b}	16.25±2.67^{a}	**
		♀	24.31±0.64^{b}	25.13±0.66^{b}	25.38±1.38^{b}	18.08±0.09^{a}	**
		p	-	-	-	-	
S	L	♂	1.95±0.05^{ab}	1.63±0.04^{bc}	1.55±0.13^{c}	2.18±0.15^{a}	*
		♀	1.32±0.14	1.23±0.07	1.36±0.20	1.74±0.34	-
		p	*	**	-	-	
	M	♂	15.29±0.20^{b}	23.39±0.67^{a}	24.23±0.82^{a}	17.74±1.44^{b}	***
		♀	18.44±0.64^{a}	12.25±0.75^{b}	12.99±0.49^{b}	20.02±2.11^{a}	**
		p	**	***	***	-	
A	L	♂	0.64±0.04^{a}	1.76±0.05^{b}	1.72±0.09^{b}	2.00±0.015^{b}	***
		♀	3.61±0.42^{a}	1.59±0.04^{b}	1.60±0.02^{b}	1.69±0.04^{b}	***
		p	***	-	-	-	
	M	♂	18.28±1.16^{c}	26.12±1.35^{a}	27.80±0.64^{a}	22.72±0.19^{b}	**
		♀	16.19±1.31^{b}	18.24±1.17^{b}	18.61±1.26^{b}	25.87±1.00^{a}	**
		p	-	*	**	*	
W	L	♂	1.66±0.13^{a}	1.00±0.07^{b}	1.88±0.12^{a}	1.45±0.17^{a}	**
		♀	1.66±0.19^{a}	0.94±0.07^{c}	1.53±0.13^{ab}	1.16±0.11^{bc}	*
		p	-	-	-	-	
	M	♂	7.60±0.56^{c}	6.60±0.37^{c}	12.43±0.63^{a}	9.94±0.25^{b}	***
		♀	11.94±0.59^{a}	13.40±1.26^{a}	8.31±0.58^{b}	12.96±1.37^{a}	*
		p	**	**	**	-	

Note: ♂: Male, ♀: Female; p: Comparison between sexes within the same station and tissue (independent samples T-test); Pi: Comparison between stations within the same row; different letters (a, b, c) in the same row indicate significant differences between stations (duncan's multiple range test); -: P > 0.05 (Non-significant), *: p < 0.05, **: p < 0.01, ***: p <0.001.

Table 4. Comparison of reduced glutathione (GSH, µmol/g tissue) levels in the liver (L) and muscle (M) tissues of C. carpio caught in reference (Gerger) and point-source discharge (Sitilce, Hosirge, and Samsat) areas of Atatürk Dam Lake during spring (S), summer (S), autumn (A), and winter (W) seasons, by sex (S) and stations.

Season	Tissue	Sex	Gerger	Sitilce	Hosirge	Samsat	P_i
S	L	♂	1.56±0.06	1.54±0.09	2.12±0.27	1.47±0.11	-
		♀	2.15±0.28	1.77±0.13	1.72±0.10	2.36±0.27	-
		p	-	-	-	*	
	M	♂	1.24±0.01	1.25±0.06	1.27±0.01	1.20±0.01	-
		♀	1.23±0.01bc	1.25±0.02b	1.36±0.03a	1.18±0.01c	**
		p	-	-	-	-	
S	L	♂	2.37±0.35a	1.39±0.05b	1.39±0.09b	1.45±0.03b	*
		♀	2.26±0.14a	1.63±0.07b	2.41±0.10a	1.75±0.07b	**
		p	-	-	**	*	
	M	♂	1.22±0.03b	1.26±0.01b	1.46±0.04a	1.27±0.09b	*
		♀	1.24±0.06	1.24±0.04	1.38±0.05	1.20±0.01	-
		p	-	-	-	-	
A	L	♂	1.53±0.05b	2.17±0.15a	1.43±0.07b	2.44±0.06a	***
		♀	3.25±0.21a	1.91±0.09b	1.68±0.17b	1.99±0.16b	**
		p	**	-	-	*	
	M	♂	1.32±0.06	1.30±0.01	1.66±0.14	1.39±0.10	-
		♀	1.26±0.01	1.42±0.03	1.28±0.01	1.48±0.16	-
		p	-	-	-	-	
W	L	♂	2.23±0.05b	2.14±0.06b	1.87±0.06b	3.16±0.40a	*
		♀	2.04±0.10b	3.01±0.41b	3.47±0.23b	6.65±0.67a	***
		p	-	-	**	*	
	M	♂	1.61±0.02a	1.58±0.05a	1.25±0.00b	1.51±0.07a	*
		♀	1.71±0.02a	1.44±0.04b	1.28±0.00c	1.48±0.01b	***
		p	*	-	-	-	

