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Evaluation of histopathological alterations in the kidney of keting catfish (*Mystus gulio*) as a biomarker of pollution in the Welang, Gembong, and Rejoso rivers, Pasuruan, East Java, Indonesia

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ABSTRACT

Anthropogenic activities from industrial, residential, and agricultural areas degrade river water quality through the release of organic pollutants and heavy metals. The Welang, Gembong, and Rejoso Rivers in Pasuruan Regency, East Java, Indonesia, are freshwater ecosystems exposed to these pollution sources. This study evaluated kidney histopathological alterations in *Mystus gulio* as biomarkers of aquatic pollution and compared tissue damage among the three rivers. Fish were collected from three sampling stations in each river between November 2025 and February 2026. Kidney tissues were processed using the Hematoxylin–Eosin (H&E) staining method and examined microscopically at 400× magnification. Histopathological damage was assessed using a lesion-based scoring system, while water quality parameters and lead (Pb) concentrations in kidney tissues were also measured. Three major lesions were identified: congestion, degeneration, and necrosis. The highest damage occurred at Gembong River Station 3, with a histopathological score of 77% (badly damaged), whereas the lowest was recorded at Welang River Station 1 (31%, slightly damaged). Biochemical oxygen demand (BOD) and Pb concentrations exceeded permissible limits at all sampling sites, with the highest Pb concentration (1.68 mg L^{-1}) found at Gembong River Station 3. Greater Pb accumulation was associated with more severe kidney damage. These findings demonstrate that kidney histopathology in *M. gulio* is an effective biomarker for assessing freshwater pollution caused by heavy metal contamination.

Keywords: *Mystus gulio*, kidney histopathology, biomarker, river pollution, lead.

INTRODUCTION

Aquatic environmental pollution has become a serious and escalating issue driven by anthropogenic activities, including industrial, agricultural, and commercial operations (Orso *et al*., 2023). Significant deterioration in freshwater quality began during the Industrial Revolution and has intensified with increasing human activities that have not been accompanied by adequate environmental management practices. Consequently, pollution has led to ecological disturbances, imbalances, and degradation of aquatic ecosystems. At present, freshwater pollution, particularly in riverine systems, has emerged as a global environmental concern. In general, aquatic pollutants can be classified into organic and inorganic contaminants. Inorganic pollutants are known to interfere with a wide range of biological processes in aquatic organisms (Atli *et al*., 2015). Common pollutants contributing to water turbidity include salt deposits, fine sand, soil particles, clay, and industrial effluents containing dyes and heavy metals. Recent studies have reported increasing levels of heavy metal accumulation in freshwater environments. The presence of these contaminants has been associated with numerous adverse effects, including reproductive impairment, nervous system disorders, elevated carcinogenic risks, and reduced disease resistance in aquatic organisms (Hussain *et al*., 2019). Consequently, poor water quality exerts detrimental effects on aquatic biota by inducing physiological stress and compromising overall organismal health.

Rivers are among the aquatic ecosystems most vulnerable to contamination from the indiscriminate discharge of xenobiotic substances and various waste products. The introduction of toxic chemicals and untreated effluents into river systems alters key abiotic parameters, such as pH and dissolved oxygen concentrations, thereby adversely affecting the survival and health of aquatic organisms (Orso *et al.,* 2023). In Pasuruan Regency, East Java, Indonesia, the Welang, Gembong, and Rejoso Rivers constitute three major river systems that traverse densely populated residential areas, industrial zones, and intensive agricultural landscapes. Rapid regional development has subjected these rivers to substantial anthropogenic pressures. The Welang River frequently receives large volumes of industrial wastewater, the Gembong River, which flows through urban centers, is predominantly impacted by domestic effluents and municipal solid waste, while the Rejoso River is extensively exposed to agricultural runoff containing fertilizers and chemical pesticides. The accumulation of these pollutants has contributed to the deterioration of water quality and ecological integrity, posing significant threats to the sustainability of aquatic biota inhabiting these riverine ecosystems (Herawati *et al*., 2026)

According to Herawati *et al*., (2026) the physicochemical assessment of the Welang, Gembong, and Rejoso Rivers indicated that all three river systems fall within the heavily polluted category. Water quality monitoring in these rivers has predominantly relied on physicochemical parameters, including pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), and heavy metal concentrations. Although these parameters provide accurate quantitative measurements, physicochemical analyses only reflect environmental conditions at the time of sampling and are unable to capture the cumulative biological impacts of pollutant exposure on living organisms. Consequently, reliance solely on physicochemical indicators may underestimate the long-term ecological consequences of contamination in aquatic ecosystems. Therefore, the incorporation of biological biomarkers is essential to provide a more comprehensive assessment of environmental quality and to evaluate the chronic effects of pollutants on aquatic biota.

