

# INTEGRATED RESPONSE TO HEXAVALENT CHROMIUM RIVER POLLUTION FOR ENVIRONMENTAL AND HUMAN HEALTH PROTECTION

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**Abstract.** An analysis of hexavalent chromium, Cr(VI), pollution in river ecosystems was carried out using the Driver, Pressure, State, Impact, Response (DPSIR) framework to identify key drivers, pressures, water quality decline, and the resulting environmental, health, and socio-economic impacts. The DPSIR approach effectively highlights the interconnections between these elements and supports pollution prevention and water quality management efforts in the Opak River. Cr(VI) contamination is primarily driven by economic and political pressures, weak regulations, and overlapping institutional authority. The discharge of untreated Cr(VI)-containing waste leads to serious ecological degradation, health risks, and socio-economic challenges, threatening community well-being and business sustainability. Addressing this issue requires a comprehensive strategy that includes clear policy formulation and enforcement, improved river ecosystem management, institutional coordination, and enhanced community awareness and capacity building to promote long-term sustainability and protect public health and the environment.

**Keywords:** Cr(VI), health impact, industrial area development, river pollution

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## INTRODUCTION

Hexavalent chromium, Cr(VI), is a global environmental pollutant that increases the risk for several types of cancers and is increasingly being recognized as a neurotoxicant (Wise *et al*, 2022). Cr(VI) and its metabolites, particularly chromates, take a distinct route into the human body. The main routes of Cr(VI) exposure include inhalation, ingestion, and skin contact. Depending on the duration, Cr(VI) exposure can be classified as acute (14 days), intermediate (75–364 days), and chronic (365 days) (Shekhawat *et al*, 2015; Yang *et al*, 2020). The World Health Organization's International Agency for Data on Cancer (IARC) has classified Cr(VI) compounds as group one human carcinogens with several complex modes of action based on epidemiological research tying Cr(VI) to lung cancer (Seidler *et al*, 2013; Junaid *et al*, 2016). Eardrum perforation, irritations, allergies, eczema, respiratory tract issues, skin irritations, ulceration, and lung cancer have all been linked to human exposure to Cr (VI) (Focardi *et al*, 2013).

Environmental pollution by Cr(VI) pollutants is receiving increased attention because of its widespread distribution worldwide (Pradeep *et al*, 2021). The development of industrialization in various countries is a potential environmental threat due to pollution, especially in river ecosystems, thus limiting sustainability (Alexakis, 2021), whereas the tanning industry is considered to be the most polluting sector because it produces toxic pollutants, in particularly Cr(VI) throughout the process

(Pure Earth, 2016). To produce one ton of raw leather requires about 30 to 40 m<sup>3</sup> of water and about 300 kg of chemicals. Chromium salts are the main chemicals in the tanning process, generally chromium is found in leather waste ranging from 10 to 1000 mg/l, far exceeding the required concentration limit (Suman *et al*, 2021).

Many studies have been conducted to evaluate chromium pollution. Generally, the research that has been conducted is partial, only focusing on certain aspects, such as; the level of chromium pollution in aquatic ecosystems (Singh and Sharma, 2018; Maurya and Malik, 2019; Tayone *et al*, 2020; Tumolo *et al*, 2020; Chen *et al*, 2022). Distribution and accumulation of chromium in waters (Vitasari *et al*, 2020; Ma'dika *et al*, 2021; Puspitasari *et al*, 2021; Chen *et al*, 2022), and chromium accumulation were also observed in food materials such as aquatic plants, rice and fish (Baki *et al*, 2018; Korkmaz *et al*, 2019; Arisekar *et al*, 2020; Gholamhosseini *et al*, 2021). Furthermore, several studies have revealed implications on health risks through the consumption of food products such as rice, vegetables and fish (Wahiduzzaman *et al*, 2022; Xiang *et al*, 2021; Zhang *et al*, 2021; Infante *et al*, 2021; Zulkafflee *et al*, 2021).

Various research on Cr(VI) pollution monitoring and water management generally use the "State-Impact Oriented" approach (Song *et al*, 2015), which produces reactive responses such as increasing waste processing and reducing emission concentration limits, while the root causes of pollution problems are often not identified. Considering the limitations of monitoring with a status-impact-oriented approach, it is necessary to develop a more holistic, interdisciplinary, and pressure-oriented approach (Song *et al*, 2015). One of the most widely applied interdisciplinary approaches to analyzing various environmental problems is the Driver-Pressure-State-Impact-Response (DPSIR) approach (Labianca *et al*, 2020). The DPSIR model states how socioeconomic development affects the environment and shows the relationships between environmental, economic, and social "cause and effect" (Khan *et al*, 2021).

