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IMPACT OF POLLUTANTS ON THE GILL APPARATUS OF FISH IN THE ILI-BALKHASH BASIN

The article was written as part of the Ministry of Science and Higher Education of the Republic of Kazakhstan's project AP 23486220, titled "Study of the important organ systems reactivity in the main commercial fish species of the Ile-Balkhash basin under anthropogenic load." (2024-2026). The ecological condition of the Ili-Balkhash Basin raises serious concerns due to increasing anthropogenic pressure, accompanied by the influx of heavy metals, pesticides, and other organic pollutants into water bodies. Fish gills, as a highly sensitive organ of external respiration, serve as a reliable bioindicator of water toxicity. As part of this study, morphological and histological analyses of the gill apparatus were conducted on three commercially important fish species – *Cyprinus carpio*, *Abramis brama*, and *Sander lucioperca* – caught in different areas of the Ili-Balkhash Basin. In fish inhabiting zones with elevated pollutant concentrations, pronounced pathological changes in gill tissue were observed, including epithelial hyperplasia, lamellar fusion, destruction of the capillary network, and inflammatory infiltration. The severity of these alterations correlated with the level of aquatic pollution. *Cyprinus carpio* demonstrated the highest sensitivity to pollutants, whereas *Sander lucioperca* showed relative resistance. The findings indicate a significant impact of waterborne pollutants on the morphofunctional condition of the gill apparatus, and consequently, on the viability and productivity of fish populations. These results highlight the urgent need for regular ecological monitoring and the implementation of protective measures to preserve the aquatic ecosystem of the Ili-Balkhash Basin, safeguard biodiversity, and ensure sustainable fisheries.

Keywords: Ili-Balkhash Basin, aquatic pollutants, gill pathologies, *Cyprinus carpio*, *Abramis brama*, *Sander lucioperca*, histomorphology.

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Іле-Балқаш бассейніндегі балықтардың желбезек аппаратына ластағыш заттардың әсері

Мақала Қазақстан Республикасы Ғылым және жоғары білім министрлігінің AP23486220 «Антропогендік жүктеме жағдайында Іле-Балқаш бассейнінің негізгі кәсіпшілік балық түрлерінің маңызды орган жүйелерінің реактивтілігін зерттеу» жобасы (2024-2026 жж.) аясында жазылған. Іле-Балқаш бассейнінің экологиялық жағдайы антропогендік әсердің күшеюіне, соның ішінде ауыр металдардың, пестицидтердің және басқа да органикалық ластағыштардың су айдындарына түсуіне байланысты айтарлықтай алаңдаушылық тудырады. Балықтың желбезектері, сыртқы тыныс алудың өте сезімтал мүшесі ретінде, судың улылығының сенімді биоиндикаторы. Осы зерттеу аясында Іле-Балқаш бассейнінің әртүрлі аймақтарында ауланған үш кәсіптік балық түрінің – *Cyprinus carpio*, *Abramis brama* және *Sander lucioperca* желбезек аппаратына морфологиялық және гистологиялық талдау жүргізілді. Ластаушы заттардың концентрациясы жоғары аймақтарда мекендеген балықтарда эпителий гиперплазиясы, желбезек жапырақшаларының бірігуі, капиллярлық желінің бұзылуы және қабыну инфильтрациясы түріндегі желбезек тінінің айқын патологиялық өзгерістері тіркелді. Бұзылулардың айқындығы су ортасының ластану деңгейімен өзара байланысты болды. Ластаушы заттарға ең жоғары сезімталдықты *C. carpio* көрсетсе, ал *S. lucioperca* салыстырмалы түрде тұрақтылық танытты. Алынған деректер су ластағыштарының желбезек аппаратының морфофункционалдық жағдайына, тиісінше, балық популяцияларының тіршілік қабілеттілігі мен өнімділігіне айтарлықтай әсер ететінін көрсетеді. Нәтижелер биоәртүрлілікті сақтау және тұрақты балық аулауды қамтамасыз ету үшін Іле-Балқаш

экожүйесін үнемі экологиялық бақылаудың және қорғау шараларын қабылдаудың қажеттілігін айқындайды.

