Circular impacts of hexavalent chromium pollution on the Opak River, Yogyakarta, Indonesia

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Abstract. Uncontrolled wastewater discharge containing hexavalent chromium Cr(VI) from tannery industries in Piyungan Industrial Area (PIA) in Yogyakarta, Indonesia, potentially disrupts ecological and societal elements downstream of the Opak River. We collected samples from the wastewater discharge point of several PIA connected sites and a control location. Samples consisted of river water and solid samples (sediment, aquatic plant, and fish). We also examined fish and rice samples that were dependent on the river ecosystem. Atomic absorption spectrophotometry was used to determine the Cr(VI) levels of the samples. To estimate potential economic loss from fish farming, current fish production and market price data were considered. No significant differences in Cr(VI) concentration between the examined sites and the control site ($p<0.05$) were found. The average Cr(VI) concentration in river water samples ranged from 0.117-0.397 mg/l, exceeding the required local standard of 0.05 mg/l. Increased distance did not result in lower Cr(VI) concentration in water and solid samples, except in rice grain. The potential economic loss of income is estimated at EUR 103 thousand/year. Our findings presented that persistent and intensifying Cr(VI) pollution potentially leads to a further decline in river ecosystem services, a deterioration in food production standards, and economic loss. Considering the wide distribution of the impact of chromium pollution, the management of and the local government immediately operated a communal wastewater treatment plant, increased supervision, and assistance to business actors to make efficient use of chromium and implemented a recycling process. To improve the decline in river water quality, river remediation, and restoration can be carried out by utilizing aquatic macrophytes such as water hyacinth (*Eichhornia crassipes*) or by using a wetland system. Thus, cases of chromium pollution can be reduced, and the quality of river water can meet the requirements as a source of water for agriculture and fisheries.

Key Words: deterioration, economic loss, leather industry, river ecosystem.

Introduction. Industrial expansion without considering proper wastewater treatment has reportedly led to the adverse distribution of hexavalent chromium Cr(VI) in the environment. Hence, its occurrence is continuously under concern, particularly in water bodies (Brasilia et al 2020). The United Nations Industrial Development Organization (U.N.I.D.O.) estimated the use of 175 types of chemicals in the tannery process (Suman et al 2021), one of which is Cr(VI). The wastewater from the tannery industry was among the highest contributors to global environmental contamination after the lead acid battery recycling industry, ore mining and processing, and lead smelting (SMEP 2018). Reportedly, processing 1 kg of raw leather may generate 30 L of waste, with only 20% converted into usable leather products, while more than 60% yields solid waste and wastewater (Sivaram & Barik 2018). Many studies highlighted adverse effects of Cr(VI) on ecological elements, and its intensive exposure to humans may lead to adverse health effects such as chronic fatigue, infertility, nerve pain in the legs, hypothyroidism, dermatitis, ulcers, and lung cancer in humans (Sharma et al 2009).

Rapid industrialization in Indonesia occurred between 1970 and 1997, resulting in an annual growth of nearly 12% for the industrial sector (Adam 2001). In Indonesia, the tannery industry has been playing a prominent role as one of the sources of non-oil and gas foreign exchange earnings (Poernomo 2007). One of Indonesia's regions experiencing significant growth in this industry is the Special Region of Yogyakarta (DIY). However, apart from the viewpoint of economic development, concerns about environmental impact seemed to be overlooked. Numerous tannery industries in Indonesia are not equipped with wastewater treatment, and even those with it are often ineffective (Kuncoro & Soedjono 2022). Inadequate treatment processes and a shortage of operational monitoring have contributed to Cr(VI) pollution in water bodies in Indonesia. Meanwhile, based on data from the Ministry of Environment and Forestry in Indonesia (MENLHK 2019), the national river water quality index in 2019 shows poor water conditions, namely a decrease of 20.15 points from 72.77 in 2018 to 52.62.

The Opak River is one of the largest rivers in the Special Region of Yogyakarta, with a length of ± 65 km and a flow area of 1398.18 km^2 (Wardhana 2015). The Opak River supports local ecological elements and socio-economic activities (agriculture and fish farming ponds). However, the local industrial area, the so-called Piyungan Industrial Area (PIA), located downstream on the Opak River, potentially deteriorates the water river quality, which local people mostly rely on for fish farming. Essentially, Cr(VI) has been included in the standard criteria for local river water quality, both according to Government Regulation Number 22 (2021) concerning the Implementation of Environmental Protection and Management and Yogyakarta Governor's Regulation Number 20 (2008) concerning Water Quality Standards in the Special Region of Yogyakarta. However, these monitoring regulations posed gaps. Namely, on the Government Regulation Number 22 (2021), Cr(VI) occurrence in river waters is not assigned to a mandatory assessed parameter. However, Cr(VI) is a toxic environmental pollutant for living organisms (Liang et al 2021). Cr(VI) pollutes soil, which ends up in crops and drinking water. Implications of Cr(VI) contaminations for human well-being when animals or humans eventually ingest polluted foods and waters for a certain period include increasing risk for several forms of cancer (e.g., liver cancer). This element is also recognized as a neurotoxicant that is responsible for widespread neurodegenerative diseases (Wise et al 2022).

The concentration and bioaccumulation of Cr(VI) in environmental elements, mainly organisms, might be influenced by various interacting factors, such as: 1) location and proximity to sources of pollution (Maurya & Malik 2019), 2) types and trophic status of organisms (Anwarul Hasan et al 2022), and 3) environmental conditions, environmental preferences, trophic levels, eating habits, age, sex, duration of metal exposure, and physiological regulatory activities (Arulkumar et al 2017). Meanwhile, Cr(VI) in the food chain is influenced by several transfer factors from water-organism, sediment-organism, and water-sediment-organism media through various processes such as bioconcentration, bioaccumulation, and biomagnification (Ali et al 2019).