The DPSIR framework has been widely applied to assess environmental impacts. Under the Water Framework Directive, it supports groundwater, surface water, coastal water protection, and alien species assessment. It has been used to evaluate coastal development impacts (Lin *et al*, 2007), assess pre- and post-intervention conditions (Nobre, 2009), and identify sustainability indicators (Bell, 2012). DPSIR also helps explore coastal vulnerability (Newton and Weichselgartner, 2014), assess urban expansion impacts on water balance (Haase and Nuissl, 2007), and address environmental issues in river basins for integrated management planning (Kagalou *et al*, 2012).

However, studies applying the DPSIR framework within a socio-ecological systems context to analyze heavy metal pollution, such as Cr(VI) in river ecosystems, remain limited, despite their importance for informing policymaking. Hence, this study explores the interrelationship between drivers, pressure, state, and response to Cr(VI) pollution in the Opak River to prevent further Cr(VI) pollution and encourage river water quality management.

## MATERIALS AND METHODS

### **Time frame and research design**

The research was done in Bantul Regency, Special Region of Yogyakarta (Daerah Instimewa Yogyakarta or DIY) Province, Indonesia, within the coordinate boundaries: 7°51'12" S–8°3'46" S and 110°15'57" E–110°25'26" E. The river ecosystems investigation was conducted from May to September 2023 in the downstream Opak River basin, Bantul Regency. Observations were carried out in the Piyungan Industrial Area (PIA), focusing on the environmental conditions along the river, rice field areas, and small-scale fish farming businesses.

### Case description: Cr (VI) pollution in the Opak River

The Cr(VI) pollution study area spans the downstream section of the Opak River, from the PIA wastewater discharge point in Sitimulyo Village, Piyungan, to Imogiri District (Fig 1). This river segment supports various community activities, including fishing, farming, tourism, and sand mining. Since 2013, the 373.07-ha Piyungan Industrial Area (PIA) has been developed by the local government, though only Area 1 (17.32 ha), home to 13 leather tanning factories, is currently active. Despite its eco-friendly label, only one of the 13 tanning factories has proper waste management and environmental. Untreated liquid waste from Area 1 flows into the Opak River, posing serious environmental and public

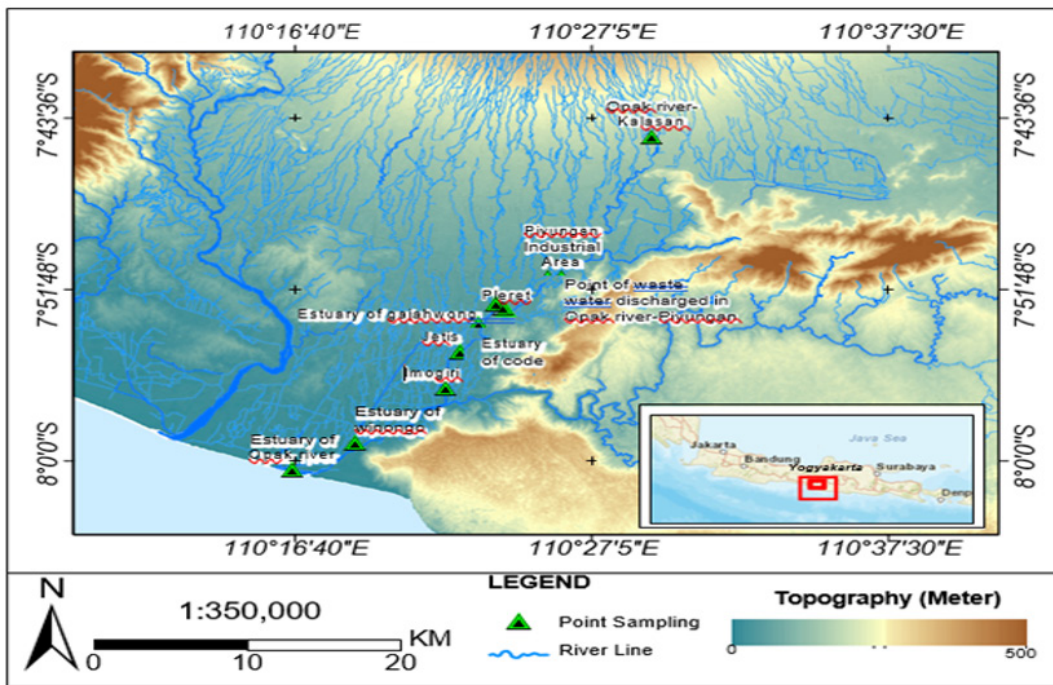


Fig 1 - Location map of the Piyungan industrial area and distribution of the areas that have the potential to become “sacrifice zones” due to liquid waste disposal activities containing Cr(VI)

Cr(VI): hexavalent chromium

health risks. Liquid waste from PIA Area 1 is channeled through a piping system as it enters the Opak River, and flows into the southern coast of the Bantul Regency.

### **Data collection methods**

This study gathered both primary and secondary data, covering environmental, economic, and social aspects, along with DPSIR elements (Table 1). Primary data were obtained through field observations and interviews with 26 respondents, including river users (farmers, anglers, fishers, tourism actors, and locals), government officials (district, provincial, and national levels), monitoring agencies, and industry representatives responsible for waste management. Interviews were conducted directly by researchers using a two-part interview guide: the first part collected personal information, while the second focused on the respondent's connection to each DPSIR element.

### **Data analysis**

We tested data normality using the Kolmogorov-Smirnov test. With the results, we analyzed Cr(VI) level in all points of collection in Opak river water and the control area, as well as land use area data comparisons using the Kruskal-Wallis test, followed by the Bonferroni test for pairwise evaluation. We performed all statistical analyses using the Statistical Package for the Social Science (SPSS) version 26 (IBM Corp, Armonk, NY), with a designated significant level as  $p$ -value  $<0.05$ .

### **Ethical consideration**

The research protocol involving respondents was reviewed and approved by the Regional Development Planning Agency, Bantul Regency

(No: 070/Reg/0012/PT/2023). All respondents participated voluntarily based on informed consent and were kept anonymous in all reports.

Table 1  
DPSIR elements and research data sources

DPSIR elements	Sources
Driver and pressures	Driving force data were obtained through secondary data reviews in the form of effluent quality monitoring reports, as well as structured observations and interviews with stakeholders (regency, province, and central) of the provincial Environment and Forestry Service, Bantul Regency Environment Service, DIY Province Regional Secretary, and Bantul Regency Regional Development Planning Agency.
State	For describing changes in environmental status, specifically the decline in water quality due to the discharge of liquid waste containing Cr(VI), primary and secondary data collection was applied. Primary data included analyzing water samples for the Cr(VI) pollutant content. Secondary data were in the form of monitoring the results of river water quality and effluent conducted by the DIY Province Environmental and Forestry Service.
Impacts	An overview of the magnitude and extent of the impact of Cr(VI) pollution was obtained through the collection of secondary data from previous research results (Rahardjo <i>et al</i> , 2021a; Rahardjo <i>et al</i> , 2021b; Rahardjo <i>et al</i> , 2023). Utilizing direct observation, interviews, valuation of ecosystem services for fish farming and analysis of local people’s health risks through consumption of fish contaminated with Cr(VI).
Responses	Data and information related to the response were obtained from interviews with stakeholders, including river user communities such as farmer groups, fish farmers, fishermen, anglers, tourism actors and local communities (14 respondents); industry (3 respondents); monitoring institutions (5 respondents); and public administrators (4 respondents).

Cr(VI): hexavalent chromium; DIY: Daerah Istimewa Yogyakarta; DPSIR: Driver, Pressure, State, Impact, Responses

## RESULTS

### **Driving forces of Cr(VI) pollution**

Economic factors are the main drivers of Cr(VI) pollution in the Opak River. The 2015 PIA project aims to boost investment, jobs, and economic growth. However, this development lacked proper waste management facilities and strong monitoring systems. From 2014 to 2017, tanneries dumped waste into irrigation channels, passing through residential areas before reaching the river. Since 2018, waste has been directly discharged into the Opak River through pipes. This shows ongoing government neglect and weak enforcement by river management authorities. Cr(VI) pollution remains unmonitored due to unclear discharge rules, lack of specific standards, and poor regulation. Political pressure and overlapping responsibilities further prevent effective action. Key informants highlighted these issues, which reflect a national problem - 67.94% of rivers in Indonesia are heavily polluted (Ministry of Environment and Forestry, 2021). Addressing these challenges requires clear regulations, regular monitoring, better coordination among authorities, and active community involvement to protect the environment and public health.