Түйін сөздер: Іле-Балқаш бассейні, ластағыштар, желбезек патологиялары, *Cyprinus carpio*, *Abramis brama*, *Sander lucioperca*, гистоморфология.

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Влияние поллютантов на жаберный аппарат рыб Или-Балхашского бассейна

Статья написана в рамках проекта Министерства науки и высшего образования РК AP23486220 «Изучение реактивности важнейших систем органов основных промысловых видов рыб Иле-Балхашского бассейна в условиях антропогенной нагрузки» (2024–2026 годы). Экологическое состояние Или-Балхашского бассейна вызывает серьёзную обеспокоенность в связи с нарастающим антропогенным воздействием, сопровождающимся поступлением в водоёмы тяжёлых металлов, пестицидов и других органических загрязнителей. Жабры рыб, как высокочувствительный орган внешнего дыхания, являются надёжным биоиндикатором водной токсичности. В рамках данного исследования проведён морфологический и гистологический анализ жаберного аппарата у трёх промысловых видов рыб – *Cyprinus carpio*, *Abramis brama* и *Sander lucioperca*, выловленных в различных участках Или-Балхашского бассейна. У рыб, обитавших в зонах с повышенной концентрацией поллютантов, зафиксированы выраженные патологические изменения жаберной ткани в виде гиперплазии эпителия, слияние лепестков, деструкции капиллярной сети и воспалительной инфильтрации. Выраженность нарушений коррелировала с уровнем загрязнения водной среды. Наибольшую чувствительность к поллютантам продемонстрировал *C. carpio*, тогда как *S. lucioperca* проявил относительную устойчивость. Полученные данные свидетельствуют о значительном влиянии водных загрязнителей на морфофункциональное состояние жаберного аппарата и, соответственно, на жизнеспособность и продуктивность рыбных популяций. Результаты подчёркивают необходимость регулярного экологического мониторинга и принятия мер по охране водной экосистемы Или-Балхашского бассейна для сохранения биоразнообразия и обеспечения устойчивого рыболовства.

Ключевые слова: Или-Балхашский бассейн, водные поллютанты, патология жабр, *Cyprinus carpio*, *Abramis brama*, *Sander lucioperca*, гистоморфология.

Introduction

The Ili-Balkhash Basin represents one of the largest aquatic ecosystems in Kazakhstan, serving as a critical determinant in sustaining regional biodiversity, securing freshwater supply for human populations, and underpinning the development of commercial fisheries [1-3]. In recent decades, the aquatic ecosystems of the basin have been subjected to a steadily increasing anthropogenic pressure, driven by intensive industrial, agricultural, and municipal activities. This has resulted in the influx of a wide spectrum of pollutants into the aquatic environment, including heavy metals, petroleum hydrocarbons, pesticides, and other xenobiotics, which are capable of inducing severe morphofunctional impairments in aquatic organisms [4]. The results of studies on the content and distribution of heavy metals in the tissues and organs of fish inhabiting Lake Balkhash indicate that zinc is among the primary bioaccumulators in fish organisms, with a tendency for preferential accumulation in the liver and gills. These organs are particularly vulnerable to toxicant exposure due to their physiological activity. The extent of accumulation is determined by the degree of environmental contamination, the trophic type of fish, the chemical properties of the metals, and their migratory potential. Variations in accumulation patterns reflect adaptive mechanisms and the relative resistance of different species to pollutant exposure, which is of particular importance for assessing the status of fish resources and for developing conservation strategies for the aquatic ecosystem of the Ili-Balkhash region [5, 6]. According to the chemical analysis of surface waters, several sites demonstrated concentrations of heavy metals exceeding the maximum permissible limits established for fisheries water bodies [7]. Histological investigations conducted by the authors revealed pronounced destructive alterations in the organs of fish inhabiting the most contaminated locations. These alterations included degenerative and dystrophic processes in