Biomarkers are biological responses of organisms to contaminant exposure that reflect alterations in their physiological condition and overall health status. In ecotoxicological studies, fish biomarkers are widely employed to detect changes at lower levels of biological organization before adverse effects become evident at the population level (Hussain *et al*., 2019). Fish are considered effective bioindicators of water quality due to their high sensitivity to environmental contamination (Shahid *et al*., 2022). Furthermore, their relatively long lifespan and broad spatial distribution enable them to integrate pollutant exposure over extended periods and across different habitats. Exposure to pollutants can induce alterations at the molecular, cellular, and tissue levels in fish (Orso *et al.,* 2023). In addition, fish are capable of absorbing and accumulating toxic chemicals directly from the surrounding environment or indirectly through trophic transfer within the food web (Zaman *et al*., 2023).

Mystus gulio is a native freshwater fish species with considerable potential as a bioindicator of aquatic environmental quality. As a demersal species that exhibits relatively sedentary behavior and forages on the riverbed, *Mystus gulio* maintains continuous direct contact with bottom sediments, which serve as major sinks for environmental contaminants, including heavy metals and persistent organic pollutants. This ecological characteristic makes the species particularly susceptible to contaminant exposure and accumulation. Consequently, physiological and structural alterations in *M. nigriceps* can accurately reflect the level of environmental contamination within its habitat (Lestariaji *et al.,* 2025).

Histological alterations serve as effective biomarkers of contaminant exposure and may reflect both direct and indirect effects of pollutants on animal tissues (Shahid *et al*., 2022). Histopathological changes in organisms exposed to environmental contaminants have long been recognized as one of the most reliable tools for assessing toxic effects in both laboratory and field studies (Shah and Parveen, 2022). Among the organs susceptible to histological damage resulting from aquatic pollution, the kidney is considered one of the most sensitive target organs (Lestariaji *et al*., 2025). The kidney is a vital organ in fish, playing a central role in maintaining fluid and ionic balance within the body. Exposure to hazardous substances can impair renal function, thereby disrupting homeostatic regulation either temporarily or permanently (Zaman *et al.*, 2023). In fish, the kidney is responsible for regulating water and electrolyte balance, ensuring the stability of the internal physiological environment. Owing to its essential functions and high sensitivity to toxicants, the kidney is widely regarded as an excellent biomarker organ for evaluating environmental pollution and stress in aquatic ecosystems (Hussain *et al*., 2019).

Although several studies have investigated pollution in the river systems of Pasuruan, most previous research has primarily focused on physicochemical water quality assessments or the accumulation of heavy metals in fish muscle tissues. The novelty of the present study lies in the application of kidney histopathology in *Mystus gulio* as a biological biomarker to comparatively assess pollution across three major river systems in Pasuruan—namely the Welang, Gembong, and Rejoso Rivers. These rivers differ in terms of their dominant pollution sources and anthropogenic pressures, providing a unique opportunity for comparative ecotoxicological evaluation. To the best of our knowledge, no previous study has employed a histopathological damage index of the kidney in *M. nigriceps* across river systems characterized by distinct pollution profiles. Therefore, this approach offers a novel and more comprehensive perspective on the ecological health and toxicity status of freshwater environments in Pasuruan Regency.

Accordingly, this study aimed to evaluate and characterize histopathological alterations in the kidneys of *Mystus gulio* collected from the Welang, Gembong, and Rejoso Rivers, and to quantify and compare the severity of renal tissue damage among these river systems in order to assess the extent of environmental pollution and its biological impacts on aquatic organisms.

