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

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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 is a major challenge for humanity in the twenty-first century, posing a risk to human health, limiting agricultural production, degrading ecosystem services, and hampering economic growth (UNESCO, 2023). The primary concern for water quality is the increasing concentration of pollutants in water bodies, which may jeopardize the attainment of sustainable development objectives (Ezbakhe, 2018). Industrialization in Indonesia poses a significant threat to environmental pollution, particularly affecting river ecosystems. 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 tanery 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 and Barik, 2018), 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 (Sharma et al. 2020). The discharge of liquid waste by tannery 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. 2019). 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; Euclid 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 and Sunbul, 2019). 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 growing development activities in the industrial zones along the downstream area of the Opak River significantly contribute to economic enhancement, job creation, growth, and equitable development. However, without effective governance, monitoring, enforcement, and compliance by entrepreneurs with environmental regulations, new issues will arise, specifically environmental pollution. The discharge of liquid waste from industrial areas is the primary source of chromium pollution in the downstream area of the Opak River. Weak supervision, enforcement, and the absence of an effective program in preventing pollution and managing river water quality are the causes of continued chromium pollution. Chromium contamination in the Opak River is a serious threat to food security and public health. Chromium contaminants have not been included in the standards for monitoring river water quality, resulting in a lack of monitoring and assessment of their environmental effect to date. This study addressed a critical knowledge gap regarding the impact of chromium contamination in the Opak River on food security and public health, particularly concerning the consumption of rice and fish. Although considerable research has focused on the health risks linked to chromium pollutants in aquatic environments and food products, specific data regarding the effects of utilizing chromium-contaminated river water for aquaculture and agriculture remains insufficient. This study aimed to address the gap in understanding the implications of industrial pollution on human health and food safety in the region by assessing chromium concentrations in fisheries and agricultural products and evaluating potential health risks to residents. This study investigated the impact of Cr(VI) contamination from the tannery on rice fields and aquaculture ponds adjacent to the Opak River. The research underscores the accumulation rates of Cr(VI) in fish and rice that were beyond acceptable intake thresholds. It signifies a significant noncarcinogenic and carcinogenic health risk for local populations dependent on these food sources. The results highlight the pressing need for enhanced industrial waste management and regulatory measures to alleviate the detrimental impacts of chromium pollution on food safety and human health, underscoring the vital role of monitoring and safeguarding aquatic environments.

2. 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. Figure 1 depicts the positioning of the industrial area within the Piyungan sub-district and the configuration of each sampling site along the Opak River.

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.