the gills, liver, and kidneys, indicating a high toxic burden on aquatic organisms [8]. Of particular concern is the impact of pollution on key commercial fish species of the Ili-Balkhash Basin, such as *Cyprinus carpio*, *Abramis brama*, and *Sander lucioperca*, which play a crucial role in the fisheries sector and regional food security [9]. The gill apparatus, being in direct contact with the aquatic environment, not only performs gas exchange but also participates in ion regulation, osmoregulation, and excretion, making it one of the most sensitive indicators of xenobiotic exposure in aquatic ecosystems [10].

The results of numerous studies indicate that exposure to toxic substances in fish may lead to morphofunctional alterations of the gill epithelium, including hyperplasia, lamellar fusion, disruption of the capillary network, and inflammatory responses [11-13]. Nevertheless, data regarding the extent and specificity of such alterations in commercially important fish species of the Ili-Balkhash Basin remain limited, fragmented, and insufficient to provide a comprehensive understanding of pollutant impacts at the ecosystem level.

Given the current level of anthropogenic pressure on the Ili River and Lake Balkhash, there is an urgent need for integrated morphofunctional and histopathological investigations of the gill apparatus in the most ecologically and economically significant fish species. Such studies not only provide an objective assessment of the toxic effects of aquatic pollutants but also form the basis for developing bioindicator criteria within ecological monitoring frameworks. The findings may be applied to the formulation of conservation strategies, the restoration of commercially valuable fish populations, and the sustainable management of fisheries resources in the region.

The aim of the present study was to perform a comparative analysis of morphological and histopathological alterations in the gill apparatus of the major commercial fish species *Cyprinus carpio*, *Abramis brama*, and *Sander lucioperca* under the influence of aquatic pollutants in the Ili-Balkhash Basin. The study further sought to assess the species-specific sensitivity of these fish to water contamination, with the ultimate goal of applying the obtained data in bioindication systems for evaluating the ecological status of aquatic ecosystems in the region.

Materials and methods

Field and laboratory studies were conducted in 2024 in various parts of the Ili-Balkhash basin, which are characterized by different levels of anthropogenic impact. The research objects were three commercial fish species: *Cyprinus carpio*, *Abramis brama*, and *Sander lucioperca*. The fish were caught using nets according to standard methods and then underwent biometric processing. For histological analysis, gill arches were removed, fixed in 10% neutral formalin, and embedded in paraffin. Serial sections were stained with hematoxylin and eosin for subsequent microscopic examination.

Concurrently with the collection of biological material, surface water samples were taken to assess the level of pollution. The water samples were analyzed for heavy metal content using atomic absorption spectrometry. All obtained data were statistically processed, including the use of the Student's t-test to evaluate the significance of differences between groups. The results are presented as the mean value with the standard deviation.

Results and discussion

Morphological and histological analysis of the gill apparatus of *Cyprinus carpio* collected from different sites of the Ili-Balkhash Basin revealed significant differences between specimens from polluted and conditionally clean (control) areas. Fish inhabiting water bodies with elevated concentrations of contaminants exhibited pronounced pathological alterations in gill structure, whereas individuals from control sites showed either no abnormalities or only minor deviations. At the histological level, specimens from polluted areas demonstrated hyperplasia of the primary gill epithelium in the region of the gill lamellae, accompanied by destruction of the secondary epithelium, indicative of a compensatory tissue response to chronic toxicant exposure (Fig. 1). Additionally, edematous changes were observed in both primary and secondary epithelial layers, pointing to disrupted osmotic balance and increased vascular wall permeability.