Note: ♂: Male, ♀: Female; p: Comparison between sexes within the same station and tissue (independent samples T-test); Pi: Comparison between stations within the same row; different letters (a, b, c) in the same row indicate significant differences between stations (duncan's multiple range test); -: P > 0.05 (Non-significant), *: p < 0.05, **: p < 0.01, ***: p <0.001.

DISCUSSION

In this study, oxidative stress parameters (MDA, SOD, GSH-Px, GSH) in liver and muscle tissues of *Cyprinus carpio* individuals caught at different stations in Atatürk Dam Lake were evaluated seasonally. The findings reveal that the oxidant-antioxidant balance is markedly disrupted at stations exposed to point-source discharges. This suggests that aquatic organisms in areas under point-source pollution pressure inevitably encounter reactive oxygen species (ROS) production, which triggers biochemically relevant responses associated with cellular damage. MDA levels, an indicator of lipid peroxidation, were found to be statistically significantly elevated at Sitilce and Hoşirge stations compared to the reference station Gerger. This difference should not be interpreted merely as a numerical increase, but as a biologically critical finding reflecting the capacity of certain pollutants to damage cell membrane phospholipids. Karadağ et al. (2014) and Fırat et al. (2018) similarly reported elevated MDA levels in areas with high pollution loads in Atatürk Dam Lake. Consistent with these data, the fact that MDA accumulation in the present study was particularly pronounced at Sitilce station — characterized by untreated urban and agricultural wastewater discharges — indicates that these pollutants contain potent pro-oxidative compounds.

Karadağ et al. (2014) reported that catalase (CAT) and MDA levels were statistically significantly elevated in fish caught at Sitilce station compared to Samsat station, while SOD activity and GSH levels were reduced. These findings are consistent with the general trend of results obtained in the present study and indicate that pollution pressure in this region has persisted over the years. Nevertheless, the fact that the present study was conducted within a seasonal design encompassing both liver and muscle tissues and multiple stations provides a significant methodological advantage over previous studies. They also examined the relationship between MDA and SOD activities across different freshwater pollution gradients, demonstrating that antioxidant defense capacity may become exhausted under high pollution loads.

Fırat and Kılınç (2022) demonstrated that heavy metals (Pb, Cd, Cr) accumulated in the liver, muscle, and gill tissues of *Cyprinus carpio* in Atatürk Dam Lake, and that this accumulation showed a strong association with oxidative stress markers. In this context, it should be considered that the MDA increases observed in the present study may be related not only to organic pollutants but also to possible metal accumulation; future studies are recommended to jointly evaluate oxidative stress parameters alongside tissue metal concentrations. The high SOD activity in muscle tissue indicates that this tissue exhibits a more active and adaptive response against oxidative damage. Indeed, Jiao et al. (2019) reported that SOD, GSH, and total antioxidant capacity decreased while MDA markedly increased in the gills of *Cyprinus carpio* exposed to the organophosphate insecticide chlorpyrifos. These tissue-level differential responses clearly demonstrate the existence of tissue- and organ-dependent defense strategies in the organism against environmental toxin exposure. The marked increase in SOD levels during summer and autumn at Samsat station — in both male and female individuals — suggests that environmental conditions specific to these periods, such as elevated water temperature, low dissolved oxygen, and increased pollutant exposure, collectively generate cumulative oxidative pressure, to which fish respond with an adaptive reaction. Seasonal thermal stratification during summer in dam lakes in inland Turkey leads to the development of anoxic conditions in surface waters, which increases ROS production and stimulates antioxidant defense. Islam et al. (2022) reported that antioxidant enzymes such as SOD and CAT are strongly induced in fish exposed to extreme temperatures, particularly when the thermal stress threshold is exceeded, and emphasized that when the activation of this response is converted into prolonged suppression, it may lead to oxidative damage. Vinagre et al. (2012), in their study on *Dicentrarchus labrax*, demonstrated that CAT and MDA levels increased under both extreme temperature conditions outside the optimal thermal range, revealing that ROS regulation is disrupted beyond the optimal temperature range. It may be argued that the seasonal SOD fluctuations observed in the present study reflect the combined effect of both pollution pressure and seasonal temperature changes.