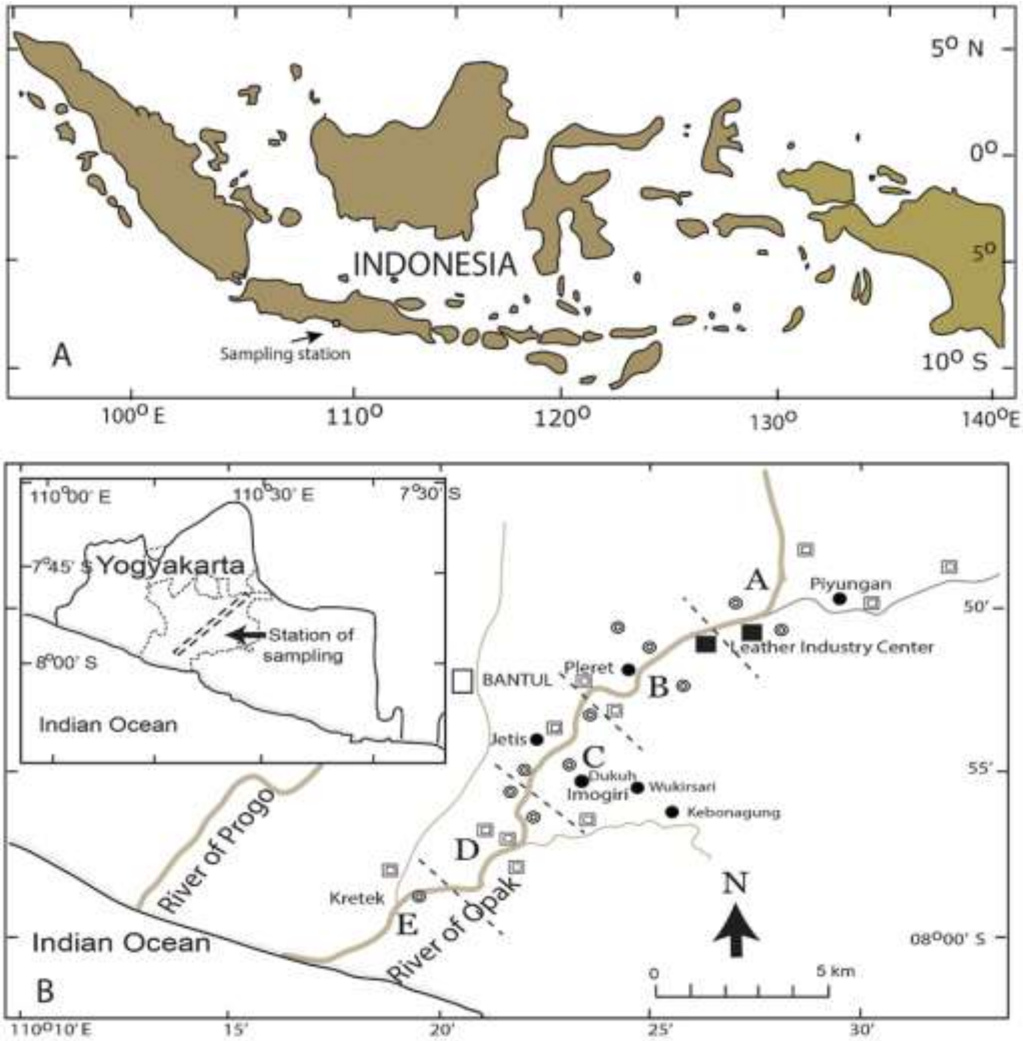

Fig. 1: Map of the territory of the Republic of Indonesia (panel A) and the location of industrial areas and distribution of sampling stations located upstream of the area 5 km away (station A), and respectively stations B, C, D, and E located downstream of the industrial area 5, 10, 15 and 20 km away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

Sampling and preparation

A total of 40 fish farming ponds were sampled, comprising four catfish ponds and four ponds of other fish species, situated upstream of the industrial area as control sites. The remaining 32 ponds were categorized into four distinct sites. The locations were situated at distances of 5, 10, 15, and 20 km from the industrial area, which was downstream and affected by the discharge of liquid waste from the tanneries. Each fish farming pond underwent water, sediment, and fish sampling, conducted in three repetitions, resulting in a total of 360 samples. The rice field samples were collected from four randomly selected areas at each location. Samples collected included water, sediment, and grain, with three repetitions, resulting in a total of 180 samples. All samples collected were placed in sterile plastic bags and transported to the laboratory in an airtight isolation container with ice packs. The samples were initially rinsed with tap water and then deionized water to remove adhesives. The consumable portions of fish samples 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% HNO3 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.

Data analysis

Fish and rice consumption data were 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):

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

Intake refers to the daily amount of Cr(VI) concentration entering the body (mg/kg-day). In this formula, C represents the concentration of Cr(VI) in food (mg/kg), R denotes the rate of consumption or the weight of food (kg/day), Fe signifies the number of days of exposure each year (days/year), 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 x 365 days/year).

The RQ value was determined based on the following equation:

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

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

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:

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

CDI refers to the daily concentration of a risk agent that is absorbed by the body, measured in mg/kg-day. In this computation, C represents the concentration of risk agents in food (mg/kg), R indicates the rate of consumption or the amount of food weight (kg/day), Fe signifies the length of days of exposure each year (days/year), 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 x 365 days/year).