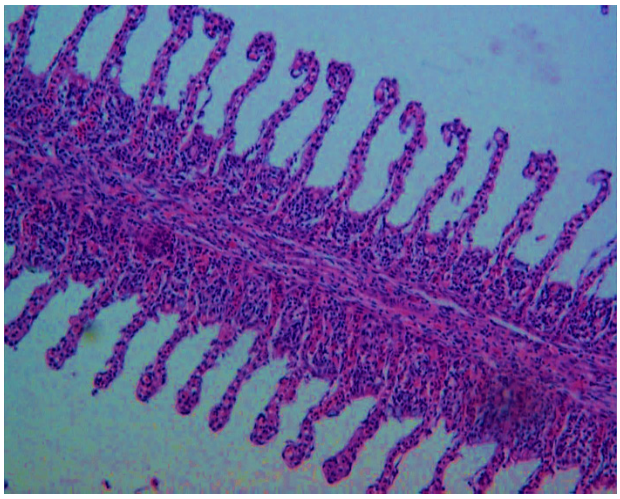


Figure 1 – Gills of *Cyprinus carpio*. Gill filament with arising lamellae. Edema of the primary and secondary epithelium, deformation of lamellae. Staining: hematoxylin and eosin, ×200.

In several cases, pronounced destructive alterations of the gill lamellae were observed, including necrosis of the respiratory cells of the secondary epithelium, their subsequent desquamation, disintegration of the vascular layer with the formation of hemorrhages, as well as deformation of individual lamellae (Fig. 2).

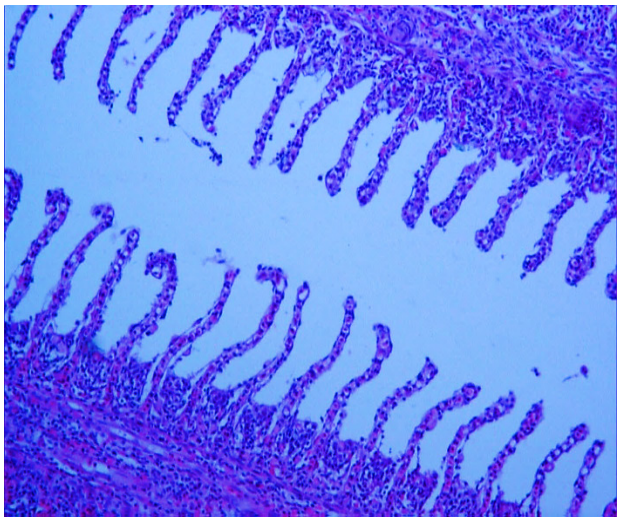


Figure 2 – Gills of *Cyprinus carpio*. Edema of the secondary epithelium, presence of mucous and rod-shaped cells in the lamellae. Staining: hematoxylin and eosin, ×200.

The most severe lesions comprised hyperplasia of the secondary gill lamellar epithelium, fusion of gill filaments, subepithelial edema, and partial destruction of the capillary network (Fig. 3). In some specimens, signs of necrosis and inflammatory infiltration were detected, indicating chronic inflammation and an immune response to the presence of toxic substances. Concentrations of heavy metals (Zn, Cu, Pb) in the studied water bodies exceeded the maximum permissible levels by 2–3 times, which is likely the main factor underlying the observed alterations.

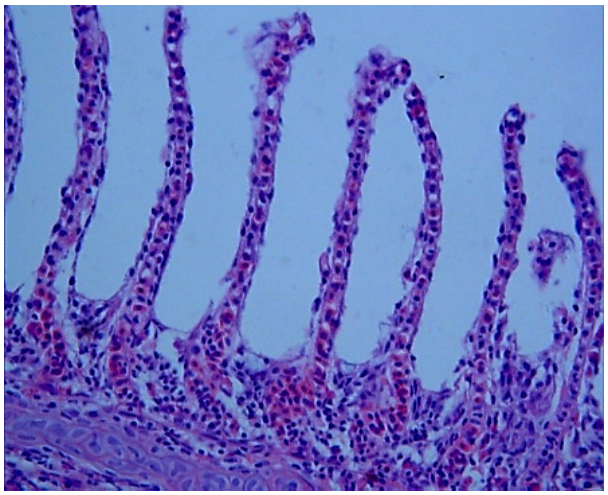


Figure 3 – Gills of *Cyprinus carpio*. Necrosis of respiratory cells of the secondary epithelium, hyperplasia of the primary epithelium. Staining: hematoxylin and eosin, ×400.