Sakuragui et al. (2013) reported that the increase in SOD activity in the gills and liver of fish exposed to various pollutants represents a compensatory response aimed at neutralizing intracellular superoxide radicals, and demonstrated that this response also activates downstream enzymes such as catalase and GSH-Px over the long term. Huang et al. (2007) reported that SOD and GST activities increased while GPx activity decreased in *Cyprinus carpio* samples collected from the Yellow River at polluted stations, emphasizing that this reflects the hierarchical and tissue-dependent functioning of the antioxidant system. The tissue- and season-dependent fluctuations in GSH-Px activity clearly demonstrate that fish exhibit different adaptive responses to environmental conditions. The extremely high GSH-Px activity observed in female individuals at Gerger station during autumn indicates that even under relatively lower pollution loads in this region, gonadal activation and reproductive physiology may enhance antioxidant defense capacity. Indeed, the high metabolic rate associated with the reproductive period in teleost fish increases the amount of ROS leaking from the mitochondrial electron transport chain, thereby creating the basis for a robust antioxidant response. Grădinariu et al. (2025) emphasized that antioxidant enzyme activities in fish exposed to pharmaceutical pollutants exhibit marked sex- and tissue-dependent differences, and reported that considering the sex variable in such studies is essential. The findings of the present study support this recommendation.

Grădinariu et al. (2025) and Perussolo et al. (2023) emphasized that GSH-Px fluctuations observed in different tissues and sexes reveal that the mechanism of action of

pollutants varies depending on dose, tissue, and sex. In this context, the high GSH-Px variability observed across different stations and seasons in the present study demonstrates that explaining all environmental stress with a single parameter is insufficient and that biomarker panels need to be interpreted through a holistic approach. The markedly elevated GSH levels in female individuals at Samsat station during winter is a noteworthy and biologically critical finding. Reduced glutathione (GSH) is a versatile non-enzymatic antioxidant that maintains cellular redox balance and directly neutralizes ROS and electrophilic compounds. The observation of higher GSH accumulation in female individuals takes on meaningful biological significance when considered in light of the fact that estrogen is known to stimulate GSH biosynthesis and the expression of key enzymes such as glutamate-cysteine ligase (GCL) and glutathione peroxidase (GPx). Liang et al. (2011) demonstrated that GSH biosynthetic capacity in female rat livers was markedly higher than in males, suggesting that this sex-specific difference originates from estrogen-mediated GCL activation mechanisms.

