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Reduced pollution level and ecological risk of mercury-polluted sediment in a alkali-chlorine factory's brine water storage pond after corrective actions: A case study in Southern Taiwan

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ABSTRACT

Mercury is a highly toxic pollutant and persistent in the sediment, which highlights the needs for remediation of sediment Hg pollution. However, the effects of remedial actions on the pollution and ecological risk of Hg in sediment are less investigated. Therefore, this study conducted an environmental risk assessment before and after corrective actions in the brine water storage pond of a closed alkali-chlorine plant with high Hg pollution in the sediment. The results showed that the accumulation of Hg in the sediment (2.59–443 mg/kg), fish and crabs (1.10–8.54 mg/kg) in the polluted pond was higher than the regulation limit in Taiwan. After implementing the corrective actions such as institutional/engineering control and remediation, we found that the Hg concentration and pollution factor (CF), in the sediment were significantly decreased by 74% and 73% ($p = 0.02$), respectively. In addition, the geoaccumulation index (I-geo) were decreased to lower pollution class after corrective actions ($p = 0.009$). The risk related indices such as potential ecological risk index (RI) and risk quotient (RQ) also showed significant decreases ($p = 0.03$) after corrective actions (71% and 73%, respectively). Although the values of pollution and risk indices were still high after remediation, the results of this study demonstrated the effectiveness of corrective actions on amelioration of sediment Hg pollution. It suggests that corrective actions should be continuously implemented to reduce the pollution and risk levels in all aspects to an acceptable level for stakeholders.

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1. Introduction

Mercury is known as the heavy metal with global public health concern, and its environmental accumulation has been reported by several studies (Zhang et al., 2018b; Chen et al., 2022). The adverse effects of Hg on human health and ecosystems contains reproductive disorders, genotoxicity, endocrine disruption, carcinogenicity, and immunosuppression (Zhang et al., 2018b; Witkowska et al., 2021). Mercury is one of the most toxic heavy metals due to its biological toxicity (Wang et al., 2021). Furthermore, after released into water bodies, Hg tends to settle in sediment (Ranjbar Jafarabadi et al., 2020), and accumulate in biological tissues through the food chain, causing significant ecological risks to benthic organisms, fish and humans (Gerson et al., 2020; Yu et al., 2021; Zhang et al., 2021a). Monitoring Hg in sediments is crucial for assessing the degree of pollution in the aquatic environment, which provides valuable information on historical and recent pollution of the surrounding environment (Li et al., 2020; Ranjbar Jafarabadi et al., 2020). For Hg monitoring, atomic absorption spectrometry (AAS), atomic fluorescence spectrometry (AFS), and ICP (Inductively coupled plasma) related techniques has been widely used (Selid et al., 2009). To detect Hg in sediment, the method of cold-vapor AAS could be applied to digest sediment samples and analyze the Hg concentration with high sensitivity (Ranjbar Jafarabadi et al., 2020; Elsagh et al., 2021). On the other hand, sediment Hg determination without digestion using thermal decomposition with AAS was rapid and less reagent (Senila et al., 2019; Yu et al., 2021). In order to further evaluate the ecological risk and the effects of remedial actions on Hg contamination, more case studies about Hg-polluted sediment are needed.