Furthermore, the ECR value was calculated using the equation:

$$ECR = Carcinogenic\ Intake\ \times CSF \tag{4}$$

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 the concentration of Cr(VI) in samples obtained from both control and affected sites. This examination evaluated pollution levels in several districts based on the samples studied. The samples examined included water, sediment, fish, rice, and several other components. In every performed study, the criteria for statistical significance were defined as a p-value less than 0.05. The statistical analysis was performed using SPSS version 21.0. Concurrently, data visualizations of the Cr(VI) concentrations in the samples were performed using R version 4.3.3. 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 through linear regression analysis employing the enter approach.

3. RESULTS

3.1. Cr(VI) contamination in aquaculture ponds and rice field

The concentration of Cr(VI) in rice fields, ponds, and sediments in the upstream and downstream areas of the Piyungan Industrial Area is presented in Fig. 2. Water in aquaculture ponds and rice fields that were sourced from the downstream section of the Opak River contained chromium, exhibiting varying levels of pollution. 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 in fish pond water samples and 0.117 to 0.197 mg/L in rice field water samples. Meanwhile, Cr(VI) levels in sediments were found in higher concentrations, ranging from 0.016-0.770 mg/kg in fish ponds and 0.016-0.320 mg/kg in rice fields.

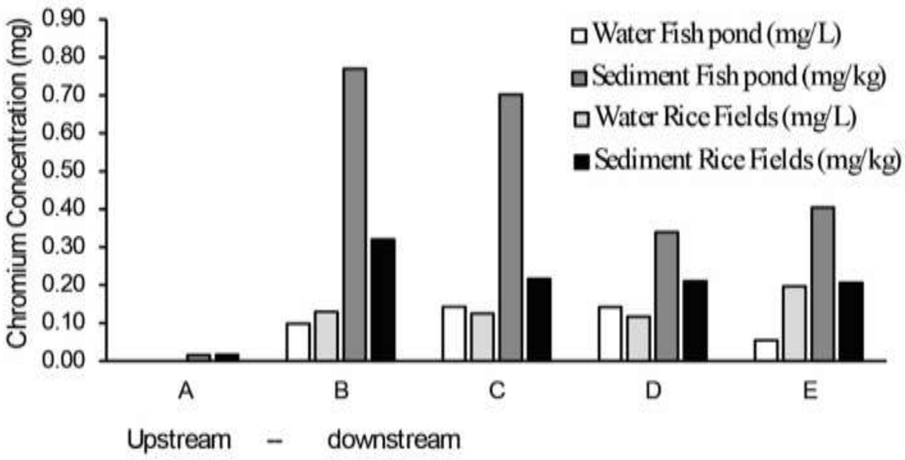

Fig. 2: The chromium concentrations at the upstream station (A) and stations B, C, D, and E were located downstream of the industrial area 5, 10, 15, and 20 km, respectively. Sediment samples from rice fields and aquaculture ponds showed higher amounts of Cr(VI) compared to water samples. Cr(VI) concentrations tended to be high at locations close to the wastewater discharge points at stations B and C, then decreased or fluctuated downstream. The results of the ANOVA analysis showed a significant difference in Cr(VI) concentrations in water and sediment samples between the control and affected locations, with a p-value <0.005.

3.2. 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 in fish and 0.023 mg/kg 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 in fish and 1.132 - 1.221 mg/kg in rice.

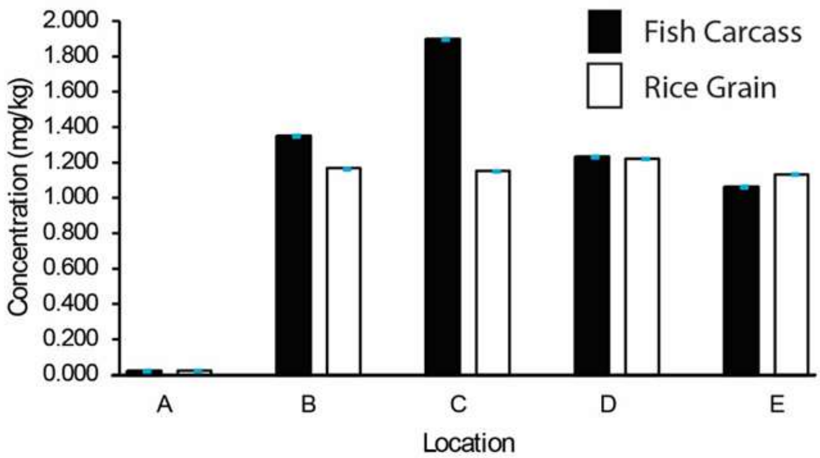

Fig. 3: Comparison of Cr(VI) accumulation in fish and rice (mg/kg)

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).