### **Pressure and state on the river ecosystem**

The results of observations and interviews with informants who manage the Waste Treatment Plant for leather tanning industry revealed that in the PIA, there are 13 leather tanning plants with production capacities varying between 5574.2 to 1114.8 m<sup>3</sup> of raw leather material/year. From this production capacity, 100-200m<sup>3</sup>/day of liquid waste will be produced for each location; therefore, the total liquid waste produced will be 1,300-2,600 m<sup>3</sup>/day. Monitoring results during the 2022-2023 period showed that the concentration of Cr(VI) pollutants in

the effluent ranged from 0.0152–0.1613 mg/l with an average of 0.0696 mg/l. This concentration is far below the effluent quality threshold set in DIY Regional Regulation No. 7 of 2016, concerning wastewater quality standards for leather tanning industry activities (using chromium), which is 0.5 mg/l (Governor of the Special Region of Yogyakarta, 2016)). Since the other plants' amount and quality of effluent discharged into the Opak River is unknown, this condition can cause an escalation of Cr(VI) pollution in the Opak River.

The water quality state of the Opak River is determined based on its compliance with class II water quality standards (Governor of the Special Region of Yogyakarta, 2008) for the Cr(VI) parameter, with the maximum limit set at 0.05 mg/l. The continuous discharge of liquid waste from the leather tanning industry from PIA has proven to be the main contributor to the decline in the water quality of the Opak River. Table 2 shows that the Cr(VI) concentration in the downstream part of the Opak River, from the waste disposal point in Piyungan to the Opak River estuary, averages 0.117-0.397 mg/l.

### **Impact of Cr(VI) pollution on the river ecosystem**

The practice of discharging liquid waste from KIP through irrigation channels and piping systems into the Opak River has a broad impact on environmental, health, and socio-economic conditions as well as business sustainability. Table 3 describes the destructive impact of Cr(VI) pollution on the downstream Opak River.

### **Response to Cr(VI) pollution prevention and water quality management**

Stakeholder response analysis highlights integrated efforts to address Cr(VI) pollution in the Opak River. Table 4 presents recommendations based on stakeholder views, emphasizing pollution

prevention and integrated water quality management. Responses are grouped into three key areas: policy and implementation, river ecosystem management, and capacity building, with a focus on community welfare

Fig 2 depicts the application of the DPSIR explaining the interrelationships between driving forces (economic, political, regulatory, and institutional) and pressures (wastewater discharge practices) that have implications for the water quality status of the Opak River.

## DISCUSSION

The average concentration of Cr(VI) in the downstream of the Opak River has exceeded the maximum limit of 0.05 mg/l. This concentration

Table 2  
Hexavalent chromium concentration in the Opak River water

Location	Cr(VI) concentration (mg/l)		Standard* (mg/l)
	Range	Mean	
Kalasan (Control)	0.000 - 0.010	0.003 <sup>b,c,d,e,f</sup>	0.05
Piyungan	0.108 - 0.158	0.129 <sup>a</sup>	
Pleret	0.105 - 0.138	0.117 <sup>a</sup>	
Imogiri	0.108 - 0.158	0.125 <sup>a</sup>	
Pundong	0.108 - 0.156	0.197 <sup>a</sup>	
Estuary	0.108 - 0.211	0.180 <sup>a</sup>	

Note: Chromium level data were compared using the Kruskal-Wallis test and followed by the Bonferroni test for pairwise evaluation

\*Governor of the Special Region of Yogyakarta (2008)

<sup>a</sup> $p < 0.05$  with Kalasan (control); <sup>b</sup> $p < 0.05$  with Piyungan; <sup>c</sup> $p < 0.05$  with Pleret; <sup>d</sup> $p < 0.05$  with Imogiri; <sup>e</sup> $p < 0.05$  with Pundong; <sup>f</sup> $p < 0.05$  with Estuary

Cr(VI): hexavalent chromium; mg/l: milligram per liter

Table 3  
Impact of Cr(VI) pollution on the Opak River

Impact category	Description
Comfort and aesthetics	The river water smells badly, is cloudy, colored, or foamy so it cannot be used by the community for bathing and washing clothes and interferes with the aesthetics.
Ecology	Biota contamination, fish mortality, decline in population and diversity of endemic fish, such as <i>Osteochilus vittatus</i> (Nilem), <i>Barbonymus gonionotus</i> (Bader), <i>Channa striata</i> (Gabus), <i>Anguilla spp</i> (Eel), <i>Mystacoleucus obtusirostris</i> (Wader kepek), <i>Lepidocephalichthys hasseltii</i> (Uceng, Sereni), <i>Hampala macrolepidota</i> (Hampala).
Public Health	Itchy skin, consumption of drinking water, and various foods contaminated with chromium has the potential to cause health problems, both non-carcinogenic and carcinogenic. Chromium contaminants have been identified in the blood, urine, hair and nails of local residents and tannery workers in PIA.
Economy	Increased economic burden on the community, declining food quality (fish, rice, and various vegetables), food products rendered non-competitive for sale or export, decreased income, decreased tourism and fishing activities. The potential economic loss does not include the decline value of the fishermen's catches, tourism activities, and water treatment costs that are realized by fish farmers and the local water company of Bantul Regency because they use polluted river water sources, etc.

