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The Impact of Chromium Contamination in Fish and Rice on Public Health Risks along the Opak River in Yogyakarta

Djoko Rahardjo[1,2]†, Gatot Sasongko[3], Suwarno Hadisusanto[4] and Djumanto[5]

[1]Doctoral Program of Development Studies, Faculty of Interdisciplinary, Universitas Kristen Satya Wacana, Salatiga 50711, Indonesia

[2]Departemen of Biology, Faculty of Biotechnology, Universitas Kristen Duta Wacana Yogyakarta, Yogyakarta 55224, Indonesia

[3]Faculty of Interdisciplinary, Universitas Kristen Satya Wacana, Salatiga 50711, Indonesia

[4]Faculty of Biology, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

[5]Department of Fisheries, Faculty of Agriculture, Gadjah Mada University, Yogyakarta 55281, Indonesia

†Corresponding author: Djoko Rahardjo; djoko@staff.ukdw.ac.id

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ABSTRACT

Access to clean water is increasingly threatened by industrial pollution, particularly from the tanning industry, which poses significant health risks and environmental challenges. This research aimed to determine Cr(VI) concentrations in water, sediment, fish, and rice samples from several sites along the river and to analyze the related health hazards. The study was conducted from March 2023 to November 2024, involving samples collected from 40 fishponds and rice fields located at different distances from the industrial area. Water, sediment, and fish samples were collected and analyzed to determine the concentration of Cr(VI) using Atomic Absorption Spectrophotometry (AAS) and spectrophotometry methods. A total of 360 samples from fishponds and 180 samples from rice fields were collected. In addition, a survey was conducted on rice and fish consumption patterns among 200 respondents from the affected areas. Cr(VI) concentrations were observed in all impacted locations, with levels significantly exceeding those found in the control area. Cr(VI) accumulation in fish and rice showed a significant increase, with health risk assessments revealing that both noncarcinogenic and carcinogenic risks surpassed safe limits. The findings indicate that industrial wastewater severely contaminates aquatic environments, posing significant health risks due to dietary exposure to Cr(VI). This study provides important insights into the prevalence of Cr(VI) contamination in agricultural and aquaculture systems, links environmental pollution to public health risks, and underscores the importance of regulatory measures to ensure food safety and public health.

INTRODUCTION

Access to clean water remains a critical challenge in the twenty-first century, impacting human health, limiting agricultural productivity, degrading ecosystem services, and constraining economic growth (UNESCO 2023). A major concern for water quality is the rising concentration of pollutants in water bodies, which can undermine the achievement of sustainable development goals (Ezbakhe 2018). Rapid industrialization in Indonesia poses a significant risk of environmental pollution, with river ecosystems being particularly vulnerable. Intensive industrialization and lax environmental regulations have led to significant pollution in many rivers (Liu et al. 2018). Accelerated economic expansion has resulted in serious environmental pollution challenges, with increased heavy metal concentration and accumulation harming freshwater ecosystems (Paschoalini & Bazzoli 2021). Approximately 80% of urban wastewater is discharged into untreated water bodies globally (WWAP 2017), while industries contribute millions of tons of heavy metals to these environments (Mateo-Sagasta et al. 2017).

The tanning industry is considered an ecological threat due to its release of hazardous waste into the environment, which contributes to environmental contamination (SMEP 2018, Suman et al. 2021). The tannery needs around 30-40 m^3 of water and 300 kg of chemicals to process one ton of leather or raw materials (Lofrano et al. 2013). Each tanning process can produce around 20% of leather goods products, while the remaining 60% consists of solid and liquid waste (Sivaram & Barik 2019), which is disposed of into the environment. Tannery significantly contributes to hexavalent chromium pollution, with wastewater exhibiting chromium concentrations ranging from 1 to 77 $mg.L^{-1}$ (Sharma et al. 2020). The discharge of liquid waste by tanneries into rivers has led to a decline in water and soil quality, with chromium contaminants widely distributed across various environmental compartments (Rahardjo et al. 2021a, 2021b, Rahardjo et al. 2023). Restoration efforts are necessary for heavily contaminated land (Irshad et al. 2021). Due to its extensive occurrence, environmental pollution resulting from hexavalent chromium is a worldwide issue (Brasili et al. 2020).

Chromium is classified as a class A carcinogen due to its significant toxicity (Sharma et al. 2021). Chromium exists in various valence states in the environment, with Cr(VI) and Cr(III) being the most stable forms, each displaying unique characteristics. Notably, hexavalent chromium (Cr(VI)) is the main contributor to pollution toxicity (Tumolo et al. 2020, Chen et al. 2022). Cr(VI) is detrimental to vegetation, aquatic species, and microorganisms. Cr(VI) is a potent epithelial irritant and a human carcinogen, ranking eighth on the ATSDR (2020) list. Cr(VI) and its metabolites, especially chromate, represent highly toxic forms that can infiltrate the human body via inhalation, ingestion, and dermal exposure. This exposure can lead to pathological changes in various organs and systems, including the respiratory tract, skin, and gastrointestinal tract, and may also increase cancer incidence and mortality rates (Sharma et al. 2022). Long-term exposure to chromium can lead to digestive disorders, respiratory complications, kidney and liver disorders, genetic alterations, and various other health disorders (Shanker et al. 2005). Chromium-induced river pollution significantly threatens ecological systems through its accumulation and biomagnification in aquatic environments, sediments, and food chains (Rahardjo et al. 2023). Excessive ingestion of chromium, when not metabolized by the body, can result in its accumulation within the intra- or extracellular compartments of organs (Briffa et al. 2020). Chromium has been detected in the tissues of fish sourced from metal-contaminated aquatic environments (Sobhanardakani et al. 2016). The accumulation of chromium in fish and rice may present a risk to both animals and humans.