.3.3. 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 impacted by the waste disposal practices of the tanneries. Rice consumption ranged from 253.00 to 312.43 g/day, with an average of 267.50 g/day. The daily fish consumption varied between 21.43 and 45.71 g/day, with an average of 33.75 g/day. 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/day at station D, 8,800 µg/kg/day at station B, 8,200 µg/kg/day at station C, and 5,700 µg/kg/day at station E.

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

Location	Consumption Rate (g/day)		Total Consumption Rate (g/day)	Chromium Concentration (mg/kg)		Total Chromium Concentration (mg/kg)	Body Weight (kg)	Daily Intake Rate (mg/kg/day)
	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

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/day, with an average of 0.0083 mg/kg/day. The highest average non-carcinogenic intake value was found at station D, with an average value of 0.0101 mg/kg/day, 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.

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

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

The RQ value was evaluated to determine non-carcinogenic risk, with an acceptable limit of one (USEPA, 2011). The results of the study showed that the RQ value at all research locations was more than one, this indicates that consuming rice and fish contaminated with chromium simultaneously can cause significant non-carcinogenic health risks, making it dangerous for public consumption. The ECR value indicates that rice and fish consumption at all research sites surpasses the established safe limit of $>10^{-4}$, thereby presenting a significant carcinogenic risk in these areas. The intake rate and duration of exposure influence the health risk linked to the ingestion of chromium-contaminated food. This was confirmed by the results of the regression analysis, which was related to risk factors and health risk levels (Table 3). Intake rate and duration of exposure had a significant relationship with health risk ($p<0.001$). In contrast, actors 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).

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

4. 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 affect water quality. The findings from the research underscore the urgent need for effective monitoring and management strategies to mitigate the detrimental impacts of such pollution. Implementing stricter regulations and promoting sustainable practices within industries is crucial for protecting water resources and ensuring the health of local communities. Furthermore, community engagement and education play a vital role in raising awareness regarding the significance of water conservation and pollution prevention. This empowers residents to advocate for cleaner practices and ensures 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. The United Nations Environment Programme/World Health Organization has established a maximum acceptable concentration (MAC) of 0.05 mg/L 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 results in elevated pollutant concentrations in soil while simultaneously lowering levels in water (Nurkhasanah, 2015).

Udosen et al. (2016) observed that sand serves as a natural adsorbent for heavy metals in aquatic environments, consequently decreasing the bioavailable fraction in the water. In contrast to aquatic settings, sediment functions as a reservoir for metals due to its unique characteristics. At present, sediment is regarded as a repository for heavy metals that accumulate due to pollution (Xia et al. 2020). Sediment is the most important source and sink for the accumulation and redistribution of heavy metals (Miao et al. 2020; Wang et al. 2020). Heavy metals in sediments are reintroduced into water, resulting in 'secondary pollution' that adversely impacts ecosystems and human health via the food chain and biological enrichment (Bing et al. 2019). Therefore, sediment is seen as a sensitive indicator for evaluating the health of aquatic ecosystems (Bastami et al. 2015). Thus, evaluating river water quality based solely on heavy metal concentrations in the water is inadequate for assessing the level of water pollution; it is essential also to measure heavy metals in sediments. The pollution of Cr(VI) in rice paddies and aquaculture ponds results in the exposure and accumulation of Cr(VI) in 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 are 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 regions affected by tannery waste discharge were significantly higher. This research significantly exceeds previous studies on chromium accumulation in fish. Notably, the investigation by Rahman et al. (2012) in Bangladesh reported accumulation levels of 0.09 to 0.4 mg/kg, while the study by Leung et al. (2014) in China indicated levels ranging from 0.2 to 0.65 mg/kg and 0.18 to 0.85 mg/kg. 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, Guo et al. (2015) in China, with an average of 0.31 mg/kg, and Jahirudin et al. (2017), who recorded an average chromium concentration of 1,058 mg/kg. 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 (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 of fish body weight (Bakshi and Panigrahi, 2018).