Cr(VI): hexavalent chromium; PIA: Piyungan Industrial Area

is the same as the maximum limit set by WHO (2011) for river water quality. Meanwhile, at the control location, the Cr (VI) concentration was very low (average: 0.003 mg/l). The Cr (VI) concentration at the location affected by the wastewater discharge was 2-4 times higher than the required limit. The concentration of Cr (VI) pollutant in river water (0.117-0.397 mg/l) in this study was much higher compared to the study

Table 4

## Integrated response to Cr(VI) pollution prevention and water quality management of the Opak River

Responses	Programs
Policies and Implementation	<ol style="list-style-type: none"> <li>1. Create regulations and guidelines for implementing environmentally friendly strategies and production methods for the leather tanning industry.</li> <li>2. Conduct studies and prepare regional regulations regarding the waste load permitted to be discharged into water bodies and determine Cr(VI) parameters as variables that must be monitored in various environmental components such as water, sediment, and biota.</li> <li>3. Increase compliance with regulations and perform strict monitoring and enforcement of all business actors.</li> <li>4. Strengthen the executive powers of the institutions responsible for the sustainable management of water bodies by the relevant national, regional, and local political authorities.</li> </ol>
River Ecosystem Management	<ol style="list-style-type: none"> <li>1. Conduct regular water quality monitoring, specifically include Cr(VI) parameters in the monitoring program.</li> <li>2. Impose Cr(VI) remediation and restoration river ecosystem restoration programs.</li> <li>3. Restock endemic fish.</li> <li>4. Improve thorough communication and synchronization between institutions that have the authority to manage Opak river ecosystems.</li> </ol>
Capacity building and Community Welfare	<ol style="list-style-type: none"> <li>1. Technical training for business actors, river ecosystem managers, and communities to increase awareness of environmental protection.</li> <li>2. Coordination between stakeholders to increase participation in pollution prevention and river water quality management.</li> <li>3. Training in satisfactory fish farming methods, development of organic farming, development of river-based livelihoods - river tourism, river biodiversity management (water hyacinth plants, fish, <i>etc</i>), fishing, water sports, <i>etc</i>.</li> </ol>

Cr(VI): hexavalent chromium

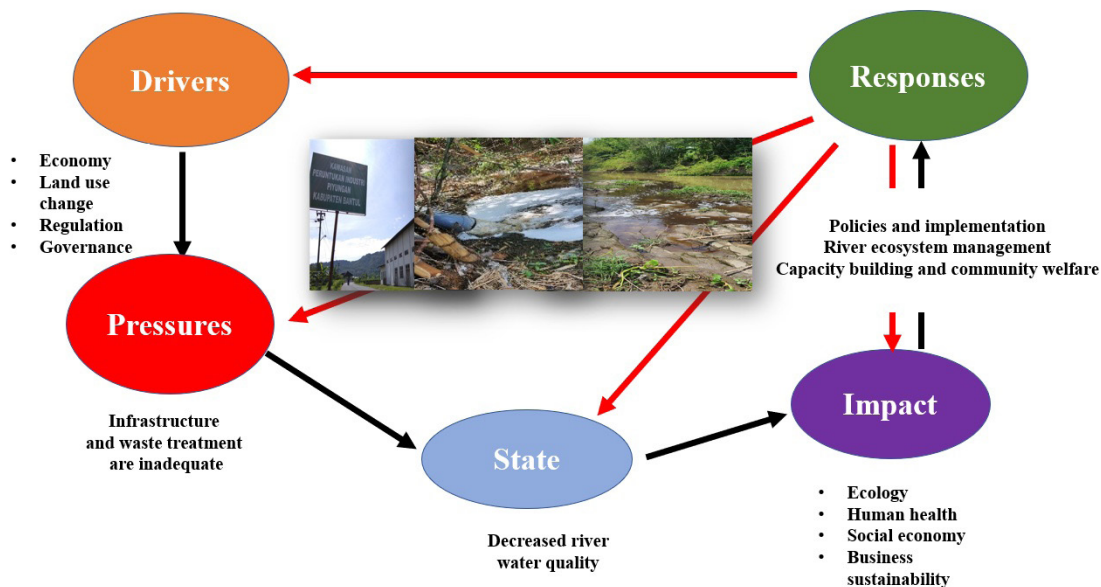


Fig 2 - Interaction patterns between DPSIR elements in cases of Cr(VI) pollution in river ecosystems