Seasonal fluctuations in GSH levels may be associated not only with pollution pressure but also with environmental factors such as water temperature, photoperiod, and reproductive cycle. Chainy et al. (2016) presented a comprehensive review of antioxidant defense systems in aquatic invertebrates and vertebrates under different seasonal conditions, reporting that seasonal GSH changes in fish originate from the interaction of both pollution and reproductive physiology. Abdallah et al. (2024) demonstrate that antioxidant biomarkers in freshwater fish are reliable indicators for assessing environmental stress. The differences in oxidative stress profiles between liver and muscle tissues reflect the distinctive nature of the biological strategies these two organs have developed against pollutants. The liver simultaneously produces large amounts of ROS while performing the biotransformation of exogenous compounds via the cytochrome P450 isoenzyme system, leading to the chronic strain of hepatic antioxidant capacity. Indeed, a study conducted on *Cyprinus carpio* samples collected from the Yellow River in China reported that pollutants caused marked oxidative damage in the hepatopancreas, kidney, and intestine. In contrast, although muscle tissue is not the primary detoxification organ, it functions as a site of pollutant accumulation and may exhibit oxidative imbalance, particularly during chronic exposure. In this study, the finding that SOD activities were higher in muscle tissue than in liver suggests that muscle cells keep ROS flux under more active control. The seasonal data obtained in our study indicate that there are marked increases in antioxidant parameters at certain stations during autumn and winter. This demonstrates that low water temperatures may also contribute to oxidative stress. Indeed, Lv et al. (2021) reported that SOD, CAT, GSH-Px, and MDA levels markedly increased in the intestine, liver, and muscle tissues of large yellow croaker exposed to low temperatures, stating that these results reflect enhanced oxidative defense under cold stress conditions. How thermal stress shapes the oxidative response was also addressed in detail in an environmental science review published within the scope of Menon et al. (2023), drawing attention to the complex interactions of physicochemical factors such as water temperature, pH, dissolved oxygen, and salinity on antioxidant enzyme activities.

In recent years, biomarker-based environmental monitoring studies have been increasingly preferred over purely chemical analyses for revealing biological effects at the ecosystem level. Abdallah et al. (2024), in a comprehensive study addressing the reliability and interpretability of antioxidant biomarkers in freshwater fish, demonstrated that these markers serve as powerful tools for environmental policy and water quality management. The multi-parametric, multi-seasonal, and tissue-sex differentiated integrated design of the present study supports this perspective; it is anticipated that integrating histopathology, genotoxicity, and metal bioaccumulation data with this biomarker framework in future studies will substantially strengthen the monitoring capacity of the dam lake.

CONCLUSION

In this study, the analysis of MDA, SOD, GSH-Px, and GSH parameters in *Cyprinus carpio* individuals caught from Atatürk Dam Lake clearly demonstrates that point-source discharge pressures increase oxidative stress in fish. The elevated MDA levels at the Sitilce and Hosirge stations confirm that lipid peroxidation is a reliable indicator of pollution-induced stress. Furthermore, the variations in SOD, GSH-Px, and GSH activities indicate that the defense mechanisms of the fish develop differentiated responses across various tissues.

In conclusion, anthropogenic pressures in Atatürk Dam Lake disrupt the oxidant–antioxidant balance of the fish. Therefore, the oxidative stress biomarkers used in *Cyprinus carpio* individuals can be evaluated as effective tools for monitoring the pollution load in the lake ecosystem and ensuring the protection of fish health.

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AUTHORSHIP CONTRIBUTIONS

Ayşe Gül Şahin managed the organization of study systems, conducted fish species and age determination, and carried out the monitoring, evaluation of all analytical data, and manuscript writing. Özden Barım Öz, Semra Türkoğlu, Fulya Benzer, and Mine Erişir performed the determination of antioxidant enzymes and supported the validation of analytical data. Rıdvan Tepe provided significant contributions to both field and laboratory

studies. Hülya Şahin and Nurten Özbey contributed to the laboratory studies and performed the analyses. Tunay Şeker performed fish species and age determination. Tacettin Yıldırım, Mehmet Küçükyılmaz, and Gürel Nedim Örnekçi carried out the collection of water and fish samples.

CONFLICT OF INTEREST

The authors assert that they have no conflicts of interest.

ETHICAL APPROVAL

This study was conducted in accordance with the principles outlined in the Directive of the Animal Experiments Local Ethics Committee of the Elazığ Veterinary Control Institute, affiliated with the Ministry of Food, Agriculture and Livestock of the Republic of Türkiye. Ethical approval for the study, titled "Effect of Heavy Metal Pollution in Keban, Karakaya, and Atatürk Dam Lakes on Biochemical Parameters and Meat Quality of Some Fish Species" , was granted by the committee on 20 September 2016 (Decision No: 16/02).

DECLARATION OF AI USE

We did not use AI-assisted technologies to create this article.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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