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Ecological and human health implications of mercury contamination in the coastal water

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ABSTRACT

BACKGROUND AND OBJECTIVES: The increasing population and anthropogenic activities in coastal areas affects the presence of mercury in coastal waters. Therefore, this study aims to 1) assess the ecological and human health risk of mercury contamination in coastal water; 2) analyze the effectiveness of polymer sulfur as an absorbent for mercury.

METHODS: A total of fifteen water samples were obtained from the coastal areas of Makassar and were analyzed using cold vapor atomic absorption spectrophotometry. Ecological and human health risks were assessed using established assessment methods by the United States Environmental Protection Agency. The uncertainty and sensitivity tests for independent variables in human health risk were assessed by the Monte Carlo Simulation method. Furthermore, polymer sulfur was used as a promising technique for capturing and reducing the level of mercury in the water column.

FINDINGS: The results showed that the mean concentration of mercury was very high and exceeded the values established by the World Health Organization, United States of Environmental Protection Agency, and Indonesian National Standards, indicating elevated risks to the ecosystem and human health in the future. Additionally, the Monte Carlo simulation model revealed that the non-carcinogenic risk caused by mercury exposure in adults and children was greater than 1 (Total Hazard Index>1), indicating the health adverse effects for both receptors. From the simulation results, the concentration of mercury at 23.3 percent and exposure time of 21.3 % were the most influential and dominant factors in non-cancer risk for adults and children, respectively. Therefore, mercury concentration needs to be reduced in coastal areas. The application of polymer sulfur is effective for reducing mercury concentration in water with a percentage reduction range of 39 – 100 percent and p-value of 0.001.

CONCLUSION: Mercury contamination of coastal water in Makassar city poses ecological and health risks. The application of polymer sulfur is an effective way for reducing mercury in the water column.

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INTRODUCTION

Mercury (Hg) pollution has become a serious threat to the marine environment, especially those adjacent to industrial zones and high urbanization due to its toxicity, accumulation, persistence, and non-biodegradable nature (Basri *et al*., 2020; Fioramonti *et al*., 2022; Rauf *et al*., 2020; Aravind *et al*., 2016; Tariq *et al*., 2015). Naturally, weathering and heavy metal pollution affect the composition of coastal sediments which are related to seawater quality (Armstrong-Altrin *et al*., 2021; Astuti *et al*., 2021a). In Jiangsu coastal region, China, the industrial activities from photovoltaic electronics, mechanical metallurgy, printing, and dyeing industries lead to increased levels and accumulation of Hg (Zhao *et al*., 2018). Hg enters the marine environment mainly from atmospheric deposition, reduces to Elemental mercury (Hg^0), and is then released back into the atmosphere, or taken up from the water column by particulate matter and eventually buried in sea sediments (Lamborg *et al*., 2014; Zaferani and Biester, 2021). In the coastal areas, pollutants are released from various sources including the spill of oil from shipping activities, land reclamation, industrial runoff, and solid waste accumulation by human. Among the various chemical forms of Hg, Methylmercury (Me-Hg) is known to be highly neurotoxic and has been identified as the cause of Minamata disease (Sakamoto *et al*., 2018). The disease stemmed from methylmercury poisoning due to the consumption of aquatic edible biota such as fish and shellfish contaminated by methylmercury in Minamata bay, Japan (Harada, 1995). It was first discovered in 1956, where the people injured by methylmercury exposure had several symptoms including auditory, motoric, and sensoric disturbances, as well as dysarthria, ataxia, tremor, and visual constriction (Harada, 1995). Furthermore, Hg exposure can attack neurological systems. Its pollution recorded at the Kao Bay has exceeded the maximum exposure limit thereby causing a high potential health risk for humans (Amqam *et al*., 2020). Skin contact with Hg from acute and repeated exposure in humans also causes pruritic skin rashes, allergies, reddening, and peeling skin on the palms of the hands, and erythematous soles of the feet (Rauf *et al*., 2020). The initial effect of Hg exposure is characterized by fever fatigue, chills, fever, and elevated leukocyte count. For acute and chronic exposure, several studies reported increased tremors, muscle fasciculations, myoclonus, or muscle pain (ATSDR, 1999). Meanwhile, South Sulawesi as the largest national marine products producer has been contaminated by pollutants released from land-based sources through rivers and land runoff over several years due to urbanization and industrialization activities (Lestari *et al*., 2021; Yap and Al-Mutairi, 2022). This condition influences the potential damage to marine ecosystems, a decline in tourism, and affects the quality of the food chain, especially seafood consumed by the community (Li *et al*., 2013). Moreover, exposure to Hg, even in small amounts, can cause serious health problems. Previous assessments have found elevated mercury in samples of hair, blood, and urine in residents. Fetuses and infants are highly susceptible to mercury exposure, and this is associated with neurological effects (Gonzalez *et al*., 2019; Ashe, 2012). Several studies on the impact of heavy metals have been carried out in the coastal areas of Sulawesi. However, the contamination of Hg in the coastal environment has not been examined. Industrial runoff and land change have a potentially great contribution to the release of Hg metal into the aquatic environment in the Makassar coastal area. This implies that Hg removal from seawater is urgently needed to prevent adverse effects and protect the ecosystem. Efforts to apply simple remediation and economical materials are a major consideration, especially for the low-middle income region. Polymer sulphur is one of the candidate mercury adsorbents for water ecosystems. This absorption method is very easy to use, convenient, cost-effective, has high competence, low-cost, and is environmentally friendly (Azman *et al*., 2020). Elemental sulphur can adsorb and stabilize mercury (Azman *et al*., 2020). Additionally, it can easily be fused into the backbone of polymers and this mixture has a large surface area with a porous structure (Xu *et al*., 2017). Based on several experimental studies, polymer sulphur can adsorb mercury effectively (Azman *et al*., 2020; Chowdhury *et al*., 2021; Mann *et al*., 2021; Xu *et al*., 2017). These previous studies focused on the experimental aspects in laboratory settings. Consequently, this study was conducted in the actual coastal water of Makassar city. To obtain a high level of accuracy, the Monte-Carlo simulation (MCS) model was also applied to determine the predictive value of non-cancer risk and the most influential health factor through sensitivity analysis.