MATERIAL AND METHOD

Collection of fish and water samples

Mystus gulio were collected from three river systems in Pasuruan Regency, East Java, Indonesia, namely the Welang, Gembong, and Rejoso Rivers (Figure 1), during January – February 2026. Fish sampling was conducted with the assistance of local fishermen using hook-and-line fishing gear. A total of nine fish specimens were

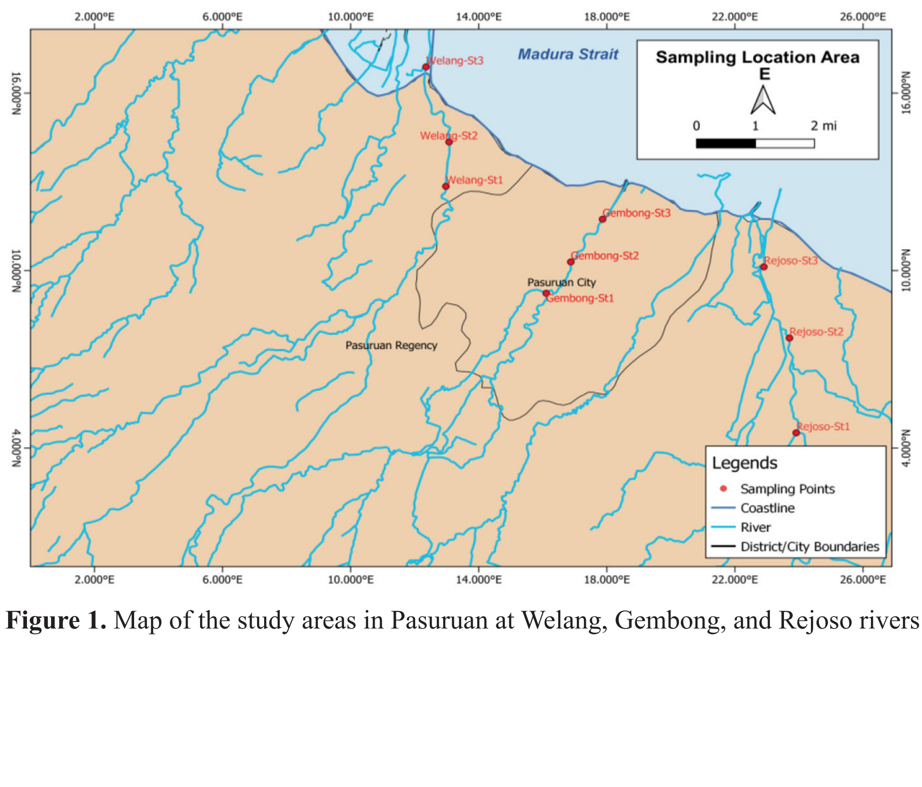


Figure 1. Map of the study areas in Pasuruan at Welang, Gembong, and Rejoso rivers

collected from each river, representing three sampling stations established along each river system. Captured fish were euthanized and dissected to obtain kidney tissues. The excised kidneys were subsequently preserved in sample bottles containing 70% formalin and in the Hydrobiology Laboratory Malang, Fish Resources Division for histopathological analysis.

Water samples were collected from each sampling station in all three rivers. Water quality assessment was performed through both in situ and ex situ measurements. In situ measurements included water temperature, pH, DO, and current velocity. Ex situ analyses were conducted for TSS, nitrate, orthophosphate, TOM, BOD, COD, and Pb. For these analyses, water samples were collected in 600-mL polyethylene sampling bottles and transported to the Hydrobiology Laboratory, Faculty of Fisheries and Marine Sciences, Universitas Brawijaya, for laboratory examination.

Histopathology

Histological preparation was performed following the protocol described by Sultana *et al*. (2016). Kidney tissue samples were fixed in 10% neutral buffered formalin (40% formaldehyde) for 2–3 days to ensure optimal tissue preservation. Following fixation, the samples were labeled and subjected to a graded ethanol dehydration series. The tissues were subsequently cleared in xylene prior to paraffin infiltration and embedding at 58 °C overnight in an oven. Any air bubbles formed during the embedding process were carefully removed, and the paraffin blocks were allowed to cool and solidify. The hardened tissue blocks were sectioned at a thickness of 5 µm using a rotary microtome. Tissue sections were then mounted on glass slides and incubated at 37 °C overnight to ensure adequate adhesion. Subsequently, the sections were stained using the Hematoxylin and Eosin (H&E) method to facilitate the examination of tissue morphology and histological architecture. After staining, the slides were mounted with Canada balsam and covered with cover slips to produce permanent preparations, which were then allowed to dry overnight. The completed histological slides were examined and documented under a light microscope at 400× magnification. Histopathological alterations were evaluated by comparing the observed tissue structures with established histopathological criteria and recent reference literature (Zaman *et al*., 2023).