Wilson and Carpenter (1999), Brauman et al (2007), Olmstead (2010), and Griffiths et al (2012) offer reviews of economic approaches to water quality assessment. They suggest that actions leading to changes in water quality can affect ecosystem goods and services, resulting in changes in the value of the services. Some studies evaluated various sites' Cr(VI) levels in the environmental elements. A study by Baizura et al (2020) detected Cr(VI) in the Sembilang River, Malaysia, within concentrations ranging from 0.004–0.008 mg/l. Meanwhile, Siddiqua et al (2021) reported Cr(VI) in the Chenab River in Pakistan in a concentration range from 0.005 to 0.028 mg/l. Furthermore, studies examining the level of Cr(VI) accumulation in food such as rice, soybeans, vegetables, fruits, fish, and shrimps and their health risks have been widely carried out in waters affected by industrial or mining waste disposal (Salihović et al 2022; López-Bucio et al 2022; Chen et al 2022). Additionally, pollution diminishes the recreational value of the river, leading to missed opportunities for nature viewing and decreased attractiveness for activities such as fishing, swimming, bathing, and washing. However, to gain insight into how significant Cr(VI) affects the environment, considering investigation from both local ecological and socio-economic perspectives is preferential.

This study aims to evaluate the Cr(VI) contamination on the Opak River downstream across selected sampling stations, ecologically connected to the point of wastewater discharges of PIA's tannery industries. In addition, we considered the socio-economic perspective by evaluating river ecosystem services of local fish farming products, including potential economic losses due to the use of polluted river water and its derivative social impacts. Specifically, this study compares Cr(VI) concentration on different districts (sites) ecologically connected to the Opak River, namely Piyungan, Pleret, Imogiri, Jetis, Banguntapan, and Pudong. In addition, some rice samples were collected from the rice fields of some regions. This study expects to reveal the significance of Cr(VI) pollution in water bodies by considering local ecological and socio-economic perspectives and promoting contamination control policies and sustainable planning, especially for Indonesia and other areas facing similar socio-environmental circumstances.

Material and Method

Framework of the study. Figure 1 illustrates the relationship between the impact of industrial wastewater disposal activities containing Cr(VI), changes in ecosystem goods and services, and changes in value. Keeler et al (2012) reviewed and reported the linkage between wastewater disposal in the river and the values of water quality-related ecosystem services. Untreated wastewater discharge declines water bodies' quality affects fish abundance and productivity and diminishes the value of river fishing and community food sources. Deteriorating river water quality potentially may render it unsuitable for irrigation and fisheries, resulting in increased costs for water treatment, health issues, or even fatalities (Wilson & Carpenter 1999; Brauman et al 2007; Olmstead 2010; Griffiths et al 2012). Additionally, potential economic loss was calculated based on data of current fish production and market price.

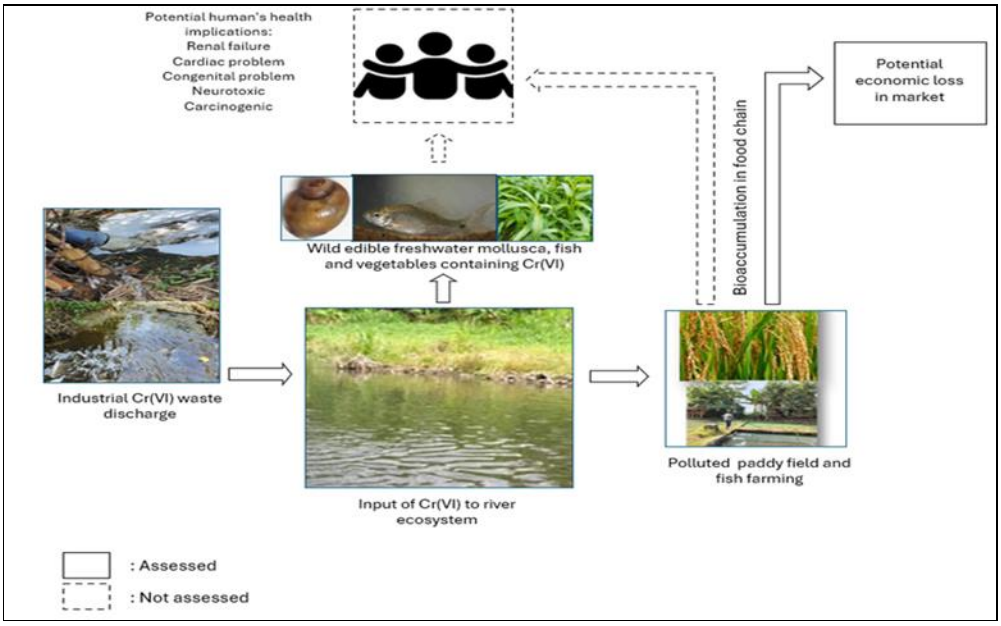

Figure 1. The interaction of Cr(VI) pollution from industrial activities discharged into the river with the threats to the environment and society.

Time frame and site description. The survey was carried out from March 2023 to March 2024. The sampling stations were alongside the downstream of the Opak River (Figure 2), starting from Piyungan (a wastewater discharge point) and extending to Pleret, Jetis, Imogori, Pundong and estuary of Opak river. The distance between PIA and Piyungan, Pleret, Jetis, Imogiri, Pundong and estuary was 0.77 km, 3.64 km, 6.42 km, and 9.08 km, respectively. Based on field observations, PIA has 13 tannery industries, but only one industry has carried out proper wastewater treatment and has a wastewater discharge permit from the local government. In the meantime, others fail to provide evidence of the so-called document "Environmental Management Efforts and Environmental Monitoring Efforts (UKL-UPL)" (Government Regulation of the Republic of Indonesia 2021). Kalasan, having a distance of 14.79 km from PIA, was used as a control region, considering its low pollution impact. Additionally, a respective industry with proper wastewater treatment was included as the comparison area for the water sample.