Given that sediment is the destination of many aquatic pollutants such as heavy metals, ecological risk assessment is required for better understanding of the environmental impacts and adverse biological effects of heavy metals in sediment (Hauer et al., 2018; Saiki et al., 2021). The concentrations of heavy metals in sediment are the basic information for assessing their ecological risk (Long et al., 1995; Zhang et al., 2015). In order to obtain reliable results, different indices calculated based on metal concentrations could be used in assessing their environmental risk in sediment (Luo et al., 2021). In general, various indicators can be used to estimate the contamination degree of sediments, such as contamination factor (CF) (Paul et al., 2021), modified degree of contamination (mCd) (Hoang et al., 2020; Antony et al., 2022), pollution index (PI) (Chen et al., 2021; Ferreira et al., 2022), and geoaccumulation index (I-geo) (Elsagh et al., 2021; Li et al., 2022). By comparing total metal concentrations with threshold values or guidelines, risk quotient (RQ) (Zhang et al., 2021b) or hazard quotient (HQ) (Vetrimurugan et al., 2019) could be calculated to quantify the ecological risks of sediment metals. The ecological risks of sediment metals might be affected by spatial and seasonal variations due to the changed sediment metal concentrations (Huang et al., 2020). In addition, threshold values based on different target organisms (e.g., benthic invertebrates, fish, or algae) might affect the risk of toxicants (El Zokm et al., 2022). Other study also reported risk assessment code (RAC) calculated based on the bioavailable fractions of toxic metals, which would be affected by the bioavailability (Zhang et al., 2018a). Furthermore, the CF and toxicity response (Tr) were also incorporated to analyze the potential ecological risk index (RI) of anthropogenic metal pollution (Dang et al., 2021; Liu et al., 2022). The abovementioned indices could also help investigate the anthropogenic heavy metals in sediment that might be resulted from industrial wastewater (Hg: 0.27–1.37 mg/kg sediment), burning fossil fuel (Pb: 0.54–3.41 mg/kg sediment) (Ranjbar Jafarabadi et al., 2020), and agricultural activities (Cu: 17.5–667 mg/kg sediment; Cd: 0.10–15.6 mg/kg sediment) (Luo et al., 2021).

For better management of heavy metal pollution in sediment, sediment quality guidelines (SQGs) are designed to reduce the anthropogenic heavy metals and improve the protection of benthic ecosystems (Batley and Warne, 2017). Taiwan's SQGs for Hg are 0.87 mg/kg (upper limit) and 0.23 mg/kg (lower limit). If the Hg concentration in the sediment is higher than the upper limit, the ecological risk must be assessed and risk-based corrective actions should be taken (Connor and McHugh, 2002). The corrective actions may include institutional control, engineering control, and remediation. Some previous studies have also applied the SQGs for heavy metal assessment (Chouikh et al., 2021; Zhang et al., 2021b; Li et al., 2022). In addition, several methods for sediment and soil Hg remediation were reviewed recently (Palansooriya et al., 2020; Wang et al., 2020b). However, the effects of corrective actions on improvement of pollution level and ecological risk of Hg in realistic pollution sites are still not fully understood.

Therefore, this study aims to evaluate the pollution and environmental risk of Hg in a polluted sediment after corrective actions by using several pollution and risk indices. The polluted sediment is in a brine water storage pond of a closed alkali-chlorine factor. We would first evaluate the Hg concentration in the sediment and biota in the storage pond, and then conduct ecological risk assessment using CF, I-geo, RI, and RQ. This study provides the information about the improvement of Hg pollution and risk in sediment by implementing corrective actions, which could help manage the toxic metals in sediment.

2. Materials and methods

2.1. The sampling sites and the sampling methods for sediment and aquatic organisms

The sampling site is located in the brine water storage pond of a closed alkali-chlorine factory in Southern Taiwan. The location of the brine water storage pond was shown in Fig. 1. The alkali-chlorine plant operated from the 1950s to the 1980s, using seawater as raw material and Hg as electrodes to electrolyze seawater to produce sodium hydroxide, chlorine, and hydrogen (Yang, 2011). There were insufficient environmental regulations in Taiwan from the 1950s to the 1970s,