Previous results in health risk assessment relied on the input variables without assessing the level of correlation and contribution of each assumption. Therefore, this study used the probabilistic risk assessment which is more developed and highly accurate than the regular assessment. The Monte Carlo model was used to investigate the distribution of a selected variable by simulating random numbers. The specific contribution of health risk due to mercury exposure can be analyzed for further policy making. Furthermore, enhanced simulation reliability can improve the information contributing to the cost-effective approach in the prevention of further damage caused by water pollution (Puno *et al.,* 2022). The results are expected to form the basis of large-scale reductions in Hg levels in this area. The aims of the present study is to investigate the ecological damage and health risk assessment of Hg pollution from estuarine water of Makassar coastal area, South Sulawesi Province, Indonesia in 2022.

MATERIALS AND METHODS

Study area descriptions

Makassar city is one of the coastal areas in the South Sulawesi Province, Indonesia located at 119°18"27,97" – 119°32"31,03" east longitude and 5°30"18" – 5°14"49" south latitude. Its climate is tropical with a distinct wet and dry season, where the wet season start from November to May, while the dry season commences from June to October. Furthermore, high humidity and an average temperature of 27.8 °C occur in the dry season. There is only a slight temperature variation throughout the year, ranging from 24°C and 32°C for minimum and maximum respectively. The areas of the city lie along the three rivers namely the Jeneberang, Tallo, and Maros. The city has experienced significant environmental degradation caused by uncontrolled land use and the geomorphological condition of the coastal area (Suleman *et al.,* 2018). The several areas that have experienced degradation include Akarena, Tanjung Bayang, Tanjung Bunga, and Losari beach. Consequently, these areas tend to have high porosity and are affected by abrasion (Suleman *et al.,* 2018). The coastal area of Makassar is the final site of pollutants carried by the water from the Jeneberang watershed and Tallo river. This area is also surrounded by various anthropogenic activities including industry, domestic, hotel, hospital, harbor, and shopping centers. These conditions might influence the accumulation of heavy metals such as Hg in the coastal area. The existence of traders who process and sell gold also contributes to the accumulation of Hg pollution in this area (Ishak, 2017).

Sampling method

The grab water samples were obtained from 15 sampling sites in the Makassar coastal area. This sample site included in this study was selected using the purposive sampling method based on the potential sources or effluent flow of water to the coastal water ecosystems as presented in Fig. 1. The sampling was performed by a water sampler in 30 – 50 Centimeter (cm) depth of water. All samples were placed in a 1 liter (L) pre-sterilized High-density polyethylene (HDPE) bottle, then acidified using nitric acid (HNO_3) to examine the potential of hydrogen (pH) to minimize precipitation and adsorption on the wall of containers. Next, a bottle of the sample was placed in the box with ice cubes to avoid Hg evaporation. A global positioning system (GPS) was used to determine the geographic coordinates of each sampling site. All samples were transported to the chemical laboratory in Makassar to determine Hg concentration after the water collection.

Total Hg concentration analysis

Total mercury concentration (THg) was determined by Cold vapor atomic absorption spectrophotometry (CV-AAS) with wavelength 253.7 nanometer (nm) following Indonesia's standard for Hg analysis in water samples namely Indonesian National Standard (INS) 6989.78.2011. About 100 milliliters (mL) of the diluted sample was placed in a 250 mL erlenmeyer glass. Next, 5 mL of sulphuric acid (H_2SO_4) and 2.5mL of nitric acid (HNO_3) were added to the water sample and homogenized. About 15 mL of Potassium permanganate ($KMnO_4$) solution was also added and left for 15 minutes until the solution changed to purple. The solution was further added with 8 mL of Potassium persulfate ($K_2S_2O_8$), homogenized, and heated for two hours at 95°C in a water bath. Afterward, the solution was cooled to room temperature and added with 5 mL of Tin(II) chloride ($SnCl_2$). The samples were then analyzed in Cold vapor atomic absorption spectrophotometry (CVAAS): Shimadzu AA-7000 with mercury analyzer. To ensure procedure validity, Certified Reference

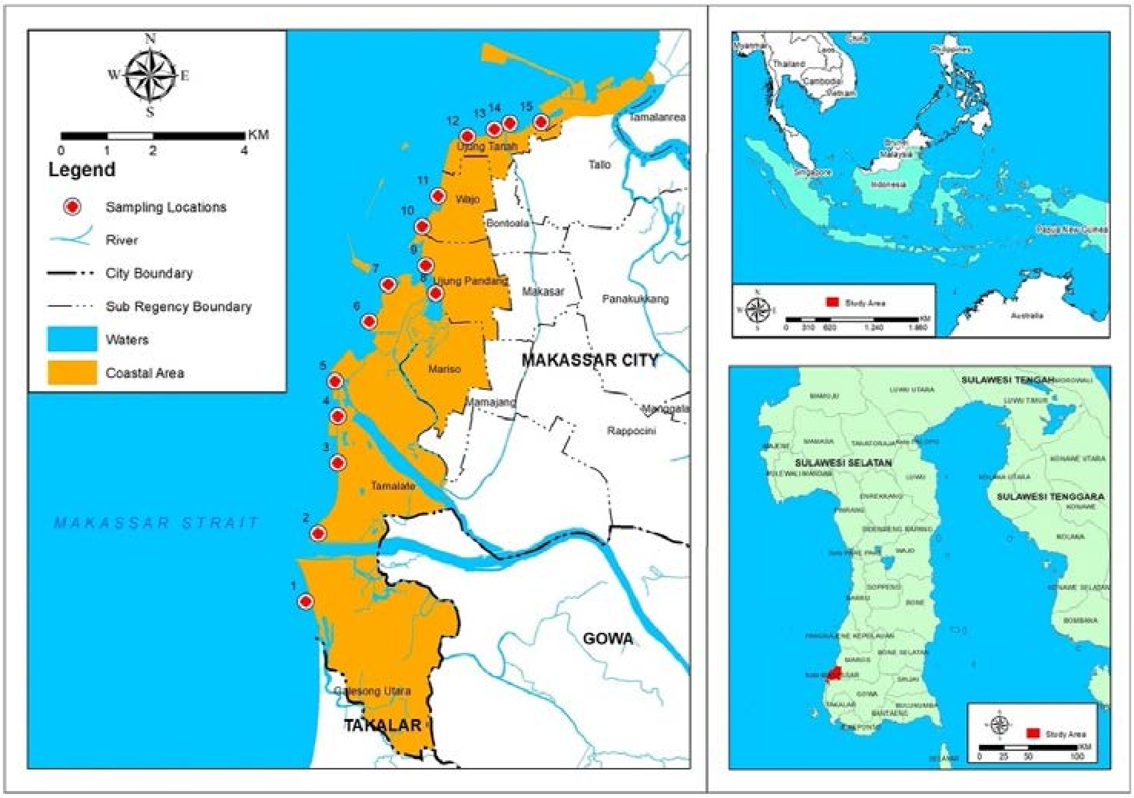

Fig. 1: Geographic location of the study area in estuarine water of Makassar coastal area, South Sulawesi Province, Indonesia

Material (CRM) from National Institute Standards and Technology (NIST) 1646a sediment estuarine was included in the analysis procedure. Moreover, sample blanks and three replications were analyzed attentively. The percent (%) recovery achieved was > 90% with linear curves R^2 of 0.95.

Ecological risk estimation

The ecological risk was estimated using Eq. 1 (Mallongi *et al*., 2020a).

$$HQ = \frac{C_{Hg}}{\text{Eco screening benchmark}} \quad (1)$$

Where, Hazard quotient (HQ) is the hazard quotient (no unit); Hg concentration (C_{Hg}) is in water (mg/L); Eco screening benchmark for Hg is 0.0011 milligram per liter (mg/L) (USEPA, 1996; Mallongi *et.al*., 2020b). HQ >1 indicates that there are adverse ecological consequences that might occur with Hg contamination in the coastal water.

Human health risks estimation

The United States Environmental Protection Agency (USEPA) method was used to estimate the human health risk caused by Hg exposure during recreational activities such as swimming, bathing, and fishing in the coastal area of Makassar city. The equations for human health risk are depicted in Eqs. 2, 3 and 4 (USEPA, 2015; USEPA, 2016; USEPA, 2021a; USEPA, 2021b; Astuti *et al.*, 2022).

$$THQ_{ingestion} = \frac{C_{Hg} \times IR_{rec-w} \times EF_{rec} \times ED_{rec} \times EV_{rec} \times ET_{rec}}{BW \times AT \times RfD_{o}} \quad (2)$$

$$THQ_{dermal} = \frac{C_{Hg} \times SA \times K_{p} \times ET_{rec} \times EV \times EF_{rec} \times ED_{rec} \times CF_{w}}{BW \times AT \times RfD_{d}} \quad (3)$$

$$THI = THQ_{ingestion} + THQ_{dermal} \quad (4)$$

Where, THQ is the target hazard quotient for ingestion ($THQ_{ingestion}$) and dermal contact (THQ_{dermal}) of Hg in water, total hazard index (THI); Hg concentration in water (C_{Hg}) is the level of Hg; Ingestion rate of water during recreation activity (IR_{rec-w}) is 0.12 L/hour for children and 0.11 for adults L/hour (USEPA, 2015; USEPA, 2021c); Exposure frequency during recreation (EF_{rec}) is 135 days/year; Duration for recreational exposure (ED_{rec}) is 26 years for adults and 6 years for children (USEPA, 2021c); Event of recreation (EV_{rec}) is the amount event of recreation (1 event/day) (USEPA, 2021c); Exposure time during recreation (ET_{rec}) is recreator time 0.54 hours/event for children and 0.71 hours/event for adults (USEPA, 2021c); human body weight (BW) is 70 kg for adults and 15 Kg for children (USEPA, 2021c); Exposure averaging time (AT) is ED x 365 = days; Skin exposed area (SA) is 19652 cm^2 for adults and 6365 cm^2 for children (USEPA, 2015); dermal permeability constant (Kp) is 0.001 cm/hour (USEPA, 2016; USEPA, 2021a); volumetric conversion for water (CF_w) is 0.001 L/cm^3 (USEPA, 1991; USEPA, 2004); Oral reference dose (RfD_o) for Hg is 0.0003 mg/kg/day (RAIS, 2020); Dermal reference dose (RfD_d) for Hg is 0.000021 (RAIS, 2020).

Monte Carlo simulation

The Monte Carlo simulation (MCS) is a mathematical approach that is applied to calculate risks (Mallongi *et al*., 2022b; Rauf *et al*., 2021a). In the past, health risks due to chemical exposure are determined only by conventional data which usually culminate in a single point of risk. Through the use of MCS, the calculation of uncertainty associated with the estimated risk is identified as a probability distribution to predict risk or exposure. It involves large random numbers from some specified theoretical probability distribution and can find the most sensitive variables contributing to the health risk (Millard, 1998). This simulation is operated by ORACLE inc software, United States of America (USA) (Crystal ball version 11.1.2) in Microsoft Excel 2019. MCS simulation is used to estimate uncertainty and health risk parameter's sensitivity with 10,000 replication. After THI calculation, independent health risk variables such as exposure time (ET), exposure frequency (EF), body weight (BW), ingestion rate from recreational activities (IR Rec-w), concentration (C), and exposed skin surface area (SA) were included in the simulation. The cumulative distribution is expressed in the 5th percentile and 95th percentile, THI or THQ < 1 is the safe limit for Hg exposure. Additionally, the sensitivity test was performed to determine the most influential factor in THI value to develop efficient risk management for the population.

Hg removal from water

The porous polymer version of the Hg absorber was fabricated and prepared by mixing and synthesizing this polymer model with sodium chloride. This process produced a rubber sorbent capable of capturing Hg species such as liquid, vapor, inorganic, and highly toxic alkyl compounds to capture the Total mercury concentration (THg) in the water along the coast area of Makassar. Application of polymer bag was carried out for 10 weeks, then, the samples were found to have no more than 1 milligram per kilogram (mg/kg) mercury. A characteristic methoxy ethyl mercuric chloride (MEMC) red color was observed from the top of the bag up to 10 cm where MEMC was applied and also for the polymer bag installed in the drain hole. After 7 and 10 weeks, all samples up to a depth of 36 centimeters (cm) contained between 0.03-0.04 mg/kg of mercury, while after 10 and 15 weeks, no more than 1 mg/kg was detected in the polymer.

Statistical analysis

A non-parametric test namely Wilcoxon was conducted using Statistical Package for the Social Sciences (SPSS) software version 22 (IBM inc) to determine the efficiency of Hg removal using co-polymerization of sulfur and cooking oil in the sampling site, and the probability value (p-value) of <0.05 was considered significant. Moreover, descriptive statistics such as mean, standard deviation (SD), and range were calculated in SPSS software.

RESULTS AND DISCUSSION

Hg concentration in water

The Hg concentration as shown in Table 1 is higher compared to the value obtained by (Mallongi, 2014). This shows that the accumulation in Makassar coastal area will become more worrisome over time without any controlling action. Previous studies in Europe, South America, and Asia region are shown in Table 1. The mean of Hg concentration in this study exceeded the acceptable limit of the World Health Organization (WHO), United States Environmental Protection Agency (USEPA), and Canadian and Indonesian standards. This implies the possibility of high ecological risk, contaminated seafood, and bioaccumulation of Hg in the aquatic ecosystem (Fioramonti *et al.,* 2022; Yap and Al-Mutairi, 2022).

Table 1: Comparison of Hg concentration in the study area with water quality standards and previous results from other countries

Organization/ Countries	Hg concentration (mg/L)	Reference
Makassar coastal water	0.205 ± 0.41	This study
Indonesia standard	0.002	Peraturan Pemerintah, 2021
WHO standard	0.006	WHO, 2017
USEPA standard	0.002	USEPA, 2009
Canada standard	0.001	Government of Canada, 1979
Background concentration	0.000015	Kowalski *et al.*, 2007
Slovenia	0.0002 ± 0.0015	Bratkič *et al.*, 2018
Argentina	0.2700	La Colla *et al.*, 2019
Saudi Arabia	0.3000	Youssef *et al.*, 2016
China	0.023	Liu *et al.*, 2022
China	0.025	Zhao *et al.*, 2018

Ecological risk assessment

Based on the calculation of ecological risk assessment in Table 2, the contamination of Hg in the coastal area of Makassar city can induce adverse impacts on the marine aquatic ecosystem (HQ > 1). This result is in line with Zhang *et al.* (2017) which mentioned that Hg contamination in water (HQ >1) has potentially harmful effects on the health and ecosystem of marine organisms such as invertebrates and phytoplankton. The highest value of HQ was located in sampling sites 9, 14, and 15 which are near the ship harbor. This result is in accordance with previous reports (Zhang *et al.*, 2012; Ndungu *et al.*, 2017). Areas near the ship harbor are polluted by various pollutants such as Hg from coal combustions or residual fuel oil, ballast water, petroleum hydrocarbon oil, organic pollutant, oil spill, and dredging (Zhang *et al.*, 2012; Ndungu *et al.*, 2017; Tang *et al.*, 2018; Wang *et al.*, 2019; Kakar *et al.*, 2021). Furthermore, Kakar *et al* (2021) found that naval and non-naval vessels contained 44 and 75 Kilogram (Kg) of Hg, respectively, per million Gross tonnage (GT). Heavy metals and other organic pollutants from various anthropogenic activities such as urban artisanal gold mining (UAGM), gas station, domestic waste, shipbuilding yard, as well as industrial and hospital waste accumulate in the coastal area (Mallongi 2014; Abbas *et al.*, 2017; Abbas *et al.*, 2020; Mallongi *et al.*, 2023; Mallongi *et al.*, 2020b; Astuti and Mallongi 2020; Astuti *et al.*, 2021b; Mallongi *et al*. 2022a; Rauf *et al.*, 2021b; Rauf *et al.*, 2022). The canals or rivers are the main input of pollutants in this area. Lack of proper wastewater treatment and low environmental law enforcement influence the high accumulation of heavy metals including Hg in the coastal area of Makassar city. A higher concentration of Hg is associated with elevated ecological risks (Mao *et al.*, 2020; Masni *et al*, 2016). Based on previous studies, Hg not only contaminates the water but also the sediment and marine aquatic biotas while a high ecological risk was detected in Losari beach (Ishak *et al*. 2014; Ishak 2017). The result obtained in this study is higher than the level of total Hg concentration in Poland and Taiwan. In Poznan, the total Hg concentration in the surface water was 0.00002 mg/L (Kowalski *et al.*, 2007), while the value obtained in Northern Taiwan was approximately 0.00005 mg/L (Fang and Lien, 2021). According to previous reports, the total concentration of Hg in the estuary and coastal sediments varies, depending on the contamination and pollution status.

Human health risk assessment

Table 2 shows the point estimate of human health risk from the coastal community of Makassar city. The majority of the Total hazard quotient (THQ) and index (THI) values was lower than 1, except for the community in the sampling site 9, 14, and 15. This indicates that adverse health impacts are unlikely to occur in these areas or people should avoid carrying out recreational activities around places near the ship harbor. The mean value of THI in adults was higher than 1, implying that this population is at risk of health problems in the future due to Hg exposure from recreational activities such as swimming, fishing, or playing around the coastal area. Based on the results, adults had a lower value of THQ and THI compared to the children which imply that children are more at risk of Hg exposure than adults. This is in accordance with another study conducted in Ankobrah and Pra, Ghana, where the THQ value of children due to Hg exposure was greater than that of adults (Kortei *et al.*, 2020). The toxic response factors of Cd and Hg

Table 2: Water Hg concentration, ecological risk (HQ), and human health risk (THQ and THI) of the Makassar coastal community