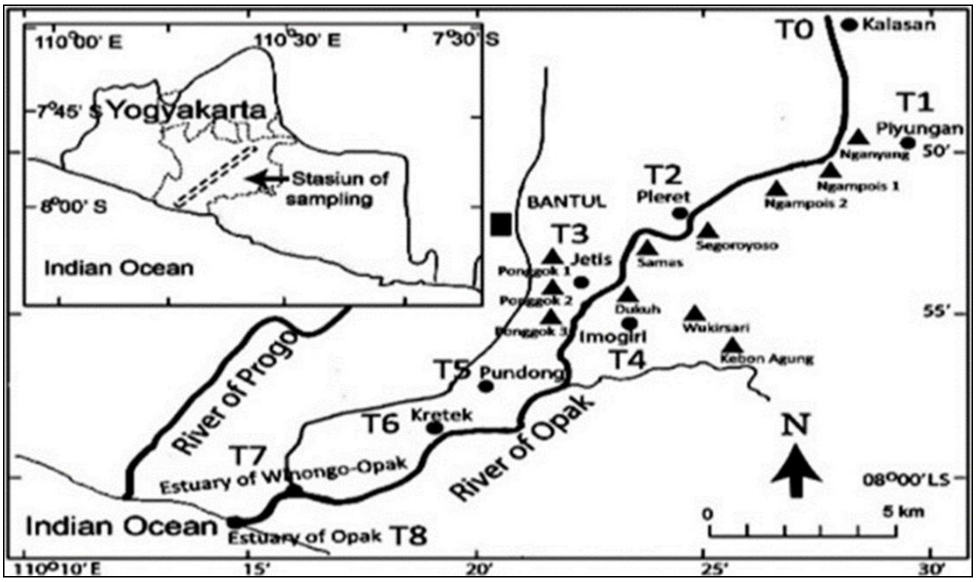

Figure 2. Description of research locations, distribution of river water sampling locations, rice fields and fish farming ponds (map generated using Adobe Illustrator 26.0.3).

Sites for agricultural and fish farming ponds were also selected to examine their dependency on the river ecosystem. The fish farming ponds evaluated were taken from Piyungan Pleret, Jetis, Imogiri, and Kalasan districts. The position of the ponds ranged between about 1 km to 4 km from the Opak River. The rice field sites were located in Piyungan, Pleret, Jetis, and Imogiri, and the distances of the site locations downstream of the Opak River ranged from about 2 km to 20 km.

Sampling protocols. Samples were collected, including river water, sediment, and biota, to assess Cr(VI) contamination in various ecological elements of the Opak River. Three replicates of each sample type were collected to determine the Cr(VI) pollution level in the examined sites. River water samples were taken at half the total river depth. The 100 g water samples were taken with a plastic scoop (according to a local standard tool of SNI 6989.57:2008 (SNI 2008). Samples from respective industries with proper wastewater treatment were also collected. Besides river water, samples of river biota, namely aquatic plants (*Ipomoea aquatica*) and fish (*Oreochromis niloticus* and *Osteochilus vittatus*) were also collected. Meanwhile, instead of a grab sampler, the sediment was taken (±100 grams) using a shovel (USEPA 2001). Samples from fish farming, such as water, sediment, and fish products, were examined in this study. Samples of fish cultivation ponds were determined based on the distribution of small-scale fish farming groups spread across the study sites in Piyungan, Pleret, Jetis, Imogiri, and Kalasan as the comparison sites. In each district, four of the farming ponds were randomly selected from the list. The fish farming products chosen were catfish (*Clarias gariepinus*) and tilapia (*Oreochromis niloticus*), as these fish types are widely consumed by the local people (KKP 2021). The fish samples were taken using fishing nets and then randomly selected with three replications. Furthermore, similar river water and sediment samples collection methods were applied to gather fish farming pond water samples in each study site.

Rice samples from Piyungan, Pleret, Jetis, and Imogiri were gathered to assess the level of Cr(VI) pollution. Each rice sample from each study site was mixed until homogenous and taken randomly for laboratory analysis, amounting to 180 rice samples (forty-five per site at 100 g/sample).

Water samples analysis. Water samples were extracted by adding 10 ml of concentrated HNO_3 to 100 ml of the water samples. The sample was heated at 100°C until the remaining volume of ±50 ml. This procedure was repeated once with the addition of concentrated HNO_3 and heating of the sample. The extracted water was filtered using filter paper soaked with 1% HNO_3 and then stored in a sample bottle. The acid digestion of sludges, solids, and soils method 3050B was used (USEPA 1996). The solid sample was heated using an oven at 60°C until the sample was dry. The 3 g of dried samples were added with 18 ml of HCl and 6 ml of concentrated HNO_3 and heated until the volume remained at ±10 ml. The procedure was repeated once concentrated HCl and HNO_3 solutions were added to the sample and heated. The sample was then filtered using filter paper soaked in 1% HNO_3.

Biota samples analysis. The biota samples (aquatic plants, mollusc and fish samples) were extracted using the acid method, by which 2 g of each sample was taken and placed into an Erlenmeyer flask. The aqua regia was then added (HNO_3:HCl=3:1), reaching a volume of 10 ml. The sample was heated using a stove, and this process was repeated twice. The extracted sample was later transferred into a 10 ml volumetric flask. If the volume was less than 10 ml, distilled water was added. Afterward, the extract was filtered using filter paper. Cr(VI) was measured using atomic absorption spectrophotometry (AAS) method based on SNI 06-6989.17-2004 (SNI 2004). The analysis process was carried out with the PerkinElmer PinAAcle 900T atomic absorption spectrometer.

Rice samples analysis. The rice sample was placed in a beaker and dissolved in distilled water at a temperature range of 75–80°C for 10 minutes. The rice to distilled water ratio was 1:3, resulting in 15 grams of rice and 45 ml of distilled water. The sample was filtered using filter paper into a 100 ml Erlenmeyer flask, transferred to a sample bottle, and labelled. The spectrophotometer used to measure Cr(VI) in rice water was the HACH 2700 1.5-diphenylcarbohydrazide technique (Method 8023, Powder Pillows), which is the USEPA-approved standard Method 3500-Cr B. Cr(VI) in rice water was analyzed using H.A.C.H. DR 2700, program 90 for Cr(VI). Subsequently, 10 ml of the extracts were placed into the sample cell. After that, the extract was added by one ampoule of ChromaVer 3 Reagent Powder Pillow and stirred until it turned purple, indicating the formation of Cr(VI). After 5 minutes, the sample was placed into a cell holder, and Cr(VI) concentration was determined in a unit of mg/l.

Valuation of river provisioning ecosystem services for fish farming. The evaluation of the Opak River's ecosystem services, particularly its provision of clean water for small-scale fish farming (fish farming ponds) by local communities, was conducted using the market valuation method (Lu 2022), which was used as an indicator of society implications in this paper. Economic valuation was carried out on the most widely cultivated fish species including *Clarias gariepinus*, *Oreochromis niloticus*, *Pangasius* spp., *Osphronemus goramy* and *Colossoma macropomum*. Changes in the water quality of the Opak River resulted in productivity changes and the quality of fish farming pond products. Product market prices were used to calculate changes in output value and potential economic losses or benefits caused by environmental changes. Calculation of the monetary value of small-scale fish farming ponds was carried out using the following equation:

$$RESFF = TFP \times P$$

Where RESFF (river ecosystem services for fish farming) is the total value of river ecosystem services for fish farming, TFP (total fish production) is the annual total fish production, multiplied by P (price) which is the price of fish per kg determined by the local market.

Data analysis. A data normality test was carried out by examining the *p*-value level using the Kolmogorov-Smirnov test. The homogeneity test was conducted using Levine's equality of error variance test. One-way ANOVA and independent T-test were used to analyze non-categorical and normally distributed data, mainly the level of contamination across the evaluated districts based on the tested samples (water, sediment, fish, etc.). A *p*-value of less than 0.05 was designated for statistical significance in all analyses. Statistical analysis was carried out using SPSS 21.0. Meanwhile, R software version 4.3.3 performed data visualizations of Cr(VI) levels in the samples.

Results

Wastewater discharge and its effect on river water. Via field observations, the 13 tannery industries had production capacities of 6,000,000 – 12,000,000 square feet/year. From these production capacities, the daily volume of wastewater generated from each sector is 100 – 200 m^3/day, estimating the total wastewater volume of between 1,300 and 2,600 m^3/day produced by all the industries. Preliminary monitoring conducted by the Environment and Forestry Service of Special Region of Yogyakarta Province from July 2022 to May 2023 observed that Cr(VI) in the wastewater discharge point of the industry equipped with wastewater treatment ranged from 0.0152 to 0.1613 mg/l with an average of 0.0696 mg/l. This concentration was far below the effluent quality threshold (0.5 mg/l), determined by Regional Regulation Number 7 (Regional Regulation of the Special Region of Yogyakarta 2016) concerning wastewater quality standards for leather tanning industry activities (using chrome). The average Cr(VI) concentration from the referral industry during monitoring was still below the required maximum permittable value (>0.5 mg/l) as specified in the local regulation of Provincial Regulation Number 7 (Regional Regulation of the Special Region of Yogyakarta 2016) concerning quality standards of wastewater for the tannery industry. This indicated that the wastewater effluent met the requirements for discharge into water bodies (<0.5 mg/l). Despite the referral industry's effluent showing lower Cr(VI) levels than the permittable limit, our study showed that the Cr(VI) levels in the water bodies of examined sites surpassed the required standard of 0.05 mg/l determined by local regulation (PERGUB 2008). The average concentration of Cr(VI) ranged from 0.118 to 0.177 mg/kg/l (Table 1).

Table 1

Cr(VI) concentration of water samples in examined site

Water samples	*Cr(VI) concentration (mg/l/kg)*		
	Range	*Mean*	*Standards*
Effluent industries	0.0152 - 0.1613	0.0696	0.5*
Opak River			
Kalasan	0.000-0.010	0.003	0.05**
Piyungan	0.108-0.158	0.129	
Pleret	0.105-0.138	0.117	
Imogiri	0.108-0.158	0.125	
Pundong	0-108-0.156	0.397	
Estuary	0.108–0.211	0.180	

Note: * The water quality standards used are in accordance with DIY Regional Regulation No. 7 (Regional Regulation of the Special Region of Yogyakarta 2016) concerning wastewater quality standards for leather tanning industry activities (using chrome); ** Special Region of Yogyakarta Province Governor Regulation Number 20 (PERGUB 2008) concerning water quality standards in the Special Region of Yogyakarta Province.