Rice is a staple food for the major population in several Asian countries, including Indonesia. Meanwhile, freshwater fish is a preferred food choice for high-quality protein, which many individuals select to enhance 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, with an average of 267.50 g/day. The average fish consumption was 33.75 g/day, ranging from 21.43 to 45.71 g/day. In the research locations, rice consumption significantly surpassed the national average of 217 g/day, whereas fish consumption was considerably lower than the national average of 51 g/day (BPS, 2024). The average rice consumption in the research community was 267.50 g/day, significantly higher than that of several other Asian countries: China at 238 g/day, Taiwan at 132 g/day, and Japan at 119 g/day (Hu, Y. 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/day. Approximately 90% of chromium intake in humans occurs through food consumption, rather than drinking water, skin contact, or inhalation (Zhang R. 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 μg/person/day, 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 & Tepe, 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 issues. The intake of heavy metals, including chromium, leads to the accumulation of chromium in body tissues, such as adipose and bone tissues. Exposure to Cr(VI) may increase susceptibility to upper gastrointestinal cancer (Manzoor et al., 2018). It may reduce human life expectancy by approximately 9 to 10 years (Guerra et al.

2012). Chemically-acquired immunodeficiency syndrome (C-AIDS) denotes a reduced immune response due to exposure to chemicals, such as heavy metals. Extended exposure to chromium in humans may lead to gastrointestinal disorders, respiratory complications, renal and hepatic damage, and genetic material abnormalities, among other health difficulties (Shanker et al. 2005). The principal pathophysiology includes DNA damage, genomic instability, and the generation of reactive oxygen species (ROS) induced by chromium (VI). Chromium (VI) increases oxidative stress and stimulates the generation of ROS in target DNA and cellular lipids, resulting in DNA damage and lipid peroxidation, respectively (Balali-Mood et al. 2021). The cancer risk linked to Cr(VI) exposure can be affected by various factors, such as the intake of Cr(VI) from contaminated sources and differing concentrations of Cr(VI) 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 needed to characterize uncertainty and variability, which are key in the health risk assessment. Health risk analysis is subject to uncertainty due to inherent variability across spatial and temporal scales (Walker et al. 2003). This variability arises from factors including the intrinsic properties of an agent, the nature of side effects, the characteristics of hazards, the relationship between the agent and side effects, the actual level of exposure, and the source of the observed effects (Jansen et al. 2019). The deterministic approach to health risk assessment has limitations, particularly the potential for underestimating or overestimating actual risk. This variability arises from metal concentrations, chromium species, consumption levels, age, sex, body weight, and physiological and 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.

5. CONCLUSIONS

There has been a significant increase in Cr(IV) 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, indicated by RQ values exceeding one and ECR values surpassing acceptable thresholds. The results highlight the critical necessity for effective management of river water quality, the implementation of stricter regulations on industrial effluents, the conduct of 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(IV) parameters should be incorporated into river water quality monitoring to facilitate routine assessments, including those of various food commodities along the downstream Opak River.

Author Contributions: For research articles with multiple authors, include a brief paragraph outlining each author's contributions using the following format: "Conceptualization, D.R., G.S. and S.H.; methodology, D.R., G.S; software, , D.R., D.M, ; validation, D.R., G.S. and S.H; formal analysis, D.R.; investigation, D.R.,.; resources, D.R..; data curation, D.R., D.M,.; writing—original draft preparation, D.R.; writing—review and editing, G.S., S.H., D.M.,; visualization, D.R., D.M.,; supervision, G.S.; project administration, D.R.; funding acquisition, D.R. All authors have read and agreed to the published version of the manuscript." Authorship should be restricted to individuals who have made significant contributions to the research.

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