Data analysis

Histological analysis was conducted descriptively based on relevant reference literature. Stained tissue sections were examined under a light microscope at 400× magnification to evaluate morphological and structural alterations in kidney tissues. The histological preparations were subsequently documented using an Optilab digital microscope camera connected to the Optilab Viewer software. Cellular lesions observed in each tissue section were identified, quantified, and analyzed according to predefined assessment criteria. The degree of tissue damage was expressed as a percentage and calculated using the formula proposed by Wolf *et al*. (2015) sebagai berikut:

$$Percentage = \frac{Number\ of\ damage\ cells}{Number\ of\ cells\ analized} \times 100\% \quad (1)$$

Damages were then matched to a Table 1.

RESULTS AND DISCUSSION

Hystopathologi kidney of *Mystus gulio*

Based on the microscopic examination of kidney tissues from *Mystus gulio* collected from the Welang, Gembong, and Rejoso Rivers, three major histopathological lesions were identified, namely degeneration, congestion, and necrosis. Quantitatively, the occurrence and severity of these lesions varied considerably among sampling stations and river systems. The highest lesion prevalence was recorded for congestion, reaching 97% in fish collected from Gembong River Station 3, whereas the lowest prevalence was observed for necrosis, accounting for 25% in fish from Welang River

Table 1. Scoring histophatology

Percentage of damage	Damage category
P < 25%	Normal
25 ≤ P < 50%	Slightly damage
50 ≤ P <75%	Moderate damage
P > 75%	Badly damage

Note: Source – Wolf *et al*. (2015).

Station 1 (Table 2). The histopathological characteristics of kidney damage observed in *M. nigriceps* from each river system are presented below.

Kongesti

Congestion is defined as the excessive accumulation of blood within blood vessels or capillaries and is commonly observed in fish tissues exposed to toxic substances (Dane and Şişman, 2021). n the present study, congestion was characterized by an abnormal accumulation of blood within the renal blood vessels and capillaries (Figure 2). This condition is generally considered an early pathological response to toxic stress, resulting from circulatory disturbances and alterations in vascular permeability. The occurrence of congestion across all sampling sites indicates that the fish experienced physiological impairment associated with prolonged exposure to environmental contaminants. Exposure to heavy metals and organic pollutants has been reported to induce circulatory dysfunction, leading to reduced oxygen supply to renal tissues and subsequent impairment of kidney function (Sayed *et al*., 2023).

Degeneration

Degenerative alterations were also observed in the kidney tissues of *Mystus gulio*, characterized by cellular swelling, cytoplasmic vacuolization, and disruption of the normal architecture of the renal tubular epithelium (Figure 3). Degeneration is generally considered an adaptive and potentially reversible response to environmental stress, provided that the source of stress is removed and normal physiological conditions are restored. However, continuous exposure to environmental contaminants may lead to the progression of degenerative changes into more severe and irreversible tissue damage (Hsu *et al*., 2025) In both fish and mammals, the progression of renal lesions commonly follows a consistent pathological pattern, beginning with tubular degeneration, hydropic swelling, and cytoplasmic vacuolization, and subsequently advancing to necrosis, fibrosis, or chronic renal dysfunction when exposure to stressors persists or water quality conditions continue to deteriorate (Stoyanova *et al*., 2025) These findings are consistent with the observations reported by Hussain *et al*., (2019) who documented epithelial hypertrophy,

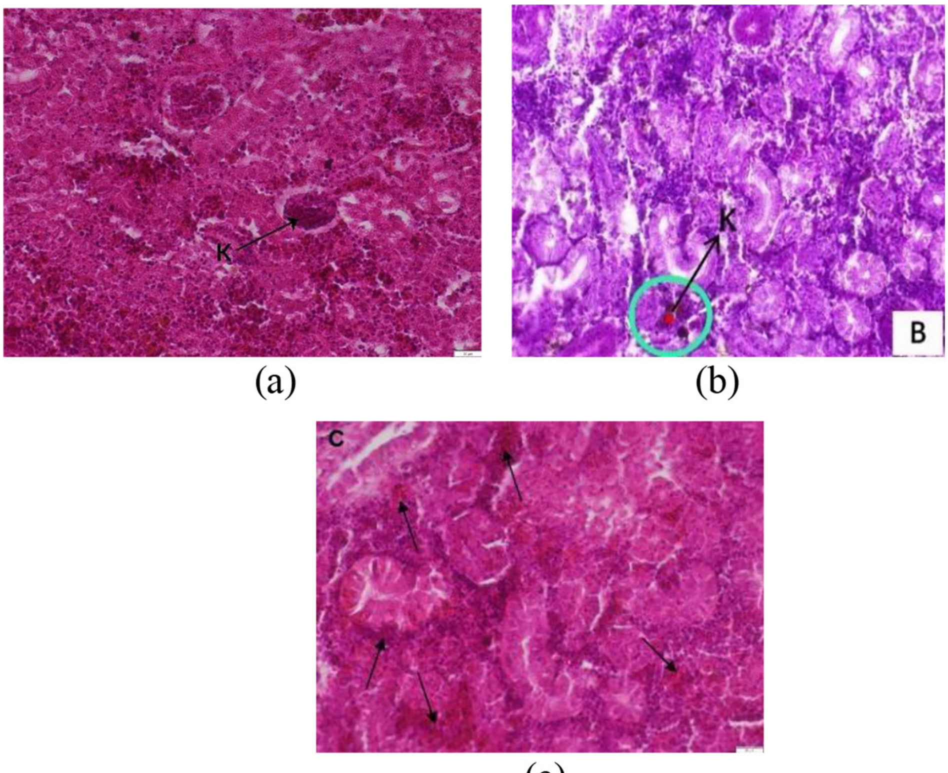


Figure 2. Renal congestion lesions in *Mystus gulio* collected from: (a) the Welang River; (b) the Gembong River; and (c) the Rejoso River

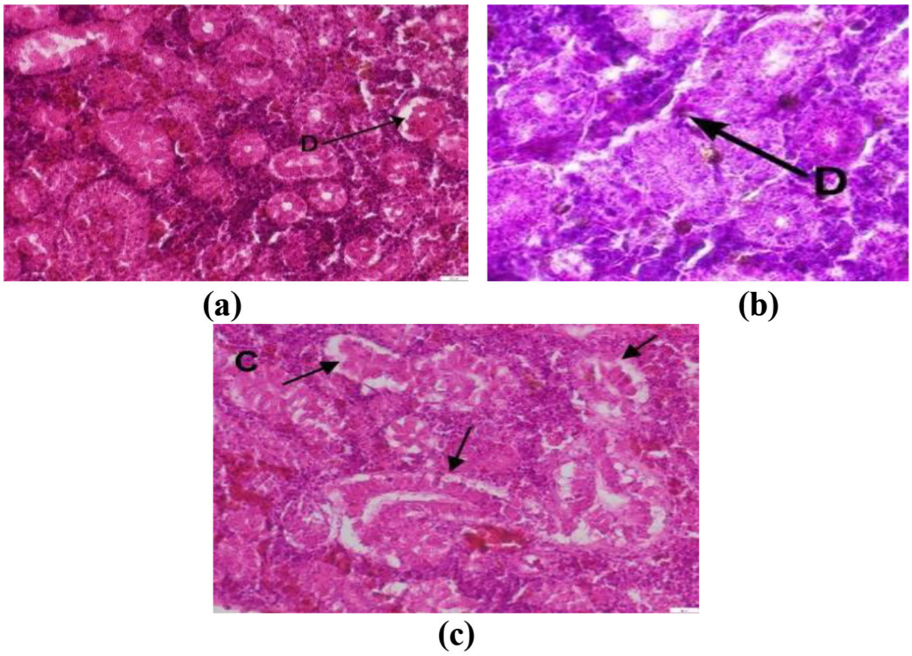


Figure 3. Renal degeneration lesions in *Mystus gulio* collected from: (a) the Welang River; (b) the Gembong River; and (c) the Rejoso River

cytoplasmic vacuolization, narrowing of the tubular lumen, tubular atrophy, and progressive degeneration leading to glomerular necrosis in fish inhabiting polluted river environments.