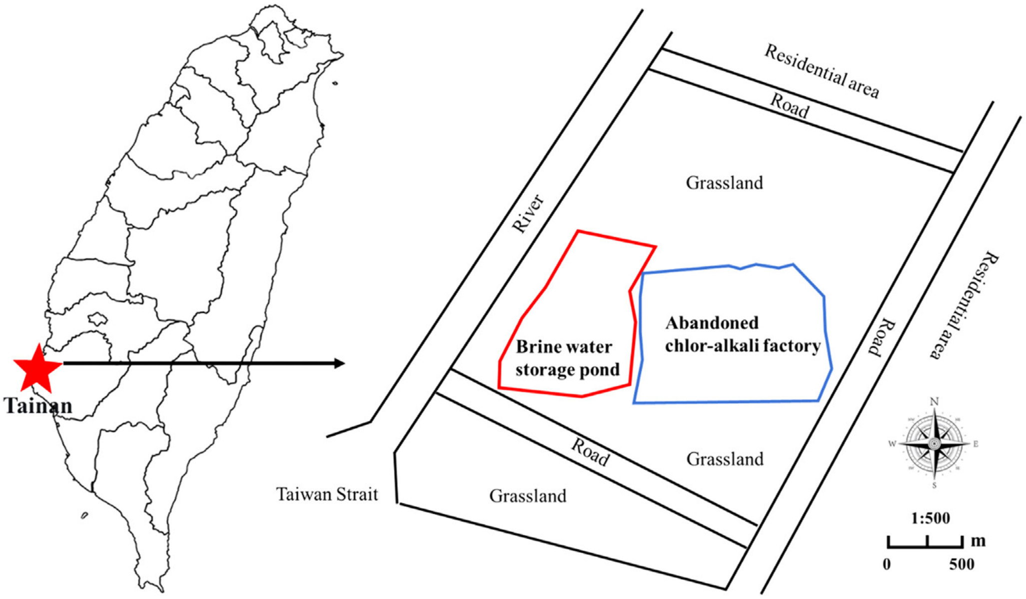

Fig. 1. Study area. The sediment samples and aquatic organisms were obtained in the brine water storage pond of a closed alkali-chlorine factory in southern Taiwan. The brine water storage pond is near the residential area and sea outlet. The sediment and organisms were evenly sampled in the brine water storage pond.

resulting in the transport of Hg through wastewater and sludge eventually contaminating the sediment of the brine water storage pond (Tseng et al., 2018; Huang et al., 2023). The Hg used in production process is one of the major pollutants in the wastewater from alkali-chlorine factories (Song et al., 2018; Takasuga et al., 2020). Therefore, the environmental pollution of Hg near alkali-chlorine factories was reported worldwide such as in China (Song et al., 2018), the USA (Dufault et al., 2009), Portugal (Takasuga et al., 2020), and Taiwan (Tseng et al., 2018). The brine water storage pond covers an area of about 5 hectares, with an average water depth of 2.5 m, and the contaminated sediment is estimated to be about 100,000 cubic meters.

Sampling was carried out according to the method announced by Taiwan's the National Institute of Environmental Analysis (NIEA), and the sediment sampling was carried out according to S104.32B (USEPA-823-B-01-002). Before the sampling operation, the sampling equipment should be cleaned, and the used equipment must be replaced or rinsed with a phosphorus-free detergent and clean water before it can be reused. The grid sampling method was adopted and the sediment samples at a depth of 0–3 m from 14 sampling points were collected directly through the direct push sampler. Fourteen randomly selected sediment samples by grid sampling method were collected before and after 3-year corrective actions. The Hg concentration was analyzed every 30 cm, and the maximum value was taken as the representative concentration of each sampling point. Aquatic animals (fish and crabs) were collected according to NIEA E102.20C and NIEA E103.20C, respectively, using nets and dredgers to capture organisms. The samples were maintained at 4 ± 2 °C during the transportation and storage. The detection method for Hg in sediments and biological tissues is NIEA M318.01C (USEPA Method 7473) (thermal decomposition, amalgamation, and atomic absorption spectrophotometry method). The sample was placed in a programmable oxygen decomposition furnace (oxygenated decomposition furnace) so that Hg would be released from the sample and selectively trapped. The Hg concentrations were then analyzed using atomic absorption spectroscopy (wave length = 253.7 nm). The sediment samples and biological samples were presented based on dry weight and wet weight, respectively.

2.2. Assessment of the Hg pollution and risk in the sediment

SQGs can be used to initially classify the Hg pollution level in the sediment from the polluted brine water storage pond. Taiwan's sediment quality guidelines for Hg are 0.87 (upper limit) and 0.23 mg/kg (lower limit), and the human health safety limit for Hg consumption is 0.5 mg/kg. In addition, this study will incorporate pollutant accumulation indices and ecological risk indicators for subsequent risk assessment as follows:

2.2.1. Pollutant accumulation index

The CF (Hakanson, 1980; Abrahim and Parker, 2008) (Eq. (1)) and the I-geo (Muller, 1969) (Eq. (2)) was calculated by dividing the metal concentration in the sediment by the background value.

$$\mathrm{CF} = \frac{C\ (contaminants)}{C\ (background)} = \frac{C_i}{C_b} \tag{1}$$

where C_i is the Hg concentration in the sediment sample, C_b is the measured lowest Hg concentration in this study (considered as background value).

$$\mathrm{I-geo} = Log_2\left[\frac{C_n}{1.5 \times B_n}\right] \tag{2}$$

where C_n is the Hg concentration in the sediment sample, and B_n is the geochemical background value (the measured lowest Hg concentration in this study is regarded as the background value).

2.2.2. Ecological risk index

The RI evaluating the degree of contamination of sediments according to the toxicity of pollutants was calculated (Eq. (3)) (Hakanson, 1980).

$$\mathrm{RI} = \sum_{\mathrm{i=1}}^{\mathrm{n}} Er_i,\ Er_i = Tr \times \mathrm{CF}_i \tag{3}$$

where Er_i is the potential ecological risk factor of Hg in the sediment sample, $\mathrm{CF_i}$ is the abovementioned CF in the *i*th sample, and *Tr* is the toxic response factor (*Tr* for Hg = 40) (Hakanson, 1980; Islam et al., 2015; Lu et al., 2015).

RQ used to describe the potential risk of toxic pollutants was calculated (Eq. (4)) (Cao et al., 2010).

$$\mathrm{RQ} = \frac{C_i}{\mathrm{PNEC}} \tag{4}$$

where C_i is the Hg concentration in the sediment sample and PNEC is the predicted no effect concentration. According to Garny et al. (1999), the PNEC of Hg was estimated to be 0.04 mg/kg. $\mathrm{RQ} \geq 1$ indicates a high risk, and $\mathrm{RQ} < 1$ indicates a low risk (Cao et al., 2010).

2.3. Risk management and corrective actions

Analysis of brine water storage pond in 2017 found high levels of Hg contamination in sediment and aquatic biota. Therefore, 3-year corrective actions were implemented for risk management of Hg, and the relevant indices after the corrective actions were analyzed in 2021. The 3-year corrective actions implemented included institutional control, engineering control, and remediation (Figure S1) (Huang et al., 2023). The institutional control was to prohibit the fishing of Hg-contaminated aquatic organisms in the brine water storage pond and to completely kill Hg-contaminated aquatic organisms to prevent them from entering the human body through the food chain. Engineering control involved monitoring illegal or harmful activities near the brine water storage pond, constructing high dike to prevent the surface runoff of Hg into the pond, preventing the water and organism in the pond from entering the sea, and building sediment curtain to stop interchange of sediment for further remediation. For the highly polluted sediment, the scrape dredging or suction dredging and the *ex-situ* process were used to prevent sediment disruption and polluted sediment resuspension. Remediation such as indirect thermal desorption/condensation recovery remediation technology is mainly adopted (Zhao et al., 2019; Eckley et al., 2020; Wang et al., 2020a; Debnath et al., 2021; Song et al., 2022). Suction dredging ships are used to remove the Hg-contaminated sediments, and the dredged sediments are pumped to the wastewater treatment plant for solid–liquid separation. The dredged sediment was heated to 500 °C for thermal desorption in a rotary kiln with a treatment capacity of 6 metric tons per hour, and then subjected to methanol heat exchange condensation at −40 °C to recover pure Hg, and the waste liquid was treated in a wastewater treatment plant and returned to the brine water storage pond (Figure S2).

2.4. Data analysis

The results were presented as boxplot using OriginPro2021 (OriginLab, USA). The statistical difference of results before and after corrective actions were analyzed by two-tailed unpaired Student's t-test ($^*p < 0.05$).

3. Results and discussion

3.1. Mercury accumulation in the biota of the brine water storage pond

Mercury accumulation in aquatic organisms such as fishes and crabs in brine water storage pond was analyzed to assess the impact of Hg contamination in the sediment. The obtained aquatic organisms contains fishes (*Morone saxatilis*, *Lates calcarifer*, *Terapon jarbua*, *Parupeneus chrysopleuron*, *Chanos chanos*, *Nematalosa come*, *Elops machnata*, *Acanthopagrus latus*, *Oreochromis sp.*, and *Sphyraena barracuda*), and crabs (*Charybdis feriatus* and *Scylla serrata*). *P. chrysopleuron*, *E. machnata*, *S. barracuda*, and *M. saxatilis* are carnivorous fish. *S. serrata* and *C. feriatus* are omnivorous crabs. The body length was between 15 and 96 cm, the body weight was between 0.30 and 9.20 kg, and the Hg concentration was between 1.10 and 8.54 mg/kg (Fig. 2). Among them, the carnivorous fish *E. machnata* had the highest Hg concentrations (8.54 mg/kg).

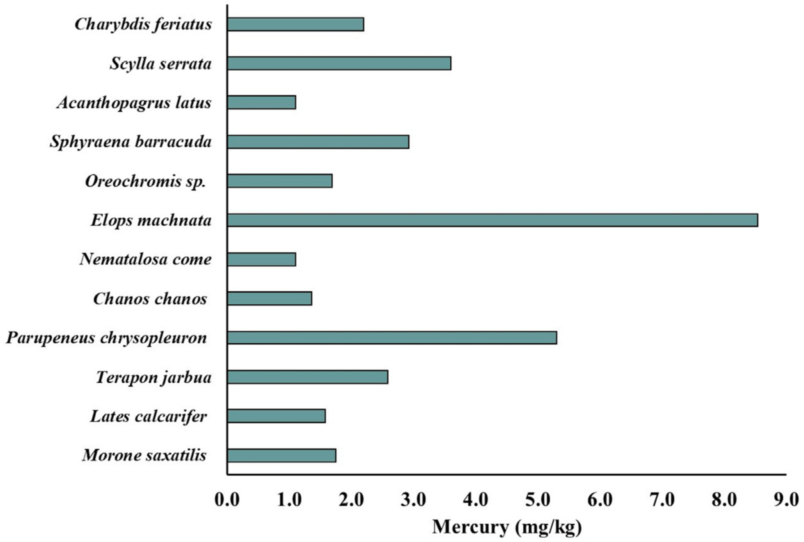

Fig. 2. The Hg concentration in the aquatic organisms in the brine water storage pond. The Hg concentration in the tissue of the fish and crabs obtained from the brine water storage pond were analyzed using atomic absorption spectroscopy (wave length = 253.7 nm). Two samples were analyzed for each species. The mean of Hg concentration of each species was presented based on the wet weight.

The results showed that most of the fish species and crabs investigated exceeded the food safety limit (0.5 mg/kg) in Taiwan. Considering the human health risks posed by the maximum safe consumption amount, fish and crabs contaminated with Hg may be of high risk (Felix et al., 2022). The highest bioaccumulation of Hg observed in carnivorous fish (*E. machnata* and *P. chrