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Monte Carlo-Based Assessment of Human Health and Ecological Risks from Chromium and Iron Contamination in Coastal South Sulawesi, Indonesia

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ABSTRACT

This study aimed to assess exposure levels and health risks associated with iron (Fe) and chromium (Cr) among coastal communities in South Sulawesi, Indonesia. A cross-sectional design was employed, involving field sampling and laboratory analysis of seawater and marine biota, combined with a health risk assessment approach. Intake analysis indicated that Fe was the dominant contributor to daily exposure, while Cr levels were relatively lower. Risk characterization showed that the average Risk Ratio (RQ) for Fe exceeded the safe threshold (RQ > 1), while the RQ for Cr remained below the safe limit. Monte Carlo simulations (MCS) confirmed that both Cr and Fe exhibited Target Hazard Quotient (THQ) values above safe levels. Sensitivity analysis revealed that exposure duration, frequency, consumption level, and metal concentration in seafood were the most influential variables. This study demonstrated that Fe is the primary risk factor contributing to non-carcinogenic health hazards in coastal areas of South Sulawesi, while Cr presents a potential long-term carcinogenic risk. These findings underscore the urgent need for integrated mitigation strategies to protect public health and ensure the sustainability of coastal ecosystems.

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1. INTRODUCTION

The presence of heavy metals in the sea is a result of contributions from anthropogenic activities that occur on land, as well as the distribution of pollutants from shipping and fishing [1]. Although industrial areas, municipal waste, and residential areas make a significant contribution to the accumulation of metals on the coast, the possibility of natural sources cannot be ruled out. Natural sources of heavy metals such as chromium (Cr) and iron (Fe) in South Sulawesi generally originate from geological processes associated with ultramafic rocks and laterite deposits that are widely distributed across the Sulawesi region [2]. The potential contaminants may originate from the weathering of ultramafic rocks, such as peridotite and serpentinite, which produce lateritic soils rich in metal minerals, where Fe and Cr often accumulate in the limonite and saprolite zones during the lateritization process.

Geochemical studies indicate that laterite deposits in Sulawesi contain various metal elements, including Fe, Cr, Ni, and Co, which are naturally formed because of the intensive weathering of ultramafic parent rocks in tropical environments [3]. Natural sources of heavy metals originate from rocks and the geological areas of an area [4,5]. For example, heavy metal accumulation was found in Sicilian volcanic sediments [6,7]. Metals such as Fe, Cr, Cu, Mn, Ni, Pb, or Zn are observed to increase in concentration and contaminate water, plants, and animals, including humans, through the food chain [8]. Efforts to detect the risk of heavy metal exposure to the environment and human health in coastal areas can be conducted by applying the health risk analysis method from the Environmental Protection Agency (EPA) [9]. This approach is one of the easy-to-use methods and involves a process for calculating or predicting health risks based on two pollution parameters [10]. If the hazard quotient (HQ) value, which reflects the level of non-carcinogenic risk >1, then the possibility of acute risks and health problems is likely to occur in the community [11]. Then, for carcinogenic risks, if the intake of heavy metals through the combined dermal and oral routes is more than 1×10^{-6}, the risk of cancer will likely arise [12,13].

To obtain a high level of accuracy in estimating carcinogenic and non-carcinogenic risks, Monte Carlo simulation models and sensitivity analyses need to be carried out [14]. These simulations can provide risk value levels with more precise estimates and indicate the main variables that are most influential in health risk analysis [15]. As the largest producer of seafood in Indonesia, the quality of the environmental areas and the accumulation of heavy metals are the most dangerous threats to the coast of South Sulawesi. Therefore, the concentration of heavy metals in marine organisms collected from the coast can not only indicate ecological conditions but also help in evaluating potential health risks from seafood consumption [16,17].

Fish, shrimp, shellfish, and crabs are the main marine species consumed by a large population in South Sulawesi and can be used as indicators of marine organism pollution [18-20]. Several years ago, this area was one of the main areas for beach recreation and family tourism [21]. However, the quality of the beach water, which looks dirty and smells, makes people uninterested in visiting this area [22]. Recreational activities such as swimming, beach tourism, and coastal fishing are becoming increasingly popular among local communities and visitors. Along the coastal areas of South Sulawesi, several city landmarks, commercial centers, and historical buildings are located near the shoreline, making the coastal zone an important source of economic activity and livelihood for the surrounding communities. However, intensive coastal utilization, including fishing activities, may contribute to environmental pollution using fishing boats, fuel combustion, discarded fishing gear, and improper disposal of fish processing residues and domestic waste from coastal settlements.

These activities can introduce various contaminants into the marine environment and potentially affect seawater quality as well as marine biota inhabiting the coastal ecosystem.

Furthermore, by applying a Monte-Carlo simulation model, it is hoped that the predicted risk of cancer and non-cancer diseases due to seafood consumption and beach tourism activities (swimming, fishing, and playing) will be more accurate [23]. This research will produce toxicity values for the biota living around the coast of South Sulawesi, especially shellfish [24]. The unique feature of this study is that it can calculate risk analysis and produce minimum/tolerance limits for metals in shellfish, using calculations that predict no effect concentrations (PNECs) or minimum toxicity levels [24]. Although numerous studies have examined heavy metal contamination in marine environments and seafood, most have focused primarily on measuring metal concentrations and evaluating general ecological impacts rather than assessing integrated human health risks associated with seafood consumption in specific coastal regions. In Indonesia, particularly in South Sulawesi, research addressing the distribution of heavy metals such as chromium (Cr) and iron (Fe) in coastal biota remains limited, and few studies have combined environmental measurements with quantitative human health risk assessment approaches.

Previous studies have also rarely applied probabilistic methods, such as Monte Carlo simulation, to estimate variability and uncertainty in exposure through seafood consumption. In addition, limited attention has been given to shellfish as bioindicator organisms despite their high capacity to accumulate contaminants due to their filter-feeding behavior. Therefore, a research gap exists in providing a comprehensive assessment that integrates heavy metal contamination in shellfish, probabilistic health risk modeling, and potential exposure pathways among coastal communities in South Sulawesi. This study aims to address this gap by evaluating heavy metal concentrations in shellfish and estimating both carcinogenic and non-carcinogenic health risks using a probabilistic risk assessment approach.

2. METHODS

This study was conducted in coastal areas of South Sulawesi, specifically the coastal areas of Makassar City, Gowa Regency, and Takalar Regency. These three areas are located along the western coast of South Sulawesi Province and serve as major seafood production hubs. Besides being prime areas for seafood consumption, these areas are also popular tourist destinations, resulting in bustling beach activities on weekends. This coastal area also supports the economic sector with the presence of buildings. historical, government offices, business centres, ports, factories, and housing.