Thus, the results of the study demonstrate the high sensitivity of the gill apparatus of *Cyprinus carpio* to anthropogenic pollution of the aquatic environment, particularly to the action of heavy metals. Morphological and histological changes in the gills impair their respiratory and osmoregulatory functions, thereby reducing the overall resistance of the organism to external stressors. The findings confirm that gills, as organs directly interacting with the environment, can be considered reliable bioindicators of the ecological status of aquatic habitats. These data highlight the need for regular environmental monitoring and the implementation of measures aimed at reducing pollution levels in freshwater ecosystems.

In the gills of the examined *Cyprinus carpio* specimens, pathomorphological changes reflecting both compensatory-adaptive and destructive processes were identified. The compensatory-adaptive responses were manifested by a marked increase in the number of mucous and rod-shaped cells within the primary gill epithelium, as well as their occurrence in the lamellar epithelium.

The results of the analysis of heavy metal concentrations in water samples from different sites of the Ili-Balkhash Basin (mg/dm³) are presented in Table 1, which shows the mean concentrations of Zn, Cu, Pb, and Cd determined in samples collected from three sites characterized by varying levels of anthropogenic pressure: Site 1 – conditionally clean zone (low pollution), Site 2 – moderately polluted zone, and Site 3 – highly polluted zone.

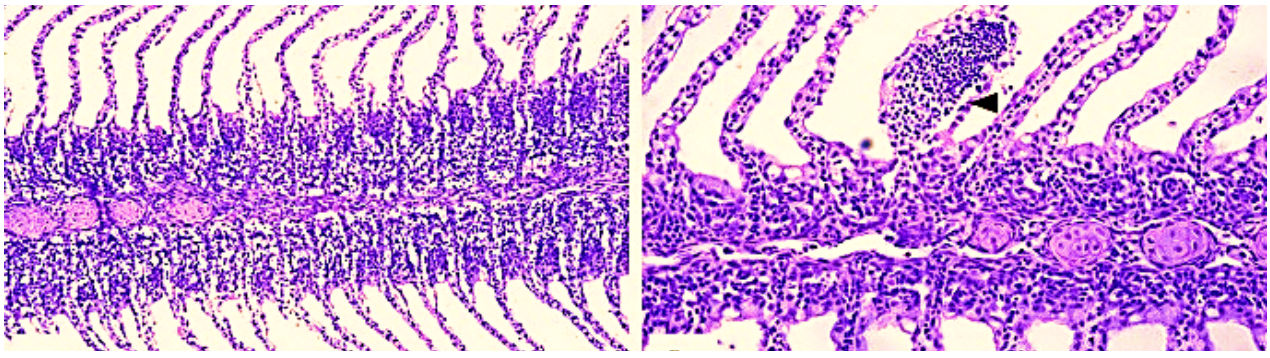
The analysis indicates that at Site 1, the concentrations of all studied metals were within the permissible limits. At Site 2, exceedances of MPC were recorded for cadmium (0.0015 mg/dm³ at MPC 0.001), suggesting moderate pollution. The concentration of copper (0.04 mg/dm³) was within the permissible limits, but close to the MPC (0.05 mg/dm³). At Site 3, the concentrations of all metals, except copper, exceeded the regulatory limits: zinc (0.35 mg/dm³) exceeded MPC by 3.5 times, lead (0.015 mg/dm³) by 1.5 times, and cadmium (0.003 mg/dm³) by 3 times.