Sampling site	Ecotoxicity screening value	Reference	Measured Hg concentration (mg/L)	HQ	THQ Ingestion		THQ dermal		THI	
					Adult	Children	Adult	Children	Adult	Children
S1	0,0011	(USEPA 1996)	0.0071	6	0.010	0.0003	0.025	0.029	0.035	0.029
S2			0.0081	7	0.011	0.0003	0.028	0.033	0.040	0.033
S3			0.0055	5	0.008	0.0002	0.019	0.022	0.027	0.022
S4			0.0081	7	0.011	0.0003	0.028	0.033	0.040	0.033
S5			0.0052	5	0.007	0.0002	0.018	0.021	0.025	0.021
S6			0.0025	2	0.003	0.0001	0.009	0.010	0.012	0.010
S7			0.0032	3	0.004	0.0001	0.011	0.013	0.016	0.013
S8			0.0035	3	0.005	0.0001	0.012	0.014	0.017	0.014
S9			0.0095	9	0.013	0.0004	0.033	0.038	0.046	0.039
S10			1.0013	910	1.377	0.0395	3.515	4.041	4.893	4.080
S11			0.0091	8	0.013	0.0004	0.032	0.037	0.044	0.037
S12			0.0056	5	0.008	0.0002	0.020	0.023	0.027	0.023
S13			0.0089	8	0.012	0.0004	0.031	0.036	0.043	0.036
S14			1.0019	911	1.378	0.0395	3.517	4.043	4.895	4.083
S15			1.007	915	1.385	0.0397	3.535	4.064	4.920	4.104
Mean			0.205	187	0.283	0.0081	0.722	0.830	1.005	0.839
Standard deviation			0.410	375	0.5	0.01	1.4	1.6	2	1.6
Minimum value			0.0025	2	0.003	0.0001	0.009	0.010	0.012	0.01
Maximum value			1.007	915	1.385	0.0397	3.535	4.064	4.920	4.104

are significantly higher than other heavy metals, this indicates that exposure to Hg is more dangerous to human health, especially among young children (Renieri *et al.,* 2014).

Based on Fig. 2, the Total hazard index (THI) values in percentile 95th of adults at 1.008 and children 1.554 exceeds the acceptable limit from the United States Environmental Protection Agency (USEPA) namely THI >1 (USEPA, 1989). Both age categories are at risk of experiencing adverse effects of Hg exposure through multiple sources. However, children have a greater non-cancer risk than adults. This is due to the different body ratios where the amount of intake is greater in children. Early stage of neurodevelopment, the physiological structure, and the vulnerable immune system put children at greater risk (Al-Saleh *et al*., 2020; Du *et al*., 2021). These results are consistent with previous studies conducted in Italy and Japan where repeated exposure to total Hg and methylmercury (Me-Hg) made young children more vulnerable to neurologic changes than adults due to greater sensitivity during the early stages of brain development (Barone *et al*., 2021; Iwai-Shimada *et al*., 2021).

Fig. 3 shows that Hg concentration (C) 23.3% and exposure time (ET) 21.3% are the most dominant or influential variables in non-cancer risk for adults and children, respectively. These results indicate that an increase in chemical concentration will affect the intake value and elevate the risk of developing adverse health effects (Saha *et al*., 2016; Rauf *et al*., 2021c). Meanwhile, body weight (BW) has no effect on the non-cancer risk for adults and children. This is consistent with a previous study which stated that BW has a negative and insignificant contribution to health risk assessment (Orosun *et al.,* 2020). The limitation of this study is that human exposure pattern was not collected directly from the people around coastal areas. The human data used was adapted from the USEPA standard value.

Hg removal application

Based on the Monte Carlo Simulation (MCS), Hg concentration is the most influential factor in human health risk. Therefore, there is a need to control Hg concentration in the coastal area of Makassar city. Polymerized sulfur and unsaturated cooking oil were used to absorb mercury in the water column along the sampling sites. From the non-parametric test result, this method is effective for absorbing mercury from water with a p-value <0.005. The range of percentage (%) reduction of Total mercury concentration (THg) in the water column was 39 – 100%. This implies that polymer sulfur can be alternatively used by local authorities to reduce mercury from the water and prevent ecological as well as human health