2.1. Regional Overview

The selection of these locations was based on the characteristics of coastal areas, which are densely populated by human activity, such as fishing, seafood trade, and residential areas. The areas are shown in the map below in **Figure 1**.

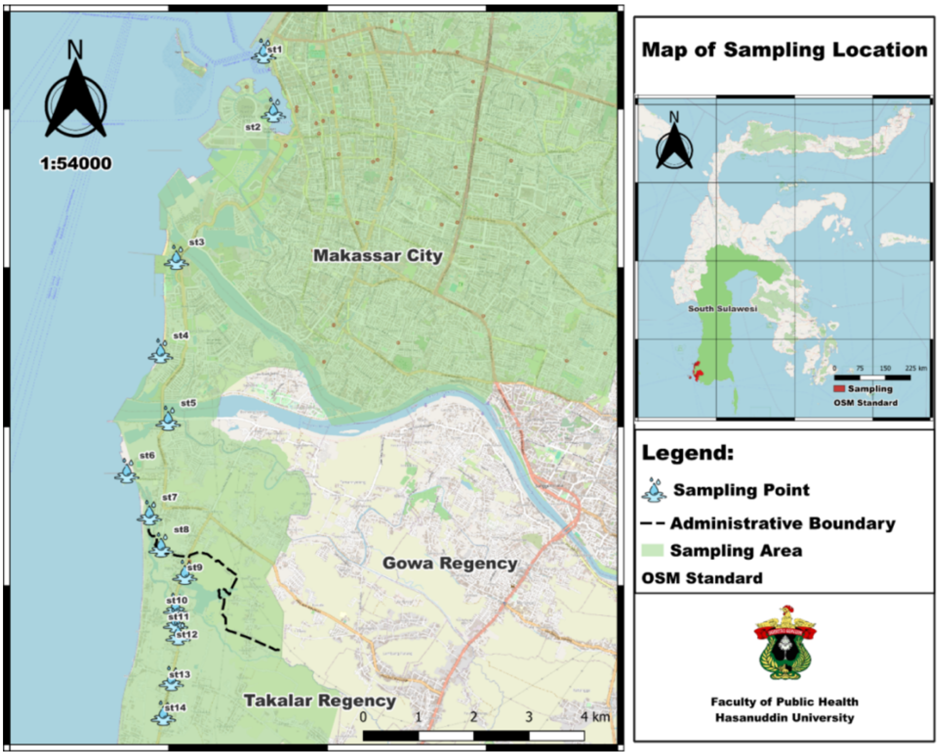

Figure 1. Map of sampling site.

These activities have the potential to become sources of pollution, including domestic waste, small-scale industrial activities, and fishing-related operations that occur in coastal areas. In addition, inadequate waste management practices in coastal settlements and fish trading areas can further introduce pollutants into the marine environment, potentially affecting seawater quality and the biota that inhabit these waters. Shellfish, as filter-feeding organisms, continuously filter suspended particles from the surrounding water, making them particularly susceptible to accumulating pollutants, including heavy metals and pathogenic microorganisms. Therefore, laboratory analysis of water and shellfish samples at these locations is expected to provide a comprehensive picture of the aquatic environmental quality and the potential health risks for coastal communities that consume shellfish as a food source.

2.2. Environmental Sampling Procedures

Environmental samples taken were water, sediment, and biota (shellfish) samples found around the coast. The number of samples required was 30. Mapping of quality and accumulation of heavy metals was carried out using a Geographical Information System (GIS). In addition to heavy metal concentrations (Cr, Pb, Zn, and Fe), parameters required for water and sediment analysis were pH, inorganic substances, temperature, electrical conductivity (EC), total dissolved solids (TDS), and salinity. Seawater samples were placed in 500 mL high-density polyethylene (HDPE) plastic bottles. Sediment was placed in 250-gram sterile plastic bottles and stored in sterile plastic before being sent to the laboratory. Water quality measurements were carried out in situ (directly at the research location). Water samples were acidified with a solution of high-purity concentrated hydrofluoric acid, concentrated nitric acid, and hydrogen peroxide (5:1:1), heated to 190°C, and cooled for 25 minutes. The digested samples were reconstituted with 0.5 mL of HNO3 diluted with ultrapure water in a 50 mL flask and analyzed by Atomic Absorption Spectrometry (AAS). For QC/QC analysis, sample calibration using blank and regression samples was used.

2.3. Environmental Health Risk Analysis

The method for estimating *the Target Hazard Quotient* (THQ) occurs when a person consumes or inhales a substance contaminated with a food ingredient or certain toxic contaminants that are non-carcinogenic and carcinogenic [25,26] (see Eq. 1).

$$THQ = \frac{EF\ x\ ED\ x\ FIR\ x\ C}{RfD\ xBw\ x\ AT} x10^{-3} \tag{1}$$

Information:
EF : Frequency of exposure (365 days/year)
ED : Duration of exposure (70 years)
FIR : Intake rate (grams/individual/day)
C : Metal concentration
RfD : Reference dose / Concentration
Bw : Body weight (kg)
AT : average exposure time for non-carcinogenic (365 days/year x ED)

To determine the risk of exposure to carcinogenic substances, a Cancer Slope Factor (CSF) value is required for each element [27-29]. This value is the default, and every element with the potential to cause cancer will have this value. The formula used to determine the risk of cancer exposure is as follows Eq. (2)

$$TcR = \frac{EFxED\ x\ FIR\ x\ C\ x\ CSF}{BW\ x\ AT} x10^{-3} \tag{2}$$

2.4. Monte Carlo Simulation Model

Health risk analysis is typically expressed as a single number. However, the EPA recommends using multiple risk estimation descriptors in addition to a single risk value [25]. Monte Carlo Simulation (MCS) is a statistical technique that effectively generates multiple risk descriptors. This approach minimizes uncertainty. Previous studies in health risk prediction have shown the potential for chemical exposure to affect human health [30,31]. Several issues have been identified regarding the use of MCS for risk identification and decision-making related to environmental issues. This study was conducted using Monte Carlo Simulation techniques using Oracle Crystal Ball software version 11.1.2. This research is expected to carry out multidisciplinary research activities that are relevant, sustainable, and have a positive impact on the community in accordance with the Hasanuddin University Research Strategy Plan for 2020-2024.

3. RESULTS AND DISCUSSION

3.1. Respondent Characteristics

The largest proportion of respondents came from the female group, which dominated the study population, while males accounted for a smaller proportion. This difference may reflect gender representation in the study area and should be considered when interpreting shellfish consumption patterns and the associated potential health risks. The predominance of female respondents is important to consider because several studies have reported that biological susceptibility to heavy metal exposure may vary between men and women.

These differences are often associated with physiological and metabolic characteristics, including variations in body composition, hormonal regulation, and iron metabolism. Hemoglobin, a protein responsible for oxygen transport in the blood and a major component of the body's iron system, plays an indirect role in the interaction between essential and nonessential metals in the bloodstream. Since some metals share similar transport and binding mechanisms with iron, differences in iron status and hemoglobin levels may influence the absorption, distribution, and retention of certain metals, including chromium, in the human body [32].

Furthermore, previous studies have suggested that dietary habits and seafood consumption patterns may differ between genders in coastal communities. Women are often more involved in household food preparation and consumption of locally available seafood, including shellfish, which may increase the likelihood of dietary exposure to contaminants accumulated in marine organisms [33]. Therefore, gender composition in the study population should be considered when interpreting potential exposure pathways and health risk assessments related to seafood consumption.

In terms of employment, respondents had a variety of professions, ranging from fishermen and traders to other informal sector workers. This reflects the socio-economic conditions typical of coastal communities in South Sulawesi. Communities that work directly at sea or in seafood markets tend to have higher levels of exposure, both through consumption of seafood and direct contact with seawater. Liu et al [14] found in their study in China that coastal communities whose economies depend on seafood have a higher risk of exposure to heavy metals. Thus, the nature of people's work is an important variable in health risk analysis [34].

Based on **Table 1**, the quantification of heavy metal concentrations demonstrates a distinct disparity between chromium (Cr) and iron (Fe) levels across sampling sites. Cr concentrations ranged from 0.000042 to 0.3012 µg/Nm³, with the maximum level observed at Aeng Batu-Batu, Galesong Utara, whereas Fe concentrations were markedly higher, varying from 0.396 to 5.663 µg/Nm³, with the peak concentration recorded at Jl. Pajjukkang Lbk. Overall, Fe consistently exhibited higher concentrations than Cr, indicating its dominant presence in the coastal atmospheric matrix. The spatial distribution pattern revealed that western coastal zones of Makassar, including Tanjung Merdeka, Central Point Indonesia (CPI), and Barombong Beach, contained relatively low concentrations, while the Galesong area exhibited significantly elevated levels. These findings highlight a clear spatial heterogeneity in heavy metal pollution, likely driven by localized industrial emissions, transportation activities, and domestic waste discharges. The results underscore the necessity for spatially targeted environmental management and regulatory interventions to mitigate heavy metal contamination hotspots along the Makassar coastline. The measurement results show that Cr concentrations ranged from 0.000042 to 0.3012 µg/Nm³, while Fe ranged from 0.396 to 5.663 µg/Nm³. Fe concentrations were consistently higher than Cr at all sampling points. Spatial variation was also evident, with the Galesong area showing the highest levels compared to other locations such as Tanjung Merdeka or Barombong Beach. The high Fe content most likely originated from industrial activities, maritime transportation, and domestic waste flowing into the coast. Meanwhile, the presence of Cr, although relatively low, indicated specific sources, such as metal plating industrial waste or port activity waste. These findings are in line with the research by Taghavi et al [22], which shows that the distribution of heavy metals in marine sediments is greatly influenced by anthropogenic activities on the coast [15]. Similarly, Feng et al [16] emphasize that spatial variations in heavy metals in sediments are influenced by a combination of natural factors and human activities. These results confirm that the coastal areas of South Sulawesi, which are densely populated and economically active, are highly vulnerable to heavy metal accumulation [34-36].

Table 1. Laboratory examination results.

Sampling Location	Concentration (µg/ N m 3)	
	Cr	Fe
Cape Merdeka, Tamalate	0.000042	0,275
Cape Merdeka, Tamalate	0.000012	0,28263889
Center Point Of Indonesia (CPI)	0.000012	0,21458333
Bosowa Beach, Tamalate District	0.000012	0,36527778
Makassar City, South Sulawesi	0.000012	5,972
Natural Bath Street, Barombong	0.000012	5,677
Barombong Beach	0.000012	
Pajjukuang Lbk	0.000012	5,663
Pajjukuang Lbk	0,72361111	3,353
Aene Towa, North Galesong	1,39791667	5,832
Aene Towa, North Galesong	0,90486111	3,152
North Galesong	0,77222222	4.166
Aeng Batu-Batu, North Galesong	2,09166667	2,253
Bontolanra, North Galesong	1,18888889	6,162
Baso Beta, Bontolebang	0,77222222	3,553
Barombong Beach	0.000012	6,053

3.1. Environmental Health Risk Assessment

Based on **Table 2** presents intake values for carcinogenic and non-carcinogenic heavy metals, specifically iron (Fe) and chromium (Cr), based on real-time exposure data collected in 2025. Intake values reflect the estimated amount of heavy metals absorbed by respondents through environmental exposure (such as air, water, or dietary routes) during the study period. For iron (Fe), intake values varied widely among the 16 respondents, with a mean of 9.7367, a minimum of 0.0, a maximum of 121.9048, and a median of 2.1589. The presence of a minimum value of zero implies that some respondents had negligible or unmeasured Fe exposure during the monitoring period. In contrast, chromium (Cr) intake values were consistent across all respondents, with a mean, minimum, maximum, and median of 0.00019. This indicates that Cr exposure levels were consistently low and stable, exhibiting minimal variation between individuals. Intake analysis shows that the average Fe intake reaches 9.73 µg/kg/day with a maximum value of 121.9 µg/kg/day, while Cr is much lower, at around 0.00019 µg/kg/day. The high Fe intake reflects the dominance of exposure to this metal in the daily lives of coastal communities. Although Fe is an essential element, excessive intake can cause toxic effects such as liver disorders, pancreatic damage, and increased oxidative stress [37]. Conversely, Cr intake was at a very low level, so its contribution to total exposure was smaller. This is in line with laboratory results showing that Cr concentrations were far below Fe at all sampling locations.

Table 2. Respondents' carcinogenic and non-carcinogenic intake values for real-time exposure duration in 2025.

Parameter	n	Mean	Min	Max	Median
Iron (Fe)	16.0	9.736763	0.0	121.904762	2.158936
Chromium (Cr)	16.0	0.00019	0.00019	0.00019	0.00019

3.2. Risk Characteristics

Risk characterization is performed by combining exposure and dose-response analysis. Risk characterization is expressed in *Excess Cancer Risk* (ECR) for carcinogenic effects. The level of carcinogenic risk is expressed as an exponential number without a unit. It is said to be safe if the ECR value is ≤ 1/10,000. The risk level is said to be unsafe if the ECR value is > E-4 (10^{-4}) or expressed as > 1/10,000. Meanwhile, for non-carcinogenic effects, it is stated in *the Risk Question* (RQ). It is said to be safe if the RQ < 1 and unsafe if the RQ > 1. The results of the calculation of heavy metal intake into the body in real-time projections (Dt). The mean, median, minimum, and maximum risk levels for carcinogenic effects are expressed in the *Excess Cancer Risk* (ECR) notation, while for non-carcinogenic effects, they are expressed in *the Risk Question* (RQ). The duration of real-time exposure is presented in the following **Table 3**.

Table 3. Min, max, and mean excess cancer risk (ECR) and risk question (RQ) realtime values in respondents in 2025.

Parameter	N	Mean	Min	Max	Median
RQ_Fe	16	13.909.662	00.00	17.414.966	3.084.195
RQ_Cr	16	0.063342	0.063342	0.063342	0.063342
ECR_Cr	16	0.000095	0.000095	0.000095	0.000095

Based on **Table 3**, the average Risk Quotient (RQ) for iron (Fe) was 13.91, with a maximum value reaching 174.15. These figures indicate that almost all respondents (RQ Fe ≥ 1) were exposed to Fe levels exceeding the Reference Dose (RfD) established as a safe limit by the US-EPA. An RQ value greater than 1 indicates that exposure levels exceed the acceptable daily intake, thus posing a potential non-carcinogenic health risk. The median RQ Fe of 3.08 further supports this finding, indicating that more than half of the respondents remained above the safe threshold, even when the effects of outliers were minimized. This condition confirms that iron (Fe) is a dominant contributor to non-carcinogenic risks in the studied population. The high variability in RQ Fe values also reflects spatial and behavioral differences in exposure, which are likely influenced by variations in industrial activities, environmental distribution, and daily human interactions with contaminated sources. In contrast, the average RQ for chromium (Cr) was 0.0633, with identical minimum and maximum values (0.0633) across all respondents. This uniformity indicates that Cr exposure levels are consistent and well below the risk threshold (RQ < 1), indicating that current Cr concentrations do not pose a non-carcinogenic health risk. Regarding carcinogenic effects, the average Excess Cancer Risk (ECR) for Cr was 0.000095, with identical minimum and maximum values. This value is below the carcinogenic risk threshold of 0.0004 recommended by the United States Environmental Protection Agency (US-EPA), indicating that current Cr exposure does not pose a significant carcinogenic hazard.The average Risk Quotient (RQ Fe) is 13.91 with a maximum value of 174.15. Almost all respondents have an RQ Fe value ≥ 1, meaning that Fe exposure exceeds the safe threshold recommended by the US-EPA. This condition indicates the potential for serious non-carcinogenic risks, including digestive system disorders, changes in iron metabolism, and toxic effects on the liver.

These findings are in line with the report by Briffa et al [13], which states that heavy metals, including Fe, can be toxic at high doses and cause chronic health disorders. The Risk Quotient (RQ Cr) shows an average of 0.063, well below the safety threshold (RQ < 1). Thus, Cr exposure through seafood consumption among coastal communities is still considered safe and does not pose a risk of non-carcinogenic effects. Excess Cancer Risk (ECR Cr) was obtained at 9.5 ×

10^{-5}, which is still below the carcinogenic risk threshold (1×10^{-4}). However, because the value is close to the tolerance limit, periodic monitoring remains important to anticipate potential increases in risk. A similar study by Pandion et al [18] on heavy metal risks in seafood also found that cancer risk values are generally low but still require monitoring, especially in populations with high consumption. The findings of this study provide important insights into heavy metal contamination in shellfish and the associated human health risks in coastal areas of South Sulawesi, Indonesia. However, the environmental conditions, coastal activities, and socio-economic characteristics of communities in Eastern Indonesia may differ from those in other coastal regions. Factors such as local hydrodynamics, geological background, anthropogenic pressures, and seafood consumption patterns can influence the distribution and accumulation of heavy metals in marine organisms. Previous studies have also demonstrated that heavy metal contamination in coastal ecosystems varies considerably across regions depending on local environmental and anthropogenic factors [25,26]. Therefore, while the results of this study provide valuable evidence for understanding contamination risks in the study area, caution should be exercised when generalizing these findings to other geographic settings.

3.3. Monte Carlo Simulation

Based on **Figure 2**, the sensitivity analysis shows that the variables most influential on THQ value variation are exposure duration (18.8%), followed by respondent body weight (17.4%), daily exposure frequency (17.4%), and shellfish/fish consumption rate (17.3%). The concentration of Cr in biota contributed 12.2%, while annual frequency had a relatively smaller effect. These results confirm that groups with low body weight, high seafood consumption, and long exposure duration (e.g., children, women, and fishermen) have a greater risk than other groups. The health risk assessment of chromium (Cr) contamination in coastal areas of Makassar, as illustrated in the probabilistic simulation of the Total Hazard Quotient (THQ), reveals significant findings. The probability distribution **Figure 2** shows that the THQ values of chromium range between 122.0 and 280.7, with a median of 185.1 and a mean of 191.1. The relatively high standard deviation of 240.3 indicates substantial variability in the exposure distribution. As the THQ threshold value of 1 is widely recognized as the critical limit for non-carcinogenic health risks, the consistently elevated values observed in this study demonstrate that chromium exposure in the study area may pose considerable health hazards to the local population, particularly through long-term ingestion of contaminated water and seafood [38,39].

The sensitivity analysis, **Figure 2,** further highlights the major determinants influencing THQ variability. Among the parameters, exposure duration (ED, 18.8%), ingestion rate (17.3%), and chromium concentration (C, 16.9%) contribute most significantly to the variation in THQ values. In contrast, body weight (BW, -17.4%) and exposure time (ET, -17.4%) exhibit negative contributions, suggesting that greater body mass or shorter exposure reduces the relative health risk. Additionally, exposure frequency (EF, 12.2%) demonstrates a moderate influence, although less prominent compared to the other variables. These results emphasize that chromium-related health risks in the Makassar coastal region are largely driven by environmental contaminant levels and human behavioral patterns, particularly related to ingestion and exposure duration [39-41]. Therefore, risk mitigation strategies should prioritize two complementary approaches: (1) environmental interventions, such as strengthening industrial effluent management, enforcing stricter wastewater discharge regulations, and improving water treatment systems; and (2) community-based interventions, including raising public awareness of safe consumption practices and reducing long-term exposure pathways [42-44].

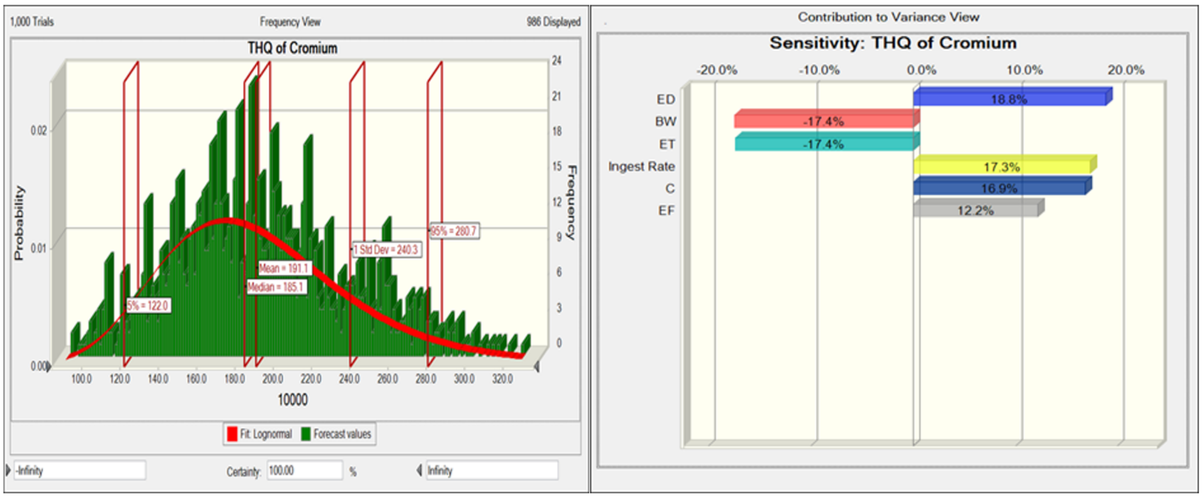

Figure 2. THQ of chromium.

Based on **Figure 3**, the probability distribution shows that the mean HQ is around 0.43 with a median of 0.43 and a range of 0.29–0.82. All HQ values generated are still below the safety threshold (HQ < 1), so Cr exposure through the analyzed pathways does not pose a significant non-carcinogenic risk to respondents. Sensitivity analysis shows that the most influential variable on the HQ value is Cr concentration (16.2%), followed by exposure frequency (EF, 19.6%), exposure duration (12.2%), body weight (12.0%), consumption rate (11.6%), and daily exposure time (11.0%). This confirms that, although the current risk is relatively low, seafood consumption and the physical condition of respondents still play a significant role in determining the level of risk, so monitoring Cr levels in coastal environments remains necessary. The probabilistic simulation of the Hazard Quotient (HQ) of chromium in the coastal areas of Makassar, **Figure 3** demonstrates that HQ values range from 0.40 to 0.90, with a median of 0.60 and a mean of 0.62. This distribution indicates that the majority of HQ values remain below the reference threshold of 1, which is commonly applied to assess non-carcinogenic health risks. Consequently, on average, chromium exposure in this area is unlikely to pose significant non-carcinogenic health effects to the local population. Nevertheless, the distribution extending to the 95th percentile of 0.90 suggests that certain subpopulations with higher exposure intensities, such as individuals with higher consumption levels or longer exposure durations, may be approaching levels of concern, necessitating precautionary measures.

The sensitivity analysis, **Figure 3** reveals that exposure frequency (EF, 20.2%), chromium concentration (C, 18.3%), and exposure duration (ED, 17.9%) are the dominant parameters influencing HQ variability. These findings underscore the importance of both environmental and behavioral factors in determining health risk. Body weight (BW, -16.2%) contributes negatively, meaning that individuals with higher body weight are relatively less susceptible to health risks under the same exposure conditions. Meanwhile, ingestion rate (15.9%) and exposure time (ET, 11.6%) also contribute to HQ variability, though to a lesser extent compared to the primary determinants. Overall, the results suggest that although the average non-carcinogenic risk from chromium exposure in Makassar's coastal region remains within the acceptable range (HQ < 1), vigilance is warranted due to the proximity of upper exposure levels to the risk threshold.

Risk management strategies should focus on reducing exposure pathways through industrial waste control, regular monitoring of water quality, and improved wastewater management systems [45]. In parallel, community-based interventions, such as public awareness campaigns regarding safe consumption habits and reduction of long-term exposure, are essential. From a policy perspective, these findings highlight the need for an integrated risk management approach that combines regulatory enforcement with community participation [46,47]. Furthermore, future studies should investigate potential long-term and carcinogenic risks, given that chromium is a heavy metal with known cumulative toxic effects. Such investigations would provide a more comprehensive understanding of health risks and strengthen the scientific basis for environmental and public health policies in coastal regions [48].

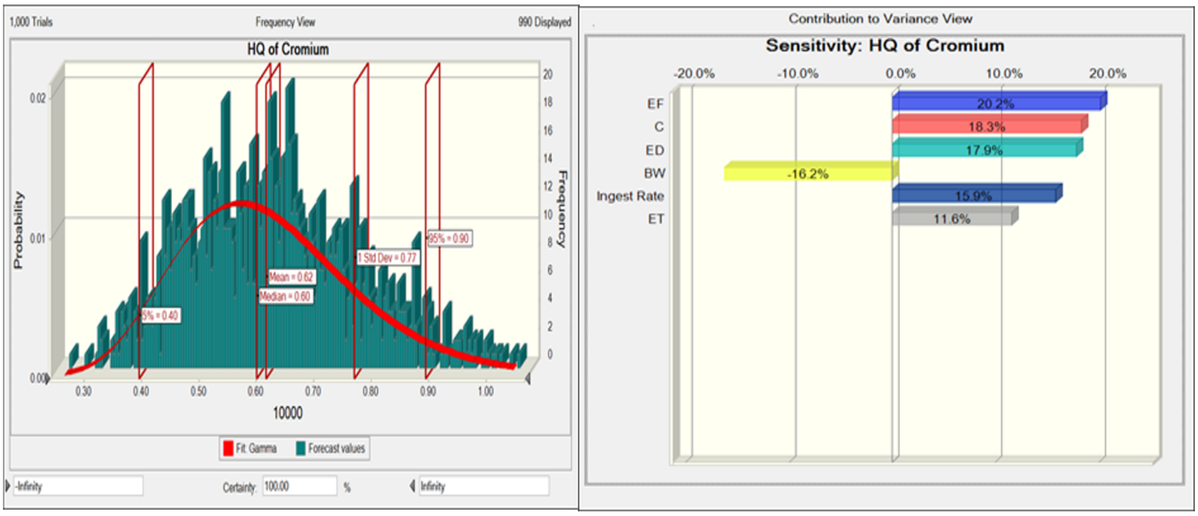

Figure 3. HQ of chromium.

Based on **Figure 4**, the simulation results show that THQ values for Cr range from 292 to 2882, with an average value of approximately 1881. In contrast, the THQ values for Fe range from 0.79 to 2.53, with an average of 1.67. These results indicate that Cr exposure consistently yields THQ values far exceeding the safety threshold (THQ > 1), signifying a high potential for non-carcinogenic health risks across all simulated exposure scenarios. The extremely high THQ values for Cr highlight the critical role of chromium as a dominant pollutant contributing to potential adverse health outcomes. Such elevated THQ levels may be associated with chronic exposure through inhalation or ingestion pathways, reflecting industrial discharges, vehicular emissions, and waste accumulation as major sources of Cr contamination. Meanwhile, although the THQ values for Fe are considerably lower than those for Cr, they still exceed the threshold of 1, implying that Fe exposure also contributes notably to non-carcinogenic health risks. This finding suggests that both metals act as co-determinants of health hazards, with Cr posing a higher level of concern, whereas Fe remains a secondary but significant risk factor.

For chromium, **Figure 4**, the THQ values ranged from 122.0 to 280.7, with a median of 185.1 and a mean of 191.1, far above the acceptable safety level. The log-normal distribution revealed a wide variability, as reflected in the high standard deviation of 240.3, indicating significant differences in exposure among individuals. This result highlights that local communities are at considerable health risk from chromium exposure, particularly given its cumulative toxicity and long-term health impacts, including respiratory disorders, renal dysfunction, and carcinogenic potential.

In contrast, iron exposure **Figure 4** exhibited THQ values ranging from 1.02 to 2.14, with a median of 1.50 and a mean of 1.53. Although the magnitude of iron exposure was lower compared to chromium, the values still exceeded the safety reference, implying potential chronic health risks [49]. Elevated iron intake can lead to metabolic disorders, liver damage, and heightened vulnerability among sensitive groups such as children and the elderly. These findings underscore the importance of addressing both chromium and iron contamination in the coastal area. The health risk assessment based on the Total Hazard Quotient (THQ) indicates that heavy metal contamination in the coastal waters of Makassar is primarily driven by chromium (Cr) and iron (Fe) exposure. The probability distributions of THQ **Figure 4** consistently show values exceeding the safety threshold (THQ > 1), suggesting potential non-carcinogenic risks to the coastal population.

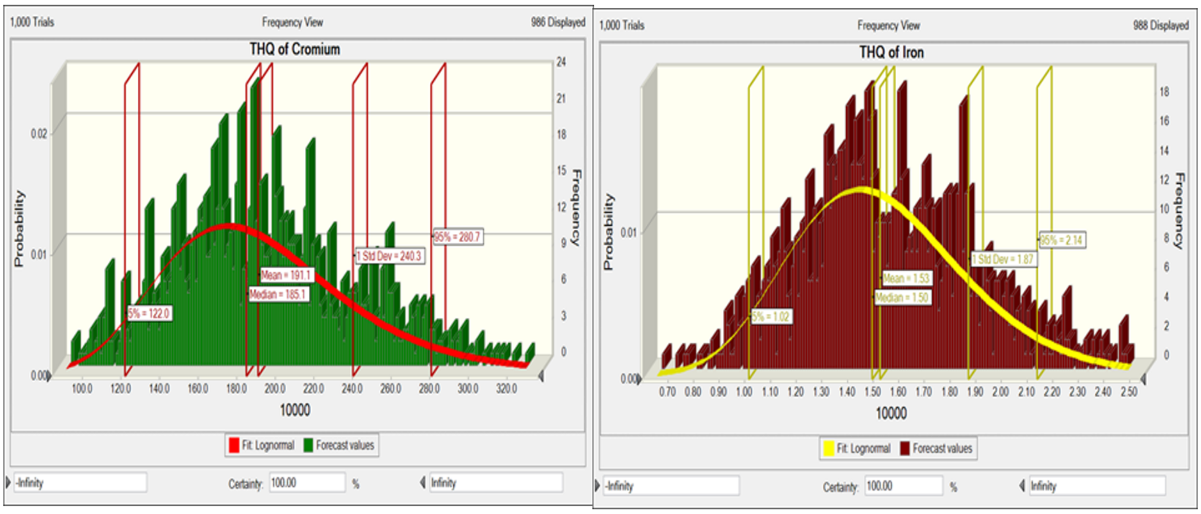

Figure 4. THQ of chromium and iron.

Based on **Figure 5**, the results indicate that for Cr, the most influential variables are exposure duration, body weight, daily exposure frequency, and seafood consumption rate. These factors collectively determine the extent of Cr intake and accumulation in the human body. For Fe, the sensitivity analysis reveals that the key determinants of THQ are exposure duration (21.6%), exposure frequency (20.6%), metal concentration (20.1%), and consumption rate (19.1%). The relatively balanced contribution of these parameters suggests that both environmental and behavioral factors influence Fe-related risk. The concentration of Fe in environmental media, combined with frequent and prolonged exposure, enhances the potential for health effects, especially among individuals with high consumption rates of contaminated seafood. These findings confirm the multifactorial nature of heavy metal exposure risk in coastal communities. Both Cr and Fe act as important determinants of non-carcinogenic health risk, with the level of risk being highly dependent on individual lifestyles, exposure intensity, and physiological characteristics.

The sensitivity analysis, **Figure 5,** further identified the key parameters influencing THQ variability. For chromium, exposure duration (18.8%), ingestion rate (17.3%), and exposure time (16.9%) were the most influential factors, indicating that both the length of exposure and local water/seafood consumption patterns play crucial roles in risk estimation. For iron, the most influential variables were exposure duration (22.2%), exposure frequency (21.6%), and Iron concentration (20.8%), suggesting that both environmental conditions and behavioral factors substantially affect the health risk outcomes. Overall, these findings demonstrate that heavy metal contamination in Makassar’s coastal waters poses a significant public health concern [50]. The consistently elevated THQ values for both chromium and iron call for urgent mitigation measures. Recommended actions include: (1) controlling pollutant sources from industrial and domestic activities, (2) strengthening water treatment and monitoring systems, and (3) raising public awareness about the risks of consuming contaminated water and seafood [51]. These results provide strong scientific evidence to support local government initiatives in implementing stricter environmental regulations and pollution control strategies to safeguard the health of coastal communities.

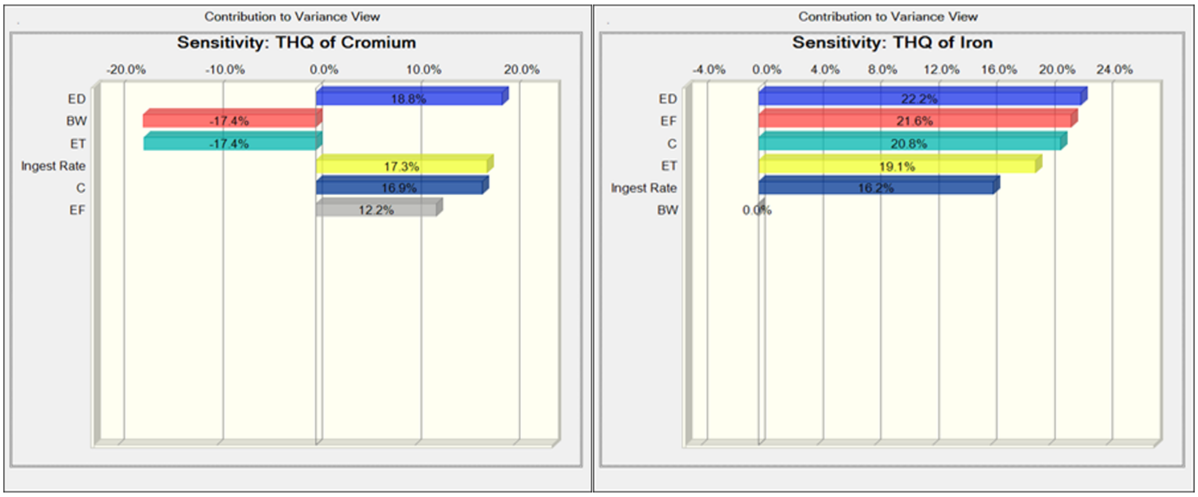

Figure 5. Sensitivity THQ of chromium and iron.

Based on **Figure 6**, the simulation indicates that the average HQ value for Cr is approximately 0.43, with a range between 0.29 and 0.82, whereas Fe exhibits an average HQ of 1.68, ranging from 1.10 to 2.43. These results reveal a distinct difference in the risk profiles of the two metals. The HQ values for Cr remain consistently below 1, indicating that Cr exposure is within the safe threshold and therefore does not currently pose a significant non-carcinogenic health risk to the population. The relatively low and narrow range of Cr HQ values suggests limited variability in exposure, likely due to stable environmental concentrations and moderate bioavailability in the local setting. Conversely, the HQ values for Fe consistently exceed 1, signifying that Fe exposure surpasses the Reference Dose (RfD) and may therefore pose potential health risks to coastal communities. The higher HQ range (1.10–2.43) suggests that certain individuals experience elevated Fe intake, possibly linked to high seafood consumption, proximity to pollution sources, or occupational exposure. The probabilistic health risk assessment conducted for chromium (Cr) and iron (Fe) in the coastal water of Makassar revealed distinct exposure characteristics and risk patterns for the local population.

The histogram and fitted probability distribution in **Figure 6** indicate that the Hazard Quotient (HQ) values for both Cr and Fe exceeded the safe threshold of 1.0 in a considerable portion of the simulations, suggesting potential non-carcinogenic health risks through chronic exposure. For chromium, the HQ distribution followed a gamma fit with a mean of 0.62 and a 95th percentile of 0.90. Although the mean HQ value was below the acceptable risk threshold, the tail of the distribution suggests that a subset of the population could still be at risk, particularly those with higher exposure scenarios. The relatively low median (0.60) and narrow spread imply that chromium risks are generally moderate but cannot be overlooked given chromium's cumulative toxicity and potential carcinogenic effects. It is often known that metals contribute to environmental pollution and toxicity, and that they pose serious health concerns to living things [19]. In contrast, iron exposure presented a more critical scenario. The HQ distribution followed a lognormal fit with a mean of 1.68, a median of 1.64, and a 95th percentile reaching 2.43. These values indicate that most of the population may already be experiencing HQ > 1, signifying significant potential non-carcinogenic health effects [52]. The broad variance and right-skewed distribution reflect a higher degree of uncertainty and variability in iron-related risks, emphasizing the need for urgent mitigation strategies [53].

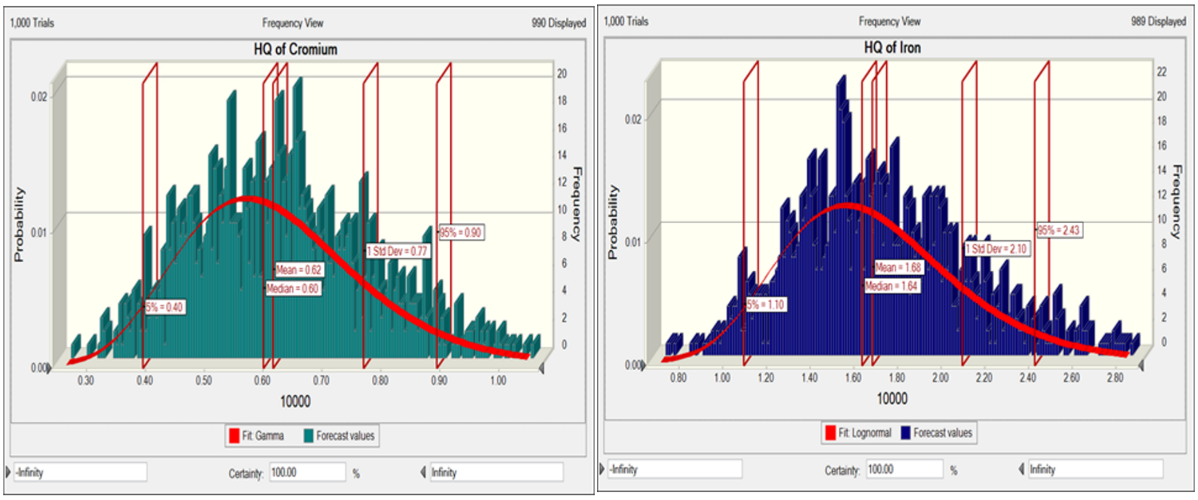

Figure 6. HQ of chromium and iron.

Based on **Figure 7**, for Cr, the most influential factors affecting HQ were exposure frequency (20.2%), metal concentration (12.8%), and exposure duration (12.3%). This indicates that the frequency and duration of contact with contaminated sources, as well as the environmental concentration of Cr, play critical roles in determining the overall exposure risk. However, the relatively moderate sensitivity percentages suggest that Cr-related risks are less variable and more stable across individuals, reflecting lower Cr bioaccumulation and limited exposure pathways in the coastal environment. In contrast, for Fe, the dominant variables influencing HQ were exposure frequency (18.0%), exposure duration (17.6%), and seafood consumption rate (16.8%). These findings demonstrate that Fe-related risk is more strongly associated with behavioral and dietary factors, particularly the frequency of exposure and the rate of seafood consumption, two parameters directly linked to local lifestyles and food habits. The nearly equivalent contribution of these parameters implies that prolonged exposure and high consumption of Fe-contaminated seafood significantly elevate non-carcinogenic health risks among coastal residents.

The sensitivity analyses in **Figure 7** further clarified the key drivers of risk variability. For chromium, exposure frequency (EF), concentration (C), and exposure duration (ED) were the most influential parameters, contributing approximately 20.2%, 18.3%, and 17.9% to the overall variance, respectively. This indicates that risk management for chromium should prioritize reducing direct exposure time and controlling contaminant levels in water sources. In the case of iron, the most influential factors were exposure time (18.6%), exposure duration (17.9%), and ingestion rate (16.8%), with body weight (–13.3%) showing a negative correlation. This suggests that iron-related risks are strongly associated with cumulative intake, highlighting the importance of dietary and water quality interventions. Overall, the findings underscore that while chromium remains a pollutant of concern due to its toxicological profile, iron poses a more immediate non-carcinogenic risk to the coastal communities of Makassar. The dominance of exposure-related parameters in both sensitivity analyses suggests that behavioral interventions (e.g., reducing reliance on contaminated water sources) and environmental management (e.g., pollution control and remediation measures) will be critical in mitigating health risks. These results not only contribute to a better scientific understanding of metal-related risks in coastal ecosystems but also provide an evidence-based foundation for local policymakers to strengthen water quality monitoring, enforce regulatory standards, and implement community-based risk communication programs.

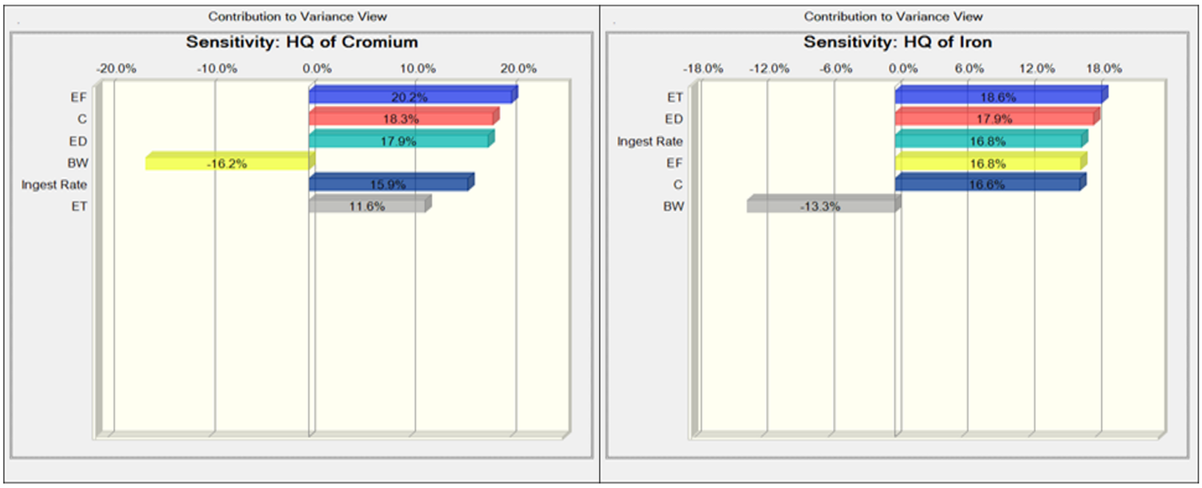

Figure 7. Sensitivity HQ of chromium and iron.

3.4. Limitation

This study has several limitations that should be considered when interpreting the results. First, the sampling of seawater and shellfish was conducted at specific locations and within a limited time frame, which may not fully capture temporal variations in heavy metal concentrations influenced by seasonal changes, hydrodynamic conditions, and anthropogenic activities along the coast. Second, the health risk assessment relied on standard exposure parameters and assumptions commonly used in environmental risk models, which may not completely reflect the variability of individual consumption patterns, body weight differences, and lifestyle factors among coastal populations. Third, the analysis focused on selected heavy metals and did not include other potential contaminants, such as organic pollutants or emerging contaminants that may also contribute to cumulative health risks. Finally, although the Monte Carlo simulation approach was applied to address uncertainty in exposure estimation, the accuracy of the results still depends on the availability and quality of input data. Future studies are therefore recommended to include broader spatial and temporal sampling, incorporate additional contaminants, and collect more detailed dietary and behavioral data to improve the robustness of human health risk assessments in coastal ecosystems.

4. CONCLUSION

This study revealed that the coastal areas of South Sulawesi, particularly Makassar City, Gowa Regency, and Takalar Regency, have experienced the accumulation of heavy metals, especially chromium (Cr) and iron (Fe), which potentially pose health risks to coastal communities. Laboratory analysis showed that Fe concentrations were consistently higher than Cr at almost all sampling points, with spatial variations influenced by industrial activities, maritime transportation, and domestic waste. The intake assessment indicated that Fe was the main contributor to exposure, while Cr was relatively lower but still requires monitoring.

Risk characterization demonstrated that the average Risk Quotient (RQ) for Fe was far above the safe threshold (RQ > 1), indicating a serious potential for non-carcinogenic health risks, whereas the RQ for Cr remained below the safety limit. Nevertheless, the Excess Cancer Risk (ECR) value for Cr was close to the tolerable threshold, suggesting that regular monitoring is still necessary. The Monte Carlo simulation further supported these findings by presenting a probabilistic distribution of risks: both Cr and Fe THQ values consistently exceeded the safe limit, indicating a potential for chronic non-carcinogenic health effects among populations exposed through seafood consumption and coastal activities. Sensitivity analysis highlighted that exposure duration, exposure frequency, ingestion rate, and the concentration of metals in biota were the most influential factors in determining health risks. This implies that individuals with lower body weight, higher seafood consumption, and prolonged exposure (such as fishermen, women, and children) are more vulnerable to the adverse effects. In conclusion, this study emphasizes that heavy metal pollution, particularly Fe, has become a tangible threat to public health in the coastal areas of South Sulawesi. Therefore, integrated mitigation strategies are urgently needed, including the control of industrial and domestic pollution sources, strengthening monitoring systems for seawater and marine biota quality, and public education on safe seafood consumption patterns. These findings provide a scientific foundation for local government policies to enhance coastal environmental management.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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