Research has extensively examined the transmission of contaminants from the environment to food and ultimately to humans. Extensive research has been conducted on the health risks associated with chromium pollutants in aquatic biota and food products, including rice, vegetables, and fish in public waters (Gomah et al. 2019, Tayone et al. 2020, Wahiduzzaman et al. 2021, Xiang et al. 2021, Zulkafflee et al. 2022, Ogbuene et al. 2024). However, there has been inadequate research to assess the effects of using chromium-contaminated river water for aquaculture and rice agriculture, particularly regarding contamination, bioaccumulation, and potential health risks to residents. Therefore, it is critical to assess the concentration of chromium heavy metals in fisheries and agricultural products and to perform health risk evaluations concerning rice and fish consumption. Health risk assessment methods enable researchers to examine and measure the potential health effects of heavy metal exposure (Varol & Sünbül 2020). Human health risk assessment methods can evaluate both non-carcinogenic and carcinogenic health risks, specifically Risk Quotient (RQ) and Excess Cancer Risk (ECR). This study analyzed the quantity and frequency of rice and fish consumption to evaluate the potential health impacts of heavy metal exposure (USEPA 2011, 2012, 2018).

The expanding industrial activities along the downstream area of the Opak River contribute significantly to economic growth, job creation, and regional development. However, without effective governance, monitoring, enforcement, and compliance with environmental regulations, these activities give rise to environmental pollution. The discharge of liquid waste from industrial areas is the primary source of chromium contamination in the downstream section of the Opak River. Weak supervision, inadequate enforcement, and the absence of effective pollution prevention and water quality management programs have perpetuated this issue. Chromium pollution in the Opak River poses a serious threat to food security and public health, yet chromium has not been included in river water quality monitoring standards, resulting in limited assessment of its environmental impact to date. This study addresses a critical knowledge gap concerning the impact of chromium contamination on food security and public health, particularly through the consumption of rice and fish. Although prior research has explored the health risks of chromium in aquatic environments and food products, specific data on the effects of using chromium-contaminated river water for aquaculture and agriculture remain limited. This study aimed to fill this gap by assessing chromium concentrations in fisheries and agricultural products and evaluating the potential health risks for local residents. The research specifically investigated the impact of Cr(VI) contamination from tannery activities on rice fields and aquaculture ponds adjacent to the Opak River. The findings revealed that Cr(VI) accumulation in fish and rice exceeded acceptable intake thresholds, posing significant non-carcinogenic and carcinogenic health risks for populations reliant on these food sources. The results underscore the urgent need for improved industrial waste management and regulatory measures to mitigate the adverse effects of chromium pollution, highlighting the essential role of monitoring and protecting aquatic environments.

MATERIALS AND METHODS

Characterization of Temporal Characteristics and Location

The study was carried out from March 2023 to November 2024 in rice paddies and aquaculture ponds reliant on the Opak River for water and fishing activities. Pollution from tanneries significantly increases chromium concentrations in the aquatic environments downstream of the Opak River (Rahardjo et al. 2021a, Rahardjo et al. 2021b). The increase in chromium levels presents a risk to aquatic organisms and human health, resulting in detrimental impacts on numerous species and polluting drinking water sources. Prolonged exposure to chromium pollution could reduce biodiversity, disrupt local ecosystems, and necessitate costly remediation efforts to enhance water quality and protect public health. Station (A) was located in the upper section of the Opak River, about 5 km from the industrial zone, and served as a benchmark location. The concentration of heavy metals in wastewater from tanneries was evaluated at four sites: B, C, D, and E, situated approximately 5, 10, 15, and 20 km away, respectively. Fig. 1 depicts the positioning of the industrial area within the Piyungan sub-district and the configuration of each sampling site along the Opak River.

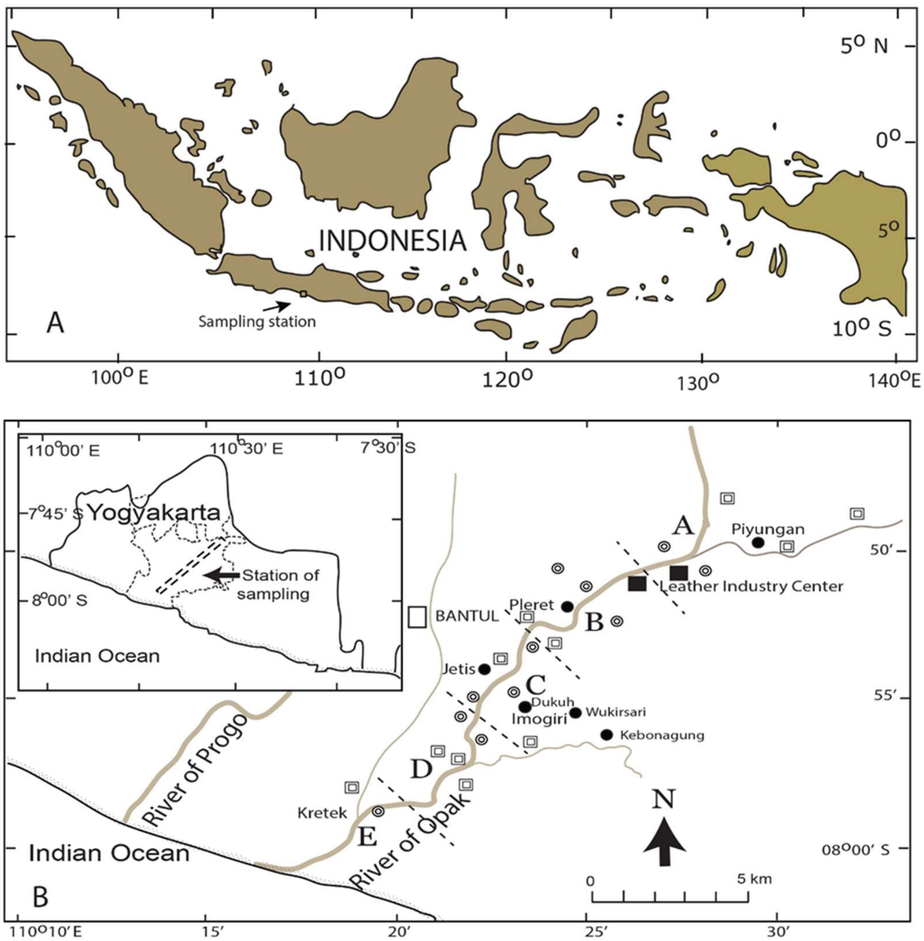

Fig. 1: Map of the territory of the Republic of Indonesia (panel A) and the location of industrial areas and distribution of sampling stations located upstream of the area 5 km away (station A), and respectively stations B, C, D, and E located downstream of the industrial area 5, 10, 15 and 20 km away (panel B).

The absence of a control station in this study was due to the use of existing upstream locations as benchmarks for comparison with downstream sites impacted by industrial pollution. Station A, positioned 5 km upstream from the industrial zone, served as the reference point for assessing the impact of chromium contamination from tanneries on aquatic environments. The study design focused on assessing the effects of pollution at various downstream distances (stations B, C, D, and E), rather than establishing a separate control station, as the upstream site was deemed sufficient for understanding baseline conditions. This approach directly compared pollution levels and related health risks without the need for additional control stations.

Sampling and Preparation

A total of 40 fish farming ponds were sampled, including four catfish ponds and four ponds of other fish species located upstream of the industrial area as control sites. The remaining 32 ponds were distributed across four sites situated 5, 10, 15, and 20 km downstream of the industrial area, which is impacted by tannery liquid waste discharge. Water, sediment, and fish samples were collected from each pond in triplicate, resulting in a total of 360 samples. Rice field samples were collected from four randomly selected areas at each location, including water, sediment, and grain, also in triplicate, yielding 180 samples. All samples were placed in sterile plastic bags and transported to the laboratory in airtight containers with ice packs. Samples were initially rinsed with tap water followed by deionized water to remove surface contaminants. Consumable portions of fish were excised using a ceramic knife, homogenized, and stored in plastic containers at –20°C.

Sample Analysis

The process for chromium removal from water samples complied with the APHA/AWWA/WEF Standard Methods, 20th Edition, 2001. The Environmental Protection Agency (2001) states that acid extraction is effective for acquiring solid materials, especially fish and detritus. The wet weight was measured with an analytical scale, and the sample was then dried in an oven at 60˚C to remove moisture. The dried weight was subsequently reevaluated, and the sample was pulverized using a mortar before being stored in a hermetically sealed container. A total of 3 g of sample was mixed with 18 mL of hydrochloric acid and 6 mL of concentrated nitric acid. The sample was then heated until it reached a volume of approximately 10 mL. The sample underwent repeated exposure to hydrogen nitrate solutions and strong hydrochloric acid before heating. The extract was subsequently filtered using filter paper that had been treated with 1% hydrogen nitrate. AAS was employed to ascertain the chromium content of the extract in accordance with the procedures outlined in SNI 06-6989.17-2004. The Perkin Elmer AAS PinAAcle 900T was employed to perform an analytical operation. All glassware and polyethylene bottles used in this study were pre-soaked with 10% HNO_3 for 24 h, rinsed with ultrapure water, and then air dried before use. Three samples, including one procedural bank, one matrix spike sample, and one bank spike sample, were analyzed along with every batch of digestion samples. The accuracy of replicate analyses of reference material showed good agreement, with a recovery rate of 85% and a detection limit of 0.003 $mg.kg^{-1}$.

Data Analysis

Fish and rice consumption data was collected from respondents in four affected areas. A total of 200 respondents were randomly selected, with 50 individuals from each location. The effects of non-carcinogenic and carcinogenic health risks were analyzed, referring to the US EPA's metal risk assessment guidelines (US EPA 2012). The calculation of non-carcinogenic health risks expressed in the RQ was carried out by comparing non-carcinogenic intake with RfD (Reference Dose):

$$\boldsymbol{Non\ Carcinogenic\ Intake} = \frac{\boldsymbol{C \times R \times Fe \times Dt}}{\boldsymbol{Wb \times Tavgk}} \quad ...(1)$$

Intake refers to the daily amount of Cr(VI) concentration entering the body ($mg.kg^{-1}.day^{-1}$). In this formula, C represents the concentration of Cr(VI) in food ($mg.kg^{-1}$), R denotes the rate of consumption or the weight of food ($kg.day^{-1}$), Fe signifies the number of days of exposure each year ($days.year^{-1}$), and Dt indicates the number of years of exposure (years). Additionally, Wb denotes human body weight (Kg), while Tavgk represents the average duration of days for non-carcinogenic effects (30 years × 365 days.$year^{-1}$).

The RQ value was determined based on the following equation:

$$\boldsymbol{RQ} = \frac{\boldsymbol{Non\ Carsinogenic\ Intake}}{\boldsymbol{RfD}} \quad ...(2)$$

Where Intake is the amount of concentration of Cr(VI) that enters the body every day ($mg.kg^{-1}.day^{-1}$), and RfD is the Reference Dose of hexavalent chromium in food according to the US EPA (2018), which is 0.003 $mg.kg^{-1}.day^{-1}$.

Carcinogenic health risks were expressed in exponential numbers without units and were assessed using the ECR metric. The risk was considered safe (acceptable) if the ECR value was $\leq 1 \times 10^{-4}$ or expressed as ECR ≤ 1/10,000.

Carcinogenic health risks were deemed unsafe if the ECR value exceeded 1×10^{-4} or ECR was greater than 1/10,000 (Ministry of Health 2012). The ECR value was calculated by multiplying the carcinogenic intake by the Cancer Slope Factor (CSF) as demonstrated below:

$$Carcinogenic\ Intake\ (CDI) = \frac{C \times R \times Fe \times Dt}{Wb \times Tavgh} \quad ...(3)$$

CDI refers to the daily concentration of a risk agent that is absorbed by the body, measured in $mg.kg^{-1}.day^{-1}$. In this computation, C represents the concentration of risk agents in food ($mg.kg^{-1}$), R indicates the rate of consumption or the amount of food weight ($kg.day^{-1}$), Fe signifies the length of days of exposure each year ($days.year^{-1}$), and Dt denotes the number of years of exposure (years). In the denominator, Wb represents human body weight (kg), while Tavgk denotes the average duration in days for non-carcinogenic effects (70 years × 365 $days.year^{-1}$).

Furthermore, the ECR value was calculated using the equation:

$$ECR = Carcinogenic\ Intake\ \times CSF \quad ...(4)$$

Where CSF stands for Cancer Slope Factor (CSF) value, and ECR stands for Excess Cancer Risk. The US EPA states that the value for chromium hexavalent is 0.5 (US EPA 2011).

A one-way analysis of variance (ANOVA) was employed to evaluate non-categorical data that followed a normal distribution, specifically focusing on Cr(VI) concentrations in samples from both control and affected sites. This analysis assessed pollution levels across multiple districts based on the collected samples, which included water, sediment, fish, rice, and other relevant components. In all analyses, statistical significance was defined as $p < 0.05$. The statistical analyses were performed using SPSS version 21.0, while data visualizations of Cr(VI) concentrations were generated using R version 4.3.3. Additionally, the relationship between independent variables-including hexavalent chromium concentration in food, intake rate, exposure duration, and body weight-and the dependent variable of health risk (RQ) was evaluated using linear regression analysis with the enter method.

RESULTS AND DISCUSSION

Cr(VI) Contamination in Aquaculture Ponds and Rice Fields

The concentrations of Cr(VI) in rice fields, ponds, and sediments in the upstream and downstream areas of the Piyungan Industrial Area are presented in Fig. 2. Water from aquaculture ponds and rice fields sourced from the downstream section of the Opak River contained chromium, showing varying levels of contamination.. There was no indication of Cr(VI) concentrations in water samples collected from fish ponds or rice fields at an upstream industrial site. Cr(VI) concentrations were detected in water samples from downstream areas of the industrial zone, with levels ranging from 0.054 to 0.143 $mg.L^{-1}$ in fish pond water samples and 0.117 to 0.197 $mg.L^{-1}$ in rice field water samples. Meanwhile, Cr(VI) levels in sediments were found in higher concentrations, ranging from 0.016-0.770 $mg.kg^{-1}$ in fish ponds and 0.016-0.320 $mg.kg^{-1}$ in rice fields.

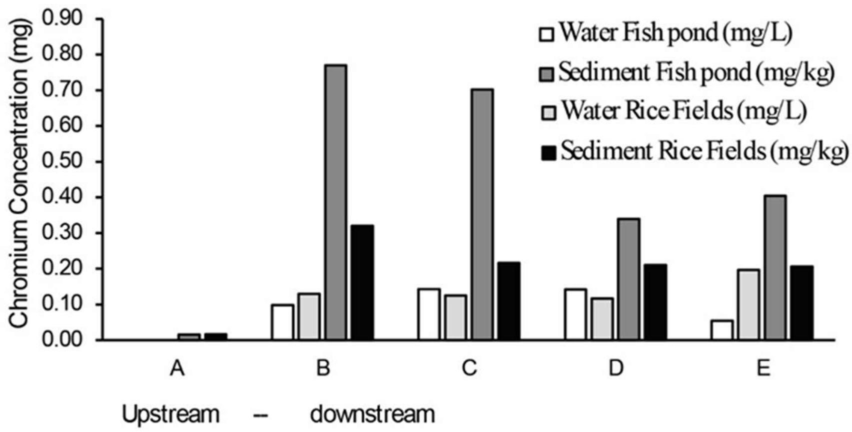

Fig. 2: The chromium concentrations at the upstream station (A) and at stations B, C, D, and E—located 5, 10, 15, and 20 km downstream of the industrial area, respectively—were measured to assess pollution patterns. Sediment samples from rice fields and aquaculture ponds contained higher levels of Cr(VI) than the corresponding water samples. Cr(VI) concentrations were highest near the wastewater discharge points at stations B and C, then decreased or fluctuated further downstream. ANOVA results showed a significant difference in Cr(VI) concentrations in both water and sediment samples between the control and affected locations, with a p-value < 0.005.

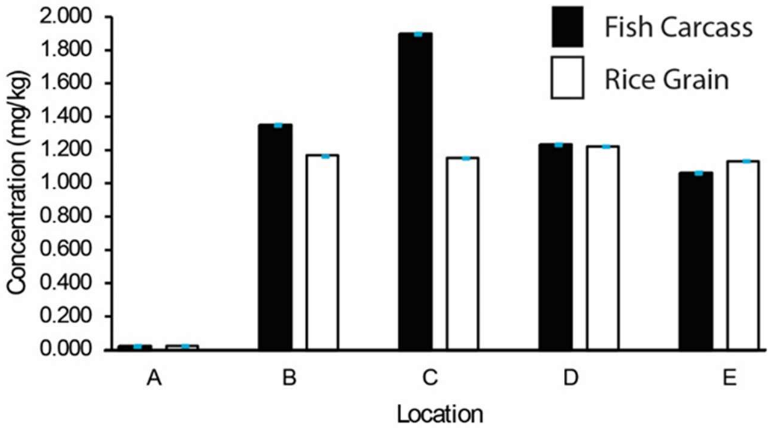

Fig. 3: Comparison of Cr(VI) accumulation in fish and rice (mg.kg^{-1}).

Chromium (VI) Accumulation in Fish and Rice

The accumulation levels of Cr(VI) in fish and rice samples from four areas downstream of the tanneries are presented in Fig. 3. Chromium pollutants contaminated all fish and rice samples in all study locations. However, the average accumulation of Cr(VI) in fish and rice in the upstream locations of the industrial area was found in very small concentrations, i.e., 0.020 mg.kg^{-1} in fish and 0.023 mg.kg^{-1} in rice. It was very different from the accumulation levels of Cr(VI) in the affected locations, which ranged from 0.860 -1.740 mg.kg^{-1} in fish and 1.132 - 1.221 mg.kg^{-1} in rice.

The mean Cr(VI) accumulation varied depending on the organism type and sampling station location. Fish samples exhibited a greater accumulation of Cr(VI) compared to rice samples. The ANOVA analysis indicated a significant difference in Cr(VI) concentration between fish and rice samples from control and affected zones (p-value < 0.005).

Consumption Rate, Estimated Daily Intake, and Health Risk

Table 1 displays the distribution of rice and fish consumption levels within the community, along with daily intake statistics. The rice and fish consumption patterns of the population vary across the four regions affected by tannery waste disposal practices. Rice consumption ranged from 253.00 to 312.43 g.day^{-1}, with an average of 267.50 g.day^{-1}. The daily fish consumption varied between 21.43 and 45.71 g.day^{-1}, with an average of 33.75 g.day^{-1}. The daily intake value was determined by the amount of food consumed and the concentration of chromium contained in the meal. The daily chromium intake from rice and paddy consumption was 10,000 µg.kg^{-1}.day^{-1} at station D, 8,800 µg.kg^{-1}.day^{-1} at station B, 8,200 µg.kg^{-1}.day^{-1} at station C, and 5,700 µg.kg^{-1}.day^{-1} at station E.

Health risk characterization was carried out by determining the RQ and ECR values based on the community's rice and fish consumption patterns. The daily non-carcinogenic intake values ranged from 0.0057 to 0.0101 mg.kg^{-1}.day^{-1}, with an average of 0.0083 mg.kg^{-1}.day^{-1}. The highest average non-carcinogenic intake value was found at station D, with an average value of 0.0101 mg.kg^{-1}.day^{-1}, followed by stations B, C, and E. Table 2 presents the non-carcinogenic intake, chronic daily intake, RQ, and ECR values associated with the consumption of rice and fish contaminated with chromium.

The RQ value was evaluated to determine non-carcinogenic risk, with an acceptable limit of one (USEPA

Table 1: Consumption levels and estimated daily intake values of chromium in rice and fish.

Location	Consumption Rate [g.day^{-1}]		Total Consumption Rate [g.day^{-1}]	Chromium Concentration [mg.kg^{-1}]		Total Chromium Concentration [mg.kg^{-1}]	Body Weight [kg]	Daily Intake Rate [mg.kg^{-1}.day^{-1}]
	Fish	Rice		Fish	Rice			
B	25.00	267.00	292.00	1.47	0.248	1.718	57.00	0.0088
C	42.85	253.00	295.85	1.74	0.206	1.946	59.00	0.0100
D	45.71	259.00	304.71	1.41	0.199	1.609	57.00	0.0082
E	21.43	291.00	312.43	0.86	0.168	1.028	56.00	0.0057
Mean	33.75	267.50	301.25	1.47	0.205	1.575	57.25	0.0081

Table 2: Non-carcinogenic intake, Chronic Daily Intake, RQ, and ECR.

Location	Non-Carcinogenic Intake [mg.kg^{-1}.day^{-1}]	RQ	Chronic Daily Intake ([DI]	ECR
B	0.0088	2.93	0.0037	7.4 x 10^{-3}
C	0.0082	2.73	0.0043	8.6 x 10^{-3}
D	0.0101	3.37	0.0035	7.0 x 10^{-3}
E	0.0057	1.90	0.0024	4.8 x 10^{-3}
Mean	0.0083	2.77	0.0035	7.0 x 10^{-3}

2011). The study results showed that the RQ values at all research locations exceeded one. This indicates that the simultaneous consumption of rice and fish contaminated with chromium can pose significant non-carcinogenic health risks, rendering them unsafe for public consumption. The ECR values further demonstrated that rice and fish consumption at all sampling sites surpassed the established safe limit of 1.0×10^{-4}, thereby presenting a substantial carcinogenic risk in these areas. The intake rate and duration of exposure also influence the health risks associated with ingesting chromium-contaminated food. This was confirmed by the regression analysis, which examined the relationship between risk factors and health risk levels (Table 3). Intake rate and duration of exposure were significantly associated with health risk ($p < 0.001$). In contrast, factors such as chromium concentration, consumption amount, body weight, and age did not demonstrate statistical significance. The intake rate and duration of exposure were significant predictors of health risk, as indicated by high regression coefficients. Multicollinearity and interaction effects were not examined in the regression analysis (VIF <10).

Discussion

Water pollution, especially from industrial activities, presents a considerable risk to human health and the environment (Ogbuene et al. 2024, Yustiati et al. 2024). In developing countries like Indonesia, rapid industrialization has led to increased contamination of water bodies, particularly rivers. The Opak River, heavily impacted by the leather tanning industry, is a stark example of how industrial waste can severely degrade water quality. The findings from this research underscore the urgent need for effective monitoring and management strategies to mitigate the harmful impacts of such pollution. Implementing stricter regulations and promoting sustainable industrial practices are crucial for protecting water resources and safeguarding the health of local communities. Moreover, community engagement and education play vital roles in raising awareness about the importance of water conservation and pollution prevention. This empowers residents to advocate for cleaner practices and strengthens accountability among industries.

Chromium-contaminated river water used for agricultural irrigation and fishing activities is the main source of pollution in aquaculture ponds and paddy fields. The absence of hexavalent chromium in water samples from aquaculture ponds and rice fields located upstream of the industrial area supports this claim. In contrast, hexavalent chromium was detected in downstream regions linked to the leather tanning sector during wastewater discharge. According to Xu et al. (2023), tannery is identified as the primary source of environmental chromium contamination. The average concentration of hexavalent chromium in water samples exceeds the established limits for aquaculture quality. As per Government Regulation 82 of 2002, the allowable concentration of chromium is 0.05 mg.L^{-1}. The United Nations Environment Programme/World Health Organization has established a maximum acceptable concentration (MAC) of 0.05 mg.L^{-1} for chromium to protect aquatic ecosystems (UNEP 2008). Soil samples showed higher concentrations of hexavalent chromium compared to water samples. This study reveals that heavy metal levels are low in water but considerably higher in sediment and biota (Paller & Littrell 2007). Chromium quickly bonds with organic molecules and accumulates rapidly in sediments (Ipinmoroti et al. 2022, Ehiemere et al. 2022). Heavy metals, especially chromium, exhibit an increased propensity to associate with sediment, leading to its sequestration (Brady et al. 2015). The movement of heavy metals into sediments

Table 3: Results of linear regression analysis of risk agents and health risks (R^2=0.823).

Variables	B	Standard Error	95% Confidence Interval	p-*value*
Constant	-0.259	0.065	-0.0426 – -0.0151	<0.001
Intake Rate [R]	473.818	12.257	215.412 – 432.181	<0.001
Duration of Exposure [Dt]	0.008	0.003	0.006 – 0.009	<0.001
Hexavalent Chromium [C]	-0.242	0.092	-0.219 – 0.045	0.110
Amount of consumption	0.0007	0.002	0.00013 – 0.00019	0.432
Weight [BB]	0.003	0.001	-0.002 – 0.004	0.122
Age [A]	0.002	0.002	-0.001 – 0.004	0.279

results in elevated pollutant concentrations in soil while simultaneously lowering levels in water (Nurkhasanah 2015).

Udosen et al. (2016) observed that sand acts as a natural adsorbent for heavy metals in aquatic environments, thereby reducing the bioavailable fraction in the water. Unlike water, sediment functions as a reservoir for metals due to its distinct physicochemical characteristics. Currently, sediment is widely regarded as a major repository for heavy metals that accumulate as a result of pollution (Xia et al. 2020). It serves as both a source and a sink for the accumulation and redistribution of heavy metals (Miao et al. 2020; Wang et al. 2020). Heavy metals stored in sediments can be reintroduced into the water column, causing "secondary pollution" that adversely affects ecosystems and human health through the food chain and biological enrichment (Bing et al. 2019). Therefore, sediment is considered a sensitive indicator for evaluating the health of aquatic ecosystems (Bastami et al. 2015). Assessing river water quality based solely on heavy metal concentrations in the water is inadequate; it is essential to also quantify heavy metals in sediments. The contamination of rice paddies and aquaculture ponds with Cr(VI) leads to exposure and subsequent accumulation of Cr(VI) in both rice and fish.

Heavy metals may significantly contaminate the ecosystem as a result of chromium deposition in fish and rice (Makedonski et al. 2017). Chromium accumulation in fish and rice occurs through the uptake of water, sediment, or dietary sources, such as algae, consumed by herbivorous and omnivorous fish (Joshi et al. 2002). The accumulation of Cr(VI) in fish and rice samples is variable and influenced by many variables, including Cr(VI) concentrations in water and sediment, along with the physical and chemical characteristics of the environment at each research location. Moreover, heavy metal absorption is influenced by biota species, organism tolerance thresholds, sensitivity, and water's physical and chemical characteristics (Yousafzai et al. 2010). The variability of chromium accumulation in rice and fish may be caused by chromium concentration in sediment, bioavailability, physical and chemical characteristics of the environment, and types of organisms (Wu et al. 2021). Heavy metal contaminants in aquatic ecosystems may accumulate in fish via bioaccumulation and bioconcentration (Korkmaz et al. 2019, Arisekar et al. 2020). Factors such as sex, age, size, reproductive cycle, swimming behavior, dietary preferences, and environmental conditions significantly affect the accumulation of heavy metals in fish. The consumption of contaminated fish introduces heavy metals into the human body (Gholamhosseini et al. 2021). The accumulation of chromium in foods such as rice and fish is concerning, as its consumption may lead to health risks. Identifying chromium in rice fields, aquaculture ponds, and food, such as rice and fish, establishes a baseline for evaluating the food safety risk to consumers of these products.

Concentrations of Cr(VI) in fish and rice samples from areas affected by tannery effluent discharge were significantly higher. The findings of this research indicate chromium accumulation levels in fish that substantially exceed those reported in previous studies. Notably, the investigation by Rahman et al. (2012) in Bangladesh reported accumulation levels of 0.09 to 0.4 $mg.kg^{-1}$, while the study by Leung et al. (2014) in China indicated levels ranging from 0.2 to 0.65 $mg.kg^{-1}$ and 0.18 to 0.85 $mg.kg^{-1}$. The concentration of Cr(VI) in rice samples was significantly higher than the results reported by Gomah et al. (2019) in Monrovia, which indicated an average hexavalent chromium level of 0.4245 $mg.kg^{-1}$, Guo et al. (2019) in China, with an average of 0.31 $mg.kg^{-1}$, and Jahirudin et al. (2017), who recorded an average chromium concentration of 1,058 $mg.kg^{-1}$. However, this concentration is considered safe for consumption according to the maximum limit established by the Director General of the Food and Drug Authority, which is 2.5 $mg.kg^{-1}$ (Dirjen POM 1989). This stands in stark contrast to the concentration limits established by the WHO and the Federal Environmental Protection Agency, which specify that the maximum allowable amount of chromium in food, including fish, is 0.05-0.15 $mg.kg^{-1}$ of fish body weight (Bakshi & Panigrahi 2018).

Rice is a staple food for a large portion of the population in many Asian countries, including Indonesia. Meanwhile, freshwater fish is a preferred source of high-quality protein, chosen by many individuals to support their health. (Parvin et al. 2023). Consequently, chromium pollution in river ecosystems and the food chain can be transmitted to humans via rice and fish consumption, potentially harming human health. The rice consumption among individuals in the four research locations was notably high, varying from 253.00 to 312.43 $g.day^{-1}$, with an average of 267.50 $g.day^{-1}$. The average fish consumption was 33.75 $g.day^{-1}$, ranging from 21.43 to 45.71 $g.day^{-1}$. In the research locations, rice consumption significantly surpassed the national average of 217 $g.day^{-1}$, whereas fish consumption was considerably lower than the national average of 51 $g.day^{-1}$ (BPS 2024). The average rice consumption in the research community was 267.50 $g.day^{-1}$, significantly higher than that of several other Asian countries: China at 238 $g.day^{-1}$, Taiwan at 132 $g.day^{-1}$, and Japan at 119 $g.day^{-1}$ (Hu et al. 2016). The significant consumption of chromium-contaminated food, particularly rice, results in a daily chromium intake in the community at the research site, estimated to be between 0.0057 and 0.0100 $mg.kg^{-1}.day^{-1}$. Approximately 90% of chromium intake in humans occurs through food consumption, rather than drinking water, skin contact, or inhalation (Zhang et al. 2020). Diet is the major source of chromium exposure. Estimated daily oral intakes for infants (1 year), children (11 years), and adults are 33-45, 123-171, and 246-343 $\mu g.person^{-1}.day^{-1}$, respectively (Rowbotham et al. 2000). The daily intake of chromium at each research site differs due to variations in consumption patterns and the level of chromium contamination in food. Consuming foods contaminated with chromium presents a public health risk (Varol & Sünbül 2020). Even in low concentrations, chromium remains dangerous because it can accumulate in the body and reach toxic levels (Chen & Chau 2019, Ustaoglu et al. 2019).