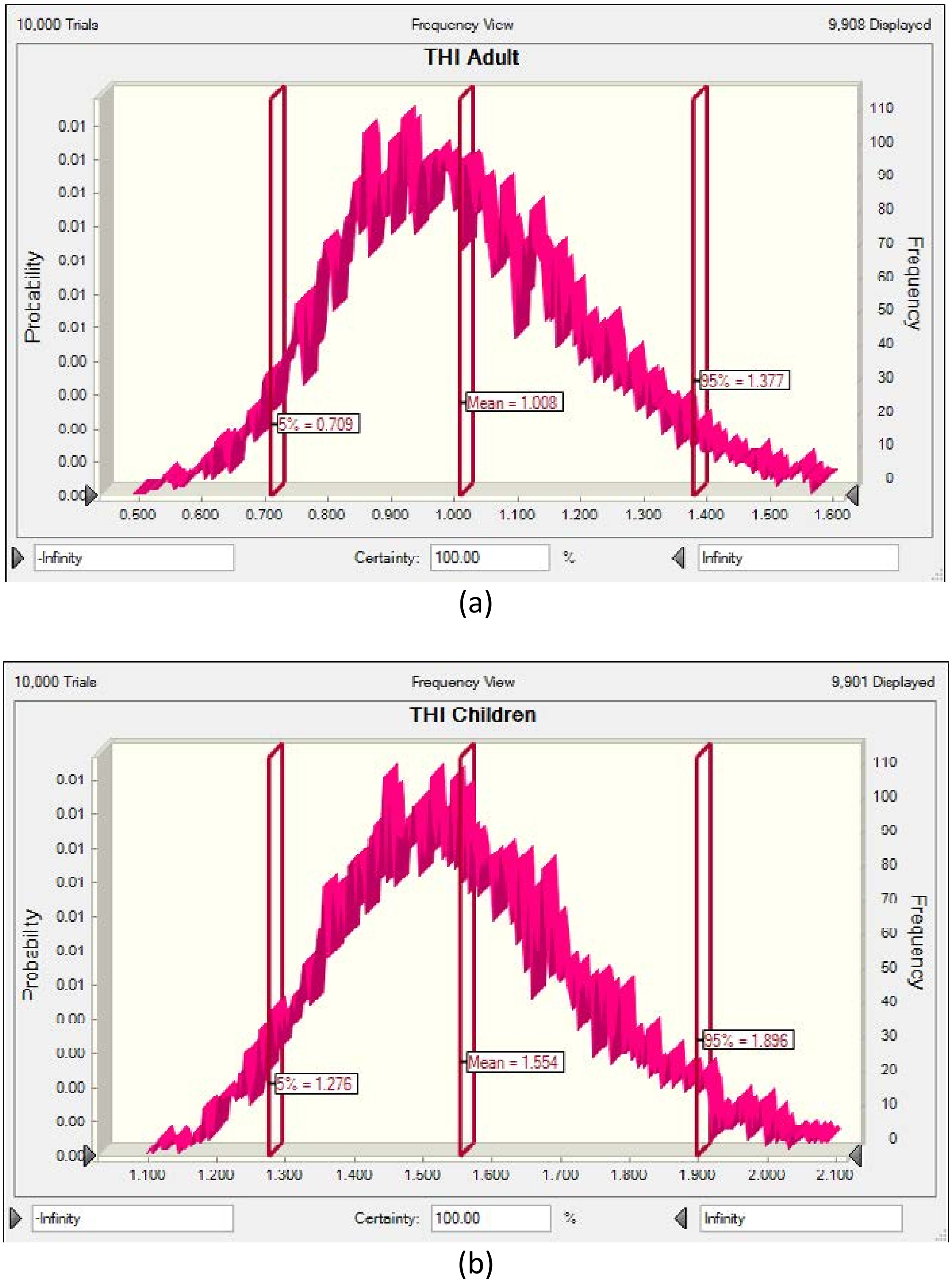

Fig. 2: Total Hazard Index (THI) of adults (a) and children (b) using the MCS model

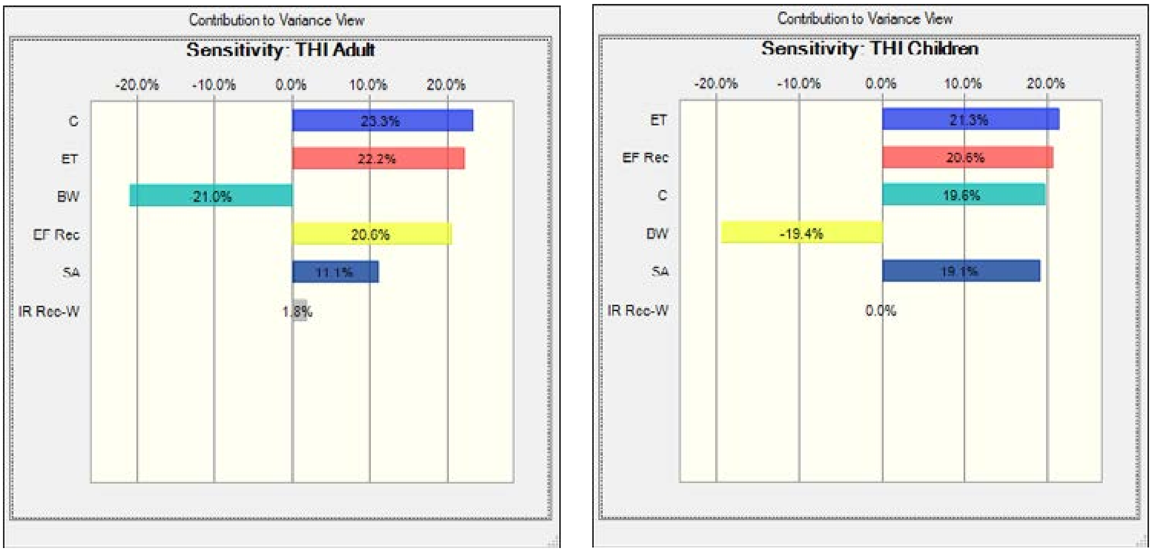

Fig. 3: Sensitivity analysis for all selected variables in health risk

Table 3: The percent reduction of polymer sulfur (PS) to total Hg concentration in coastal water of Makassar City