The data confirm a high level of heavy metal contamination in the aquatic environment at Site 3. The obtained results demonstrate considerable variability in the chemical composition of water across the basin, which was taken into account when assessing the ecological status of water bodies and the histopathological alterations in aquatic organisms. Exceedances of MPC values for zinc, cadmium, and lead in the most polluted zone were associated with pronounced histological impairments of the gill apparatus in the studied fish species, particularly in *Cyprinus carpio*.

Table 1 – Concentrations of heavy metals in water samples from various sites of the Ili-Balkhash Basin, mg/dm³

Metal	Site 1 (low pollution)	Site 2 (moderate pollution)	Site 3 (high pollution)	MPC (mg/dm³)
Zn	0.05	0.15	0.35	0.10
Cu	0.01	0.04	0.12	0.05
Pb	0.002	0.006	0.015	0.01
Cd	0.0005	0.0015	0.003	0.001

Morphological changes in the gills of *Abramis brama* inhabiting the zone of intense anthropogenic pollution were characterized by severe pathological alterations of gill structure (Fig. 4A, B). These included epithelial hyperplasia, fusion of gill lamellae, intercellular edema, destruction of the epithelial layer, and the presence of inflammatory infiltrates. In certain areas, tissue necrosis and vascular changes were observed, indicating both destructive and adaptive responses.



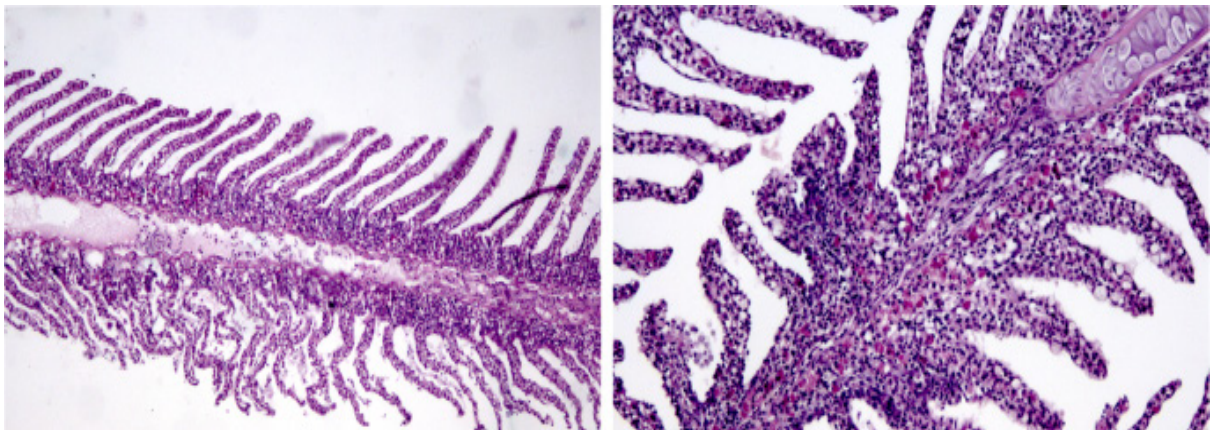
A B

Figure 4 – Histopathological changes in the gills of *Abramis brama* from a highly polluted area. Staining: hematoxylin and eosin, A×100, B×200

The histological alterations observed in the gill apparatus of the studied fish species represent characteristic morphological manifestations of chronic exposure to toxicants and aquatic pollutants. These changes included hyperplasia, thickening of the epithelial layer, edema, vascular impairments, and inflammatory infiltration–typical indicators of disrupted tissue homeostasis under the influence of contaminants, particularly heavy metals. Pronounced histopathological changes in the gills were recorded, such as epithelial thickening, detachment, and localized necrotic foci. The damage was found to be less severe than in *Cyprinus carpio*, although still indicative of significant physiological stress. Such alterations may substantially reduce the efficiency of gas exchange, compromise the immune defense system, and diminish the adaptive potential of the species under deteriorating environmental conditions. This suggests a limited, yet present, resilience of *Abramis brama* to long-term pollutant exposure, which is important to consider in bioecological assessments of population status.