Cr(VI) concentration and accumulation in various types of samples. The Cr(VI) concentration of all solid samples in the control site of Kalasan was significantly lower (*p*<0.05) compared to the examined sites of Opak River, indicating Cr(VI) pollution occurred in the examined sites. We generally denoted that the Cr(VI) concentration across the solid samples showed a similar trend. Predominantly, Cr(VI) concentration in all examined sites was in a corresponding order of sediment > fish > aquatic plant. The lowest concentration of Cr(VI) in aquatic plants (*Ipomoea aquatica*) could probably be linked to their ability to remove heavy metals from their tissue. However, among all the examined sites, Imogiri showed a different trend as higher Cr(VI) concentration in fish (*Osteochilus vittatus*) than in sediment (average of 0.963 mg/kg vs 1.480 mg/kg) (Table 2).

Table 2

Average Cr(VI) concentration in various samples (mg/l/kg)

Type of samples	*Sampling location*				
	Kalasan	*Piyungan*	*Pleret*	*Jetis*	*Imogiri*
Water	0.003	0.129	0.117	0.125	0.397
Sediment	0.030	1.360	1.223	0.899	0.963
O. niloticus	0.026	0.638	0.492	0.342	0.322
O. vittatus	0.054	0.776	0.553	1.100	1.480
Ipomea aquatica	0.012	0.124	0.169	0.185	0.162
Molusca	0.049	0.851	0.709	0.707	0.675

Cr(VI) concentrations in rice grains. The Cr(VI) concentration in rice grains was 0.018–0.802 mg/kg with an average of 0.183 mg/kg. In Table 3, it can be seen that the highest to the lowest average of Cr(VI) concentration was detected in the following districts, i.e., Piyungan (0.248 mg/kg) > Pleret (0.206 mg/kg) > Jetis (0.199 mg/kg) > Imogiri (0.171 mg/kg). Different from the trend of Cr(VI) concentrations in water and other solid samples in Opak River, rice samples indicated decreasing Cr(VI) concentrations with the increase of distance. In addition, based on the ANOVA test, it was known that there was a significant difference (p<0.05) of Cr(VI) in rice across the districts; the highest was in Piyungan, followed by Pleret, Jetis, and Imogiri.

Table 3

Cr(VI) concentration in rice grains

No	*Sub-districts*	*Total samples*	*Concentration (mg/kg)*	*Average (mg/kg)*	*SD*	*Sig.*
1	Piyungan	45	0.102-0.480	0.248	0.088	0.002
2	Jetis	45	0.060-0.802	0.199	0.112	
3	Pleret	45	0.069-0.366	0.206	0.07	
4	Imogiri	45	0.018-0.390	0.171	0.079	
5	Pundong	45	0.000-0.724	0.127	0.102	
Total samples		225	0.018-0.802	0.183	0.104	

Cr(VI) concentrations in fish farming ponds. The concentration of Cr(VI) level in all samples (water, sediment, and fish samples) was significantly lower in the control site (Kalasan), and the examined sites (p<0.05). In Kalasan, Cr(VI) concentration was low in sediment and fish. The Cr(VI) concentrations in all media were more profound in the examined sites. Results of the independent t-test showed that there was a difference between tilapia and catfish ponds (p<0.05). Cr(VI) was observed in high concentrations in fish samples, followed by sediment samples, and the lowest in water samples in both tilapia and catfish ponds. The average Cr(VI) concentration in water samples in tilapia ponds was higher than in catfish ponds (0.1242 mg/l vs. 0.0875 mg/l, Table 4). In comparison, the average Cr(VI) concentration in the catfish pond sediment was around four times higher than the average of the tilapia ponds.

Table 4

Concentration of Cr(VI) in fish farming ponds (mean± SD)

Sites	*O. niloticus pond*			*C. gariepinus pond*		
	Water (mg/kg/l)	*Sediment (mg/kg)*	*Fish (mg/kg)*	*Water (mg/kg/l)*	*Sediment (mg/kg)*	*Fish (mg/kg)*
Kalasan	0.0000±0.000	0.0150±0.017	0.0158±0.010	0.0000±0.000	0.0158±0.013	0.0225±0.019
Piyungan	0.0217±0.009	0.1250±0.038	1.5833±0.022	0.0983±0.024	0.7700±0.027	1.3508±0.137
Pleret	0.3458±0.010	0.1833±0.244	1.5833±0.025	0.1433±0.031	0.7025±0.022	1.8983±0.038
Jetis	0.2467±0.004	0.3708±0.119	1.5792±0.030	0.1417±0.002	0.3400±0.017	1.2333±0.112
Imogiri	0.0067±0.013	0.1650±0.573	0.6583±0.037	0.0542±0.013	0.4050±0.031	1.0642±0.024
Average	0.1242±0.004	0.1718±0.380	1.0840±0.057	0.0875±0.012	0.4467±0.045	1.1138±0.079

Note: permittable limit for Cr(VI) in food=2.5 mg/kg (Dirjen POM 1989).

We found that catfish appeared to accumulate more Cr(VI) than tilapia on the control site and examined sites (Table 1) (1.1138 vs. 1.0840 mg/kg). Relevant to the sediment, the average Cr(VI) concentrations were higher in catfish than in the tilapia pond (0.4467 vs. 0.1718).

Potential threats to river ecosystem services for fish farming. Pollution of the downstream Opak River by Cr(VI) can potentially disrupt the use of the Opak River ecosystem services for fish cultivation, agriculture, tourism, angling, and fishing communities. Table 5 shows the results of calculating the economic value of utilizing ecosystem services as a fish-farming water source in four areas affected by Cr(VI) pollution. Based on the calculation of the valuation of ecosystem services for fish cultivation, it is known that the potential loss of income for fish-cultivating community groups is IDR 1,790,500,000. These economic losses are based on the assumption that Cr(VI) contamination of fish causes a decrease in quality and rejection by consumers.