Sampling sites	THg before application PS	THg after application PS	reduction (%)	p-value
S1	0.0071	0.0043	39	
S2	0.0081	0.0032	60	
S3	0.0055	0.0012	78	
S4	0.0081	0.0023	72	
S5	0.0052	0.0022	58	
S6	0.0025	0.0003	88	
S7	0.0032	0.0011	66	
S8	0.0035	0.0012	66	0.001
S9	0.0095	0.0032	66	
S10	1.0013	0.0011	100	
S11	0.0091	0.0043	53	
S12	0.0056	0.0024	57	
S13	0.0089	0.0041	54	
S14	1.0019	0.0993	90	
S15	1.007	0.0487	95	

adverse impacts in the future. Additionally, strict environmental monitoring and pollution control in coastal areas such as reducing vehicle activities and throwing garbage into the sea are needed.

CONCLUSION

The mean Hg concentration in the coastal water of Makassar city is high and above the water quality standard value in several countries. The Hazard quotient (HQ) was >1 in all sampling sites, which indicates that Hg contamination is likely to cause adverse impacts on the ecosystem, especially in invertebrates and phytoplankton. Based on the Human health risk estimation, communities near the ship harbor namely sites 9, 14 and 15 are at risk of adverse health impacts from Hg exposure. Furthermore, the Monte Carlo simulation (MCS) showed that children are at higher risk of Hg exposure than adults. This condition allows for the possibility of developing non-cancer risk. Children are the most vulnerable subject in terms of rudimentary development. They absorb more Hg during neurodevelopment compared to adults. The most impactful factor for health risk is Hg concentration with a contribution of 23.3 %. The presence and high level of Hg in the environment will cause ecological damage and health problems. Efforts are needed from the government and all institutions for protection policy and remediation of Hg, especially in coastal areas. This metal is one of the most dangerous and has been shown to cause cardiovascular disease and cancer from long-term exposure. Therefore, the applicable risk reduction effort is reducing Hg concentration in the water column. Based on the results, the application of polymer sulfur (PS) is effective in reducing Hg concentration in the coastal water of Makassar city in the range of 39 – 100%. Due to its high efficiency, polymer sulfur (PS) has broad prospects for the remediation of Hg or other heavy metals in various contaminated media.

AUTHOR CONTRIBUTIONS

A. Mallongi prepared the original draft, methodology and conceptualization. A.U. Rauf performed the data analysis, software and editing. R.D.P. Astuti organized the data curation and validation. S. Palutturi performed the draft review, interpreted the data and results. H. Ishak performed the draft review and data curation.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

%	Percent
°C	Degree of Celcius
AT	Exposure averaging time
ATSDR	Agency for toxic substances and disease registry
BW	Body weight
C	Concentration
CF_w	Volumetric conversion for water
CHg	Hg concentration in water
cm	Centimeter
CRM	Certified Reference Material
CVAAS	Cold vapor atomic absorption spectrophotometry
EF	Exposure frequency
EF_{rec}	Exposure frequency during recreation
ED_{rec}	Exposure duration during recreation
EV_{rec}	Event of recreation
ET	Exposure time
ET_{rec}	Exposure time during recreation
GPS	Global positioning system
GT	Gross tonnage
HDPE	High-density polyethylene
Hg	Mercury
Hg^0	Elemental mercury
H_2SO_4	Sulphuric acid

HNO_3	Nitric acid
INS	Indonesian National Standard
IR	Ingestion rate
IR Rec-w	Ingestion rate of water from recreational activities
HQ	Hazard quotient
Kg	Kilogram
K_p	Dermal permeability constant
$KMNO_4$	Potassium permanganate
$K_2S_2O_8$	Potassium persulfate
L	Liter
Me-Hg	Methylmercury
MCS	Monte carlo simulation
MEMC	Methoxy ethyl mercuric chloride
mL	Milliliter
mg/kg	Miligram per kilogram
mg/L	Milligram per liter
NIST	National Institute of Standards and Technology
nm	Nanometer
pH	Potential of hydrogen
p-value	Probability value
R^2	R-squared
RfD_o	Reference dose for oral exposure
RfD_d	Reference dose for dermal
PS	Polymer sulfur
SA	Exposed skin surface area
SD	Standard deviation
$SnCl_2$	Tin(II) chloride
SNI	National standard of Indonesia
SPSS	Statistical package for the social sciences
THg	Total mercury concentration
THI	Total hazard index
THQ	Target hazard quotient
$THQ_{ingestion}$	Target hazard quotient for ingestion
THQ_{dermal}	Target hazard quotient for dermal
THI	Total hazard index
UAGM	Urban artisanal gold mining
USA	United States of America
USEPA	United States Environmental Protection Agency
WHO	World Health Agency

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