In contrast to the other species, *Sander lucioperca* demonstrated a higher resistance to pollutants. While its gill apparatus largely retained a well-organized structure, certain deviations from the norm were detected even at high levels of environmental contamination. These changes, indicating chronic toxic stress, included thickening of the secondary epithelium due to cell hyperplasia and hypertrophy, lamellar fusion, and epithelial lifting, as well as the formation of subepithelial edema and telangiectasia (vascular dilation). Signs of venous congestion and inflammatory infiltration were also observed, and in severe cases, epithelial necrotic foci were recorded, indicative of irreversible tissue damage. These morphofunctional disorders show that even relatively tolerant species such as *Sander lucioperca* exhibit pathological responses under conditions of critical contamination. However, the severity of these changes was substantially lower compared to common carp and bream, confirming its relative resistance to pollutants and potential suitability for fisheries use under moderate ecological stress. The histopathology of the gill apparatus in pikeperch can thus serve as a reliable tool for biomonitoring aquatic ecosystem health and assessing water quality.

Overall, the degree of histopathological alterations in the gill apparatus of fish from different areas of the Ili-Balkhash Basin correlated directly with the level of heavy metal contamination in the aquatic environment. *Cyprinus carpio* proved to be the most sensitive species, exhibiting extensive and severe gill lesions, whereas *Abramis brama* displayed moderate resilience. *Sander lucioperca* showed the least pronounced pathological changes, indicating high ecological plasticity. These findings confirm that gills represent a reliable biomarker of aquatic ecosystem status and can be effectively employed in water quality biomonitoring. A comprehensive assessment of the morphofunctional state of gill epithelium not only enables the detection of contamination but also allows evaluation of its potential impact on the health and viability of aquatic organisms, while species-specific differences in sensitivity can be applied in aquaculture management and ecological assessment of aquatic habitats.



A B

Figure 5 – Histopathological changes in the gills of *Sander lucioperca* from a highly polluted area. Staining: hematoxylin and eosin, A×100, B×200

It has been demonstrated that, compared with normal gill morphology, *Sander lucioperca* inhabiting polluted environments exhibited both compensatory and destructive alterations, indicative of prolonged toxic exposure and a decline in the overall physiological state of the organism. The gills of pikeperch showed pronounced morphofunctional disorders, including epithelial hyperplasia, hypertrophy, lifting, and necrosis, as well as vascular and inflammatory changes, reflecting the impact of aquatic toxicants. Relative to the norm, gill structure was markedly disrupted, leading to reduced functionality–primarily in respiratory and osmoregulatory processes–and increased susceptibility of the fish to external stressors. The coexistence of compensatory (hyperplasia) and destructive (necrosis, inflammation) changes points to the chronic nature of environmental contamination and the exceedance of the organism's adaptive thresholds under toxic pressure.

Gill histopathology can thus be regarded as a reliable biomarker of aquatic ecosystem health, while *Sander lucioperca* may serve as a sensitive indicator species in ecological monitoring. The findings highlight the necessity for strengthened environmental control and assessment of pollutant impacts on aquatic biota in order to prevent degradation of natural resources and biodiversity.

The histological examination of the gill apparatus in three fish species–*Cyprinus carpio* (common carp), *Abramis brama* (bream), and *Sander lucioperca* (pikeperch)–from different sites of the Ili-Balkhash Basin revealed pronounced interspecific differences in the extent and nature of pathological alterations induced by aquatic pollution. In *Abramis brama*, pathological changes were also detected, though their severity was substantially lower compared to common carp. The principal histological features included hyperplasia and partial thickening of the epithelial layer of the gill lamellae, as well as focal epithelial lifting in certain areas of the secondary epithelium.