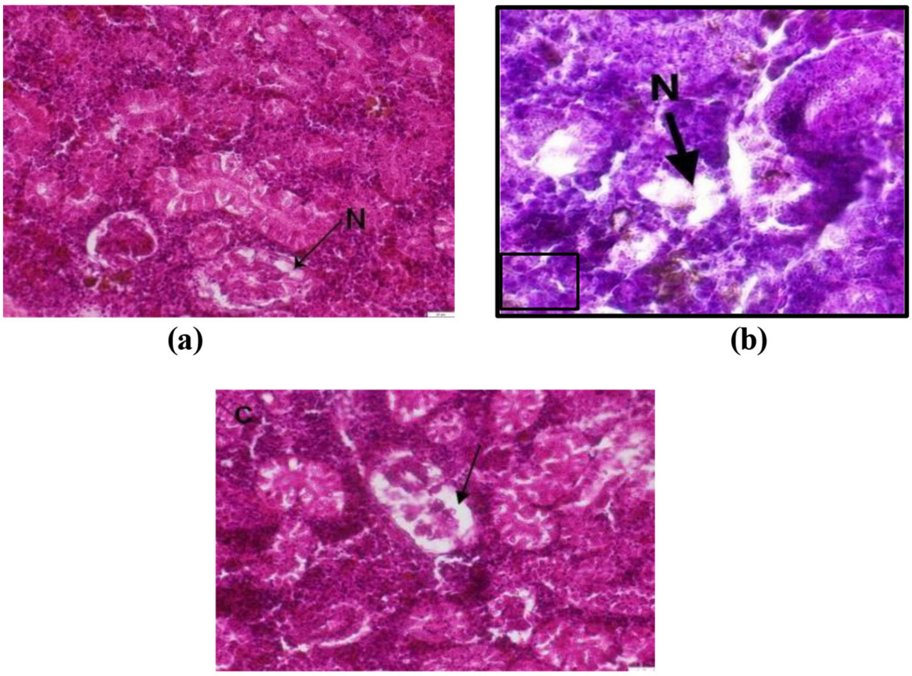
Necrosis

Necrotic lesions were characterized by pyknosis, karyolysis, cellular disintegration, and loss of tissue integrity (Figure 4). The presence of necrosis indicates irreversible cell death resulting from prolonged exposure to toxic substances (Costigan *et al*., 2023). The high prevalence of necrotic lesions observed in fish collected from the Gembong and Rejoso Rivers indicates that these river systems are subjected to substantial pollution pressure, resulting in severe physiological disturbances in resident aquatic organisms. Histopathological alterations in the kidney can impair its essential functions as an excretory and osmoregulatory organ, thereby disrupting vital physiological processes, compromising homeostatic regulation, and potentially leading to increased mortality in affected fish populations (Wahidi *et al*., 2025).

These histopathological findings are consistent with the results reported by (Herawati *et al*., 2026), ho classified the Welang, Gembong, and Rejoso Rivers as heavily polluted based on STORET analysis, with scores of −44, −36, and −48, respectively. The elevated concentrations of orthophosphate, BOD, COD, and Pb detected in these river systems are likely major contributors to the renal tissue damage observed in *Mystus gulio*. Numerous studies have demonstrated that heavy metals and organic contaminants can induce the generation of reactive oxygen species (ROS), resulting in oxidative stress, disruption of cellular metabolism, and structural alterations in vital organs, including the kidneys. Such toxic effects may ultimately impair organ function and compromise the overall health and survival of aquatic organisms exposed to contaminated environments. (Javed *et al*., 2017)

Histopathological damage scoring of the Kidney *Mystus nigriceps*

The histopathological damage scoring revealed substantial variation in the severity of renal tissue damage among the study sites (Table 2). In the Welang River, the mean percentage of kidney tissue damage ranged from 31% to 41%, corresponding to the slightly damaged category. In contrast, fish collected from the Gembong River exhibited considerably higher levels of renal damage, ranging from 62% to 77%. Notably, specimens from Station 2 and Station 3 were classified as badly damaged, with mean damage scores of 75% and 77%, respectively. Meanwhile,



(a) **(b)** **(c)**

Figure 4. Renal nekrosis lesion in *Mystus gulio* collected from: (a) Sungai Welang; (b) Sungai Gembong; (c) Sungai Rejoso

fish sampled from the Rejoso River showed renal tissue damage ranging from 59% to 65%, which falls within the moderately damaged category.