Table 5

Economic valuation of river ecosystem services for fish cultivation due to Cr(VI) pollution

District	*Types of fish cultivated*	*Fish production (kg/year)*	*Selling value at farm level (IDR/EUR/kg)*		*Fish farmer income per year (IDR/EUR)*	
			IDR	*EUR*	*IDR*	*EUR*
Piyungan	*Clarias gariepinus*	12,000	20,000	1.16	240,000,000	13,889.59
	Oreochromis niloticus	5,200	25,000	1.45	130,000,000	7,523.53
	Pangasius sp.	1,300	17,000	0.98	22,100,000	1,279.00
	Osphronemus goramy	700	35,000	2.03	24,500,000	1,417.90
	Colossoma macropomum	900	17,000	0.98	15,300,000	885.46
Pleret	*Clarias gariepinus*	15,600			312,000,000	18,056.47
	Oreochromis niloticus	7,200			180,000,000	10,417.19
	Pangasius sp.	2,000			34,000,000	1,967.69
	Osphronemus goramy	800			28,000,000	1,620.45
	Colossoma macropomum	1,200			20,400,000	1,180.62
Jetis	*Clarias gariepinus*	14,800			296,000,000	17,130.50
	Oreochromis niloticus	5,700			142,500,000	8,246.95
	Osphronemus goramy	600			21,000,000	1,215.34
Imogiri	*Clarias gariepinus*	15,360			307,200,000	17,778.68
	Osphronemus gouramy	500			17,500,000	1,012.78
			Total amount of income		1,790,500,000	103,622.14

Based on the economic valuation of the Opak River's river ecosystem services for fish cultivation, an overview of the magnitude of the financial impact received by the community due to Cr(VI) pollution is obtained. Supposing pollution persists for an extended period and increases in intensity, in that case, it will likely give rise to more complex problems such as loss of jobs, healthy food sources, social conflict, and environmental injustice.

Discussion. Rivers are vital water resources supporting various purposes such as clean water sources, fisheries, agriculture, and even wastewater disposal. Therefore, monitoring river quality, especially for heavy metal parameters such as chromium, must be carried out regularly and consistently to protect water quality and use. The results of this research indicate that the quality of the effluent meets the requirements for wastewater quality standards and is suitable for discharge into the river. The average chromium concentration during monitoring was still below the required maximum threshold value (> 0.5 mg/L) as specified in D.I.Y. Provincial Regulation Number 7 (Regional Regulation of the Special Region of Yogyakarta 2016) concerning wastewater quality standards for the leather tanning industry. However, the water quality of the Opak River has experienced a decline in water quality, with chromium concentrations along the downstream having exceeded the specified threshold (0.05 mg/L). This is caused by the activity of disposing of wastewater, which contains large amounts of chromium and occurs continuously. The results of this research show that there is a difference between the results of monitoring effluent quality and river water quality. This finding indicates that there is a contradiction between the results of monitoring the quality of the effluent that meets the requirements for disposal and the results of the wastewater disposal that causes chromium pollution. Two factors cause the inconsistency between the results of effluent quality monitoring and river water quality. Firstly, not all leather tanning industries located in KIP have carried out water treatment properly and meet the requirements for discharge into rivers. Second, the existing regulations only regulate effluent quality requirements, but the maximum load of liquid waste permitted to be discharged into rivers still needs to be determined. This situation explains the contradiction in monitoring effluent and river water quality results. Even though effluent quality monitoring has met the requirements, the water quality of the Opak River in the downstream area remains polluted by chromium. According to Yang et al (2018), the leather tanning industry is the main factor causing chromium pollution. This is confirmed by several previous studies that have reported that liquid waste disposal from the leather tanning industry reduces river quality (Uddin & Jeong 2021). Disposal of liquid waste from the leather tanning industry into the Opak River causes a decrease in water quality. It will broadly impact on aquatic life (Pushkar et al 2021) and disrupt the ecosystem (Zulfiqar et al 2023). This research shows that the development of the Piyungan Industrial Area needed to be better planned, and environmental values were ignored, thus becoming the leading cause of environmental pollution of the Opak River. This action has significantly increased chromium pollution in the environment, disrupting the natural balance.

The concentration and bioaccumulation of Cr(VI) in environmental elements especially organisms might be influenced by various interacting factors, such as: 1) location and proximity to sources of pollution (Maurya & Malik 2019), 2) types and trophic status of organisms (Anwarul Hasan et al 2022), and 3) environmental conditions, environmental preferences, trophic levels, eating habits, age, sex, duration of metal exposure, and physiological regulatory activities (Arulkumar et al 2017). Meanwhile, Cr(VI) in the food chain is influenced by several transfer factors from water-organism, sediment-organism, and water-sediment-organism media through various processes such as bioconcentration, bioaccumulation, and biomagnification (Ali et al 2019). Considering the large threat of Cr(VI) contamination to the environment and health, it is pivotal to regularly monitor Cr(VI) in river ecosystems and not only in water. In elements such as sediment, aquatic plants and fish, Cr(VI) was absorbed for the next trophic level (Rajeshkumar & Li 2018). The discovery of chromium contaminants in food such as fish and rice is an initial indication that the threat to human health through the food chain is real. The liquid waste disposal activity of the leather tanning industry is a source of river water pollution and contamination of agricultural land and fish cultivation ponds along the downstream of Opak River. The release of industrial waste containing heavy metals poses a serious threat to the environment and human health (Nakkeeran et al 2018). Therefore, many regulatory bodies in various countries, such as the United States Environmental Protection Agency (USEPA), the Food and Agriculture Organization (FAO), and the World Health Organization (WHO) in the United Nations, have strictly regulated the maximum concentrations of metals. permitted toxic traces in foodstuffs (WHO & FAO 2011; USEPA 2000). For chromium (Cr), the maximum limit allowed in rice grains is 1 mg kg^{-1}, while in Indonesia it is regulated in the Decree of the Director General of Drug and Food Research Number 03725/B/SKNII/89 concerning Metal Contamination Limits in Food with concentration limits: the maximum in food is 2.5 mg/kg (Dirjen POM 1989), and these standards have the force of law. Based on WHO criteria (WHO 1988), the chromium content in food that can be consumed is 0.5 ppm per week or 0.07 ppm per day. For this reason, the concentration of chromium in food such as rice is 0.018-0.802 mg/kg with an average of 0.183 mg/kg, and in *Clarias gariepinus* 1.0642 - 1.8983 mg/kg and *Oreochromis niloticus* 0.6583-1.5833 mg/kg, all exceed the threshold limit which is allowed. Consuming fish and other foods contaminated with chromium has the potential to cause health problems (Yin et al 2021), such as nervous disorders, kidney damage, circulatory system disorders, and increased risk of cancer (WHO 2006).

Utilization of the Opak River flow, which is contaminated with hexavalent chromium, has contaminated fish cultivation ponds developed by community groups. Contamination of hexavalent chromium in fish cultivation ponds causes the accumulation of hexavalent chromium in *Clarias gariepinus* and *Oreochromis niloticus*, thereby reducing the quality and making them unsafe for consumption. The market will likely reject fishery products if the public knows this situation well. This means a potential loss of community income of 1,790,500,000 IDR or 113,538,363 USD. The results of this research provide an overview of the impact of hexavalent chromium pollution on the water cycle and its implications for human life through the direct use of water for food production, especially in the fisheries sector. The results of this research prove that the degradation of river ecosystems not only causes a decline in environmental quality but also causes health problems and has a broad impact on the community's socio-economic system. The degradation of river ecosystems reduces the ability to provide ecosystem services, thus potentially causing negative impacts on the health and social and economic aspects of communities (UNEP 2016). Therefore, in assessing the impact of heavy metal (chromium) pollution on river ecosystems, it is conceptually essential to encourage the integration of environmental risk assessment and evaluation of ecosystem services (Maltby et al 2017). Ecosystem services assessment provides an integrative approach in which chemical impacts on water and land can be evaluated simultaneously, allowing risk managers to evaluate trade-offs and synergies. This integration is essential to provide comprehensive data in the decision-making process regarding biodiversity management and conservation (Faber et al 2019). This is based on the fact that biodiversity, ecosystem function, and ecosystem services together maintain health and provide benefits for humans in terms of productivity, clean water, healthy food, and fresh air, as well as suppressing disease-causing microorganisms (Leclère et al 2020).

Disposing of liquid waste containing chromium has the potential to have destructive circular impacts, starting from chromium contamination of river ecosystems, decreasing river water quality, impacting aquatic life, water supply ecosystem services, socioeconomics, and health to business sustainability in the area (Figure 3).

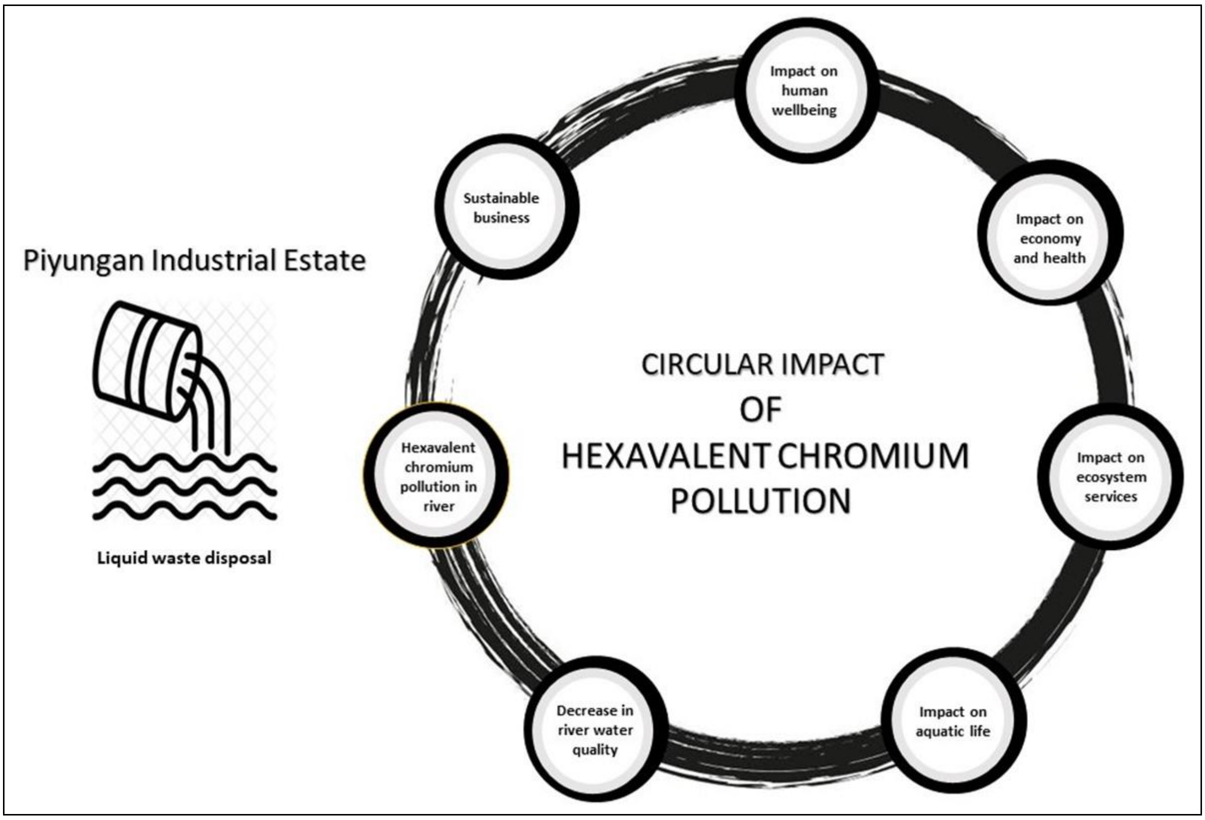

Figure 3. Destructive circular impact of hexavalent chromium pollution on Opak River with direct use for food production.