The differences in the nature and severity of histopathological alterations are determined by physiological and ecological characteristics, respiratory type, metabolic rate, feeding strategy, and detoxification capacity. The higher resilience of *Sander lucioperca* may be attributed to its predatory lifestyle and reduced duration of contact with benthic contaminants, in contrast to benthophagous species such as *Cyprinus carpio* and *Abramis brama*.

Table 2 – Comparative analysis of histopathological changes

Fish species	Main changes	Degree of severity	Resistance to pollutants
Cyprinus carpio	Hyperplasia, edema, necrosis, inflammation, hemorrhages	High	Low
Abramis brama	Epithelial thickening, cell detachment, single necrotic foci	Moderate	Medium
Sander lucioperca	Mild epithelial thickening, capillary constriction	Low	High

The obtained results are consistent with previous studies emphasizing that gills represent one of the most sensitive organs to aquatic pollutants and can be effectively employed as bioindicators of water quality. The most typical signs of lesion include multilayered epithelial hyperplasia, lymphocyte and macrophage infiltration, thickening of the lamellar structure, vascular component degradation, and focal necrosis. Such alterations reduce the surface area available for gas exchange and disrupt homeostasis, which in the long term may decrease population resilience.

Thus, a comprehensive histological assessment of the gills not only revealed the extent of water pollution but also enabled biomonitoring with consideration of species-specific sensitivity. *Sander lucioperca* may be regarded as a promising species for aquaculture and commercial exploitation in regions with moderate contamination, whereas *Cyprinus carpio* can serve as a sensitive bioindicator signaling excessive ecological pressure.

Conclusion

Gills represent one of the most sensitive target organs to aquatic pollutants, as they perform vital respiratory, osmoregulatory, and barrier functions. Morphological and histopathological alterations occurred more rapidly in gills than in other organs, serving as early indicators of environmental degradation. The presence of both compensatory (e.g., hyperplasia, epithelial thickening) and destructive (e.g., necrosis,

inflammation, vascular disturbances) processes allowed assessment not only of the fact of pollution but also of its nature, duration, and toxicity.

A comparative analysis of three commercial fish species – *Cyprinus carpio*, *Abramis brama*, and *Sander lucioperca*–revealed distinct interspecific differences in the severity of pathological changes. Common carp exhibited the most pronounced alterations, confirming its high sensitivity and value as a bioindicator of pollution. Bream demonstrated moderate resilience and partial adaptive capacity, whereas pikeperch showed the greatest ecological plasticity, maintaining basic gill structure even under substantial anthropogenic pressure.

Thus, histological examination of the gill apparatus confirmed its reliability as a biomarker of water quality and highlighted the importance of species-specific approaches in biomonitoring and in the development of conservation strategies for aquatic ecosystems in the Ili-Balkhash region.

Key Findings

1. Fish gills are highly sensitive indicators of chronic exposure to aquatic pollutants, particularly heavy metals (Zn, Cu, Pb, Cd).

2. Pathological changes, including epithelial hyperplasia, inflammation, vascular impairments, and necrosis, can serve as reliable biomarkers of ecological status.

3. Cyprinus carpio proved to be the most sensitive species and can be used as an indicator of high levels of anthropogenic pollution.

4. Abramis brama demonstrated moderate resilience, while *Sander lucioperca* showed the least pronounced pathologies, reflecting its ecological plasticity and suitability for fisheries under moderate contamination.

5. Histopathological methods provide an objective assessment of tissue damage and represent an important tool for ecological monitoring.

6. Using gills as bioindicators enables early detection of anthropogenic impacts and supports the development of strategies for biodiversity conservation and sustainable ecosystem functioning in the Ili-Balkhash region.

Conflict of interest

The authors declare no conflicts of interest.

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