The highest level of renal tissue damage was recorded at Gembong River Station 3, with a mean damage percentage of 77%. This value indicates that fish inhabiting this site experienced severe structural impairment of the kidney. The elevated degree of histopathological damage is likely associated with the high intensity of anthropogenic activities occurring along the Gembong River, particularly inputs from domestic wastewater, urban activities, and the accumulation of organic pollutants originating from densely populated residential areas (Akhtar *et al.*, 2021)

The spatial pattern of tissue damage revealed a tendency for greater histopathological impairment at downstream stations compared to upstream locations. This pattern suggests the progressive accumulation of pollutant loads along the river continuum, resulting in elevated concentrations of toxic substances in downstream areas. Such accumulation increases the likelihood of chronic contaminant exposure in aquatic organisms and exacerbates the severity of tissue damage. Consequently, fish inhabiting downstream reaches are more vulnerable to the adverse biological effects of environmental pollution due to prolonged exposure to accumulated contaminants (Islamy *et al*., 2025)

The findings of this study further strengthen the evidence that fish kidney tissue serves as a highly sensitive biological indicator of changes in aquatic environmental quality. Unlike physicochemical parameters, which only reflect water quality conditions at the time of sampling, histopathological biomarkers are capable of revealing the cumulative biological effects of pollutant exposure over extended periods (Hussain *et al*., 2019).

Furthermore, the consistent relationship between the severity of histopathological damage and the deteriorated water quality observed across the three river systems suggests that *Mystus gulio* possess considerable potential as a bioindicator species for freshwater pollution monitoring. As a demersal fish that inhabits and forages on the riverbed, this species maintains continuous contact with bottom sediments, which serve as major repositories for the accumulation of various contaminants. Consequently, the biological responses exhibited by *M. nigriceps* are likely to provide a more accurate representation of environmental conditions and contaminant exposure within aquatic ecosystems (Lestariaji *et al*., 2025).

Table 2. Percentage of tissue damage in the kidneys of fish caught in Welang, Gembong and Rejoso rivers

Rivers	Station	Damage type kidney histopatology				Type of damage
		Degeneration (%)	Congestion (%)	Necrosis (%)	Average (%)	
Welang	Station 1	27	40	25	31	Slightly damage
	Station 2	32	57	29	39	Slightly damage
	Station 3	31	57	34	41	Slightly damage
Gembong	Station 1	36	69	82	62	Moderate damage
	Station 2	59	72	94	75	Badly damage
	Station 3	47	97	88	77	Badly damage
Rejoso	Station 1	44	77	65	62	Moderate damage
	Station 2	42	72	63	59	Moderate damage
	Station 3	49	79	66	65	Moderate damage

Physicochemical analysis of water quality parameters

The results of the physicochemical water quality assessment conducted in the Welang, Gembong, and Rejoso Rivers indicated that most measured parameters remained within ranges generally suitable for sustaining aquatic life. Nevertheless, several key water quality parameters exceeded the Class III water quality standards established by the Government Regulation of the Republic of Indonesia No. 22 of 2021, suggesting the presence of significant pollution pressures within these river systems (Table 3).

As presented in Table 3, the water quality parameters that exceeded the established water quality standards were BOD and lead (Pb). In contrast, the remaining physicochemical parameters were within the acceptable range for Class III water quality standards. BOD concentrations were consistently elevated across all sampling sites, ranging from 8.95 to 11.81 mg L^{-1}. These values exceeded the Class III threshold of 6 mg L^{-1}, indicating a substantial organic pollution load within the studied river systems. Elevated BOD values reflect the presence of considerable amounts of biodegradable organic matter in the water column, which requires large quantities of dissolved oxygen for microbial decomposition. Such conditions suggest significant inputs of organic waste originating from domestic, industrial, and agricultural activities into the river systems (Zhang *et al*., 2024)

The most alarming finding of the present study was the concentration of the heavy metal lead (Pb). The results revealed that Pb concentrations at all sampling stations ranged from 0.20 to 1.68 mg L^{-1}, substantially exceeding the permissible limit of 0.03 mg L^{-1} established by the applicable water