Cr(VI): hexavalent chromium; DPSIR: Driver, Pressure, State, Impact, Responses

conducted by Rahardjo *et al* (2021a), with a Cr (VI) concentration range of 0.0521-0.0590 mg/l. The decline in water quality of the Opak River due to Cr(VI) pollution is a serious threat to the environment, health, and socio-economic conditions of communities along the downstream of the Opak River (Rahardjo *et al*, 2021a; Rahardjo *et al*, 2021b; Rahardjo *et al*, 2023).

Cr(VI) levels in the downstream part of the Opak River were significantly higher than at the control site in Kalasan, an area without industrial activity ( $p < 0.05$ , Table 2). However, the differences between Cr(VI) levels at various points along the Opak River were not statistically significant. Comparison of Cr(VI) levels in 2000 (before the presence of PIA) and in 2024 (after waste disposal activities) showed a gradual

increase in the downstream river, which was most likely caused by environmental factors at each sampling point (Rahardjo *et al*, 2021a; Rahardjo *et al*, 2021b; Rahardjo *et al*, 2023).

Untreated tannery wastewater is a major source of Cr(VI), which poses a health risk due to its carcinogenic and mutagenic properties (Kotas and Stasicka, 2000; Holmes *et al*, 2008; Kumar and Riyazuddin, 2011). Cr(VI) can be transformed to Cr(III) via reducing agents (eg, Fe(II)), but Cr(III) can also be re-oxidized (Apollaro *et al*, 2019; Vasileiou *et al*, 2019). Dissolved Cr(VI) mainly exists as anionic  $\text{CrO}_4^{2-}$  (Kotas and Stasicka, 2000). These findings underscore the need for improved wastewater treatment in PIA to reduce chromium contamination along with efforts to increase public awareness.

Cr(VI) pollution in the downstream Opak River harms the environment, economy, and society. This study supports findings by Pastapure *et al* (2023) and Ranjan *et al* (2022) who found that leather tanning factories cause serious environmental and health problems due to hazardous waste. Cr(VI) in rivers threatens human health, as many people rely on river water; Encyclopedia of Environmental Health (2011) also noted chromium's broad impacts that damage biodiversity, aquatic habitats, and leading to species loss.

Polluted water exposes nearby communities to diseases caused by harmful substances (Lobo, 2022). Cr(VI) affects several human systems, including respiratory and reproductive health, and can cause genetic damage (Sharma *et al*, 2022). Liang *et al* (2022) emphasized that industrial pollutants like chromium damage ecological foundations and threaten environmental quality downstream. Given these risks, Cr(VI) pollution in the Opak River needs urgent, coordinated action from local and regional stakeholders to support environmental protection and community well-being.

Understanding river socio-ecological systems is key to effective interventions through transdisciplinary collaboration (Fritsch, 2017; Halbe *et al*, 2018). To address Cr(VI) pollution, three aspects are crucial. First, policy development and implementation of green industrial strategy to improve efficiency, reduce waste, and promote sustainability while enhancing regulatory compliance and monitoring are needed (Dai *et al*, 2018; Zameer *et al*, 2020, Troian *et al*, 2021, Wang *et al*, 2023). Second, river ecosystem management must include routine monitoring, remediation (eg, physical and ecological engineering), and better institutional coordination (Johan *et al*, 2023). Third, improving community welfare and environmental awareness is vital. Engaging stakeholders boosts participation in water quality management. Success requires strong policies, capable institutions, human resources, and cross-sector partnerships to support sustainable environmental governance (Nian *et al*, 2019).

In conclusion, the application of the DPSIR approach to the case of Cr(VI) pollution will improve the understanding of the importance of integrated industrial area governance and guide risk assessment of industrial area development in the future. The results of this study can provide a useful framework for various interests and disciplines to make the “complexity of pollution problems” the object of further research to realize the harmony of economic development and environmental sustainability.

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### CONFLICT OF INTEREST DISCLOSURE

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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