Utilization of Cr(VI)-polluted river water increases the opportunity for trophic transfer of Cr(VI) pollutants from the main source to the waters and into the food web (Ali & Khan 2019). Water pollution threatens human health and the environment, but also economic growth and social progress (Ezbakhe 2018). This study proves that chromium pollution causes a decrease in river water quality, contamination of food products, decreased river biodiversity and has health and socio-economic impacts on the community. Based on the results of this study, neglecting the handling of chromium pollution cases in the Opak River has the potential to be a threat to the achievement of sustainable development goals. Poor water quality has significant economic impacts, hampering the socio-economic development of communities (WHO 2004), thus threatening the achievement of SDGs 1-3, namely "No poverty", "End hunger" and "Good health and well-being". The increasing cases of river pollution are an indication of the failure to achieve SDGs 6, namely "Clean water and sanitation" and SDGs 9 "Industry, innovation and infrastructure" (Ezbakhe 2018). River pollution causes failure to achieve SDGs 10, namely "Reduced inequalities". River pollution illustrates the existence of inequalities in environmental exposure that disproportionately burden segments of society that are less politically powerful, including racial and ethnic minorities, and can result in higher levels of pollution overall (Cushing et al 2015). This condition implies that the Opak River needs to be managed appropriately and integrated. It has been proven that optimizing use by the industrial sector, especially as a water body receiving wastewater, has decreased water quality and detrimental use for other sectors. Meanwhile, FAO (2008) requires that the sustainability of food production be realized only with proper water management. It was further stated that river water quality management greatly determines ecosystem productivity, guaranteeing fishing results and the livelihoods of local communities. Therefore, efforts to control Cr(VI) pollution and manage the water quality of the Opak River are urgently needed. With efforts to control and manage water quality, the desire to achieve food security and protect local livelihoods will be possible (FAO 2008). The pathway to sustainability requires a secure supply of ecosystem services that contribute to human well-being (Griggs et al 2014).

Through this research, we know that the industry's use of river ecosystem services as a "place for waste disposal and purification" has been proven to disrupt the use of other ecosystem services such as fisheries and agriculture. River ecosystems become unhealthy due to the presence of Cr(VI), non-biodegradable, chronic poison, and capable of environmental bioaccumulation and biomagnification through the food chain, thus seriously threatening human health (Liu et al 2018). Meanwhile, Aldridge and Baker (2017) stated that only a healthy river ecosystem can provide human welfare and livelihoods and maintain ecosystem functions. Conversely, degraded rivers will be unable to provide quality ecosystem services, which will disrupt cycles and impact society. PIA, through the activity of discharging wastewater containing Cr(VI) into the Opak River, has been proven to cause a decrease in water quality and has an impact on the environment, health, and socioeconomics of communities along the downstream Opak River. This pollution case has given rise to demands from the public and government for business activities to pay attention to the negative impacts of their operational activities through increasing environmental management activities. Pressure on businesses to operate environmentally friendly is increasing (DeBoe 2020). Pressure on the business world can arise from various stakeholders such as society, NGOs, the government, and various international bodies (Ahmad et al 2021). If this condition is taken seriously, it will have a boomerang effect on business actors, namely the sustainability of their business. Environmental sustainability is an essential factor in business operations, which is caused by the scarcity of natural resources (Tsuboi 2019) and increasing consumer awareness about environmentally friendly manufacturing practices carried out by companies (Sarkis & Zhu 2018; Afum et al 2020). Environmental sustainability has become essential to safe and healthy business activities (Sandrin et al 2018).

Consistent efforts to mitigate Cr(VI) pollution in river ecosystems, especially in Indonesia, are required as input in developing integrated and sustainable management strategies. Hence, intense cooperation from all stakeholders, such as the local government, private sector, and society, is imminent (Lu 2022). Considering the circular impacts of Cr(VI)-containing wastewater discharge in our case study, it is urgent to conduct future monitoring covering Cr(VI) distribution routes, waste production processes, transfer and bioaccumulation in the food chain, and water-food and food-human relationships. Effective monitoring and surveillance are needed for an integrated approach, which reduces the adverse impacts of Cr(VI) on local ecological elements and livelihoods.

Conclusions. From local ecological perspectives, our study revealed that all the examined sites downstream of Opak River were exposed to Cr(VI) pollution resulting from wastewater discharges of tannery industries in PIA. There were significant differences in Cr(VI) concentration in examined samples between the control site and examined sites ($p<0.05$). We found that Cr(VI) concentrations did not decrease with the increase in distance from the wastewater discharge point for water and solids to the Opak River. However, this trend was not observed in rice grains taken from each examined site. Besides, we confirmed that Cr(VI) tended to accumulate in catfish (*Clarias gariepinus*) rather than tilapia (*Oreochromis niloticus*), as investigated from some fish farming ponds both in control and examined sites. From local socio-economic perspectives, we observed that the ecosystem services of Opak River water were affected mainly by the quality of fish farming products due to the contamination of Cr(VI). Cr(VI) posed a circular impact on the local environment, economy, and social community, requiring further consideration and integrated alternatives of local stakeholders to support socio-economy and environmental stability. River pollution and its associated impacts will ultimately impact business sustainability in the area with the emergence of pressure from the community and government so that businesses care more about environmental sustainability.

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