Table 3. Average water quality in the Welang, Gembong, Rejoso rivers

Parameter	Location									Quality standars
	Welang			Gembong			Rejoso			
	St 1	St 2	St 3	St 1	St 2	St 3	St1	St 2	St 3	
Temperature (°C)	28.33	28.31	28.08	27.21	27.68	28.47	27.16	28.07	28.87	Dev 3
pH	7.48	7.28	7.41	7.51	7.69	7.92	6.68	7.75	7.32	
DO (mg/L)	6.18	7.54	7.10	5.57	4.83	4.02	5.20	4.47	4.67	> 3
Current (m/s)	0.42	0.34	0.43	0.14	0.11	0.16	0.32	0.17	0.16	
Nitrate (mg/L)	0.49	0.48	0.35	0.31	0.37	0.31	0.28	0.30	0.22	20
Orthophosphate	0.59	0.65	0.77	0.62	0.69	0.97	0.44	0.48	0.45	1
TSS (mg/L)	63.33	61.67	82.00	71.00	51.33	42.00	69.00	56.00	64.33	100
BOD (mg/L)	*11.48	*11.80	*11.81	*8.95	*9.76	*10.85	*9.14	*9.59	*10.09	6
COD (mg/L)	34.88	35.65	36.25	29.43	30.58	32.87	30.86	31.99	33.24	40
Pb (mg/L)	*1.81	*0.55	*0.20	*0.55	*0.87	*0.68	*0.50	*0.23	*0.28	0.03

Note: * Indicates values exceeding the Class III water quality criteria established under Government Regulation of the Republic of Indonesia No. 22 of 2021.

quality standards. The highest Pb concentration was recorded at Gembong River Station 3 (1.68 mg L^{-1}), whereas the lowest concentration was observed at Welang River Station 3 (0.20 mg L^{-1}). Chronic exposure to Pb has been reported to induce a wide range of adverse biological effects, including metabolic disruption, oxidative stress, impairment of enzymatic activities, and damage to vital organs such as the liver, kidneys, and gills. Furthermore, prolonged Pb exposure may compromise reproductive performance, reduce growth and survival rates, and ultimately threaten the ecological integrity of aquatic ecosystems (Soliman *et al.,* 2023).

Lead concentration in the kidney of *Mystus gulio*

The average concentration of lead (Pb) accumulated in the kidneys of *Mystus gulio* is presented in Table 4. Nigriceps exceeded the maximum permissible limit established by the Indonesian National Standard (SNI 7387:2009), which is 0.3 mg kg^{-1}. This condition is likely attributable to the elevated Pb concentrations detected in the waters of the three studied rivers, allowing lead to enter the fish body through multiple exposure pathways, including ingestion, respiration, and dermal absorption. In addition, the kidney functions as a primary excretory organ, making it particularly susceptible to the accumulation of heavy metals. As a key organ involved in metabolic waste excretion and detoxification, the kidney also serves as a storage site for various pollutants, including heavy metals, thereby increasing its vulnerability to tissue damage resulting from contaminant accumulation e analysis of Pb concentrations in kidney tissues revealed a pattern consistent with both the Pb levels measured in water samples and the severity of renal histopathological damage. The highest mean Pb concentration in the kidneys of M. nigriceps was recorded at Gembong River Station 3. This finding is in agreement with the water quality assessment, which identified the highest Pb concentration in the water column at the same station. Furthermore, the most severe histopathological alterations in kidney tissues were also observed at Gembong River Station 3, suggesting a strong association between environmental Pb contamination, bioaccumulation in renal tissues, and the extent of tissue damage.

Table 4. Average lead in kidney

Site	Lead in kidney (mg/kg)		
	Welang	Gembong	Rejoso
Station 1	9.82	6.75	10.36
Station 2	2.99	6.99	6.27
Station 3	4.57	13.89	11.73

CONCLUSIONS

This study demonstrated that the kidneys of *Mystus gulio* collected from the Welang, Gembong, and Rejoso Rivers exhibited histopathological alterations, including congestion, degeneration, and necrosis, as biological responses to environmental contaminant exposure. The highest degree of tissue damage was observed in fish from the Gembong River, which was classified as badly damaged, followed by the Rejoso River with a moderately damaged classification, and the Welang River with a slightly damaged classification. The severity of renal tissue damage was closely associated with elevated Pb concentrations and deteriorated water quality conditions at the study sites. These findings confirm that kidney histopathology in *Mystus gulio* can serve as an effective biomarker for assessing pollution levels and evaluating the ecological health of freshwater river ecosystems.

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