The study demonstrated that consuming food contaminated with Cr(VI) presents significant non-carcinogenic and carcinogenic health risks, as indicated by RQ values exceeding one and ECR values greater than 7.0×10^{-3}. The US EPA (2011) states that the RQ value is used to assess non-carcinogenic risk, with an acceptable maximum limit of 1 and an ECR value below 1.0×10^{-4}. Consequently, the community's consumption of rice and fish across all research regions poses significant risks of both serious non-carcinogenic and carcinogenic health effects. The intake of heavy metals, including chromium, can lead to their accumulation in body tissues such as adipose and bone tissues. Exposure to Cr(VI) may increase susceptibility to upper gastrointestinal cancer (Mensoor & Said 2018) and may reduce human life expectancy by approximately 9 to 10 years (Guerra et al. 2012). Chemically-acquired immunodeficiency syndrome (C-AIDS) refers to a weakened immune response caused by exposure to chemicals, including heavy metals. Prolonged exposure to chromium in humans may lead to gastrointestinal disorders, respiratory complications, renal and hepatic damage, and abnormalities in genetic material, among other health problems (Shanker et al. 2005). The principal pathophysiology involves DNA damage, genomic instability, and the generation of reactive oxygen species (ROS) induced by Cr(VI). Chromium (VI) increases oxidative stress and stimulates ROS production in target DNA and cellular lipids, resulting in DNA damage and lipid peroxidation (Balali-Mood et al. 2021). The cancer risk associated with Cr(VI) exposure can be influenced by various factors, including the level of Cr(VI) intake from contaminated sources and the differing concentrations of Cr(VI) present in food and drinking water. (ATSDR 2012, IARC 2012, Ukhurebor 2021).

However, the findings of this health risk analysis cannot be presented directly to the authorities for decision-making in risk management. Further efforts are required to characterise uncertainty and variability, which are essential components of health risk assessment. Health risk analysis is inherently subject to uncertainty due to variability across spatial and temporal scales (Walker et al. 2003). This variability arises from factors such as the intrinsic properties of an agent, the nature of its side effects, the characteristics of hazards, the relationship between the agent and health effects, the actual level of exposure, and the source of observed outcomes (Jansen et al. 2019). The deterministic approach to health risk assessment has limitations, particularly its tendency to underestimate or overestimate actual risk. Variability may stem from differences in metal concentrations, chromium species, consumption levels, age, sex, body weight, and physiological or metabolic parameters (Miletic et al. 2023).

Nevertheless, Cr(VI) contamination on agricultural land and aquaculture severely undermines the safe production of food crops and presents enormous latent dangers to human health. Cr(VI) pollution negatively impacts food safety and health; therefore, effective river water quality management, rigorous monitoring, and pollution prevention measures are essential to mitigate these adverse effects. These efforts can be made through better industrial waste management to prevent the discharge of pollutants into rivers, strict supervision of polluting industries, the need for regulations that limit the amount of waste that can be discharged into the environment, and increasing public knowledge and awareness of the risks of Cr(VI) to the environment and health. The findings highlight the urgent need for improved industrial waste management, stricter pollution regulations, and public awareness initiatives to mitigate the adverse effects of Cr(VI) contamination on food safety and human health. The study underscores the critical relationship between environmental pollution and public health, emphasizing the necessity for comprehensive monitoring and preventive measures.

The findings of the Opak River study highlight the urgent requirement for improved industrial waste management practices and more stringent regulatory measures to address chromium pollution. The significant health risks associated with consuming contaminated food highlight the importance of monitoring water quality and implementing effective pollution prevention strategies. Addressing these challenges is vital for safeguarding public health and ensuring food security in communities affected by industrial pollution. The research serves as a call to action for policymakers, industry stakeholders, and local communities to collaborate to mitigate environmental contamination's impacts and protect future generations.

CONCLUSIONS

There has been a significant increase in Cr(VI) contamination in water, sediment, fish, and rice downstream of the

Opak River. The findings demonstrate that all examined water, sediment, fish, and rice samples from downstream of the industrial zone exhibited varying levels of Cr(VI) contamination, exceeding the safety limits established by health authorities. The health risk assessment revealed significant non-carcinogenic and carcinogenic risks linked to the consumption of contaminated rice and fish, as indicated by RQ values exceeding one and ECR values surpassing acceptable thresholds. The results highlight the critical need for effective management of river water quality, the implementation of stricter regulations on industrial effluents, studies to assess the carrying capacity of rivers, and the establishment of maximum acceptable limits for liquid waste discharge into water bodies. To mitigate pollution and safeguard public health, Cr(VI) parameters should be incorporated into river water quality monitoring to facilitate routine assessments, including evaluations of various food commodities along the downstream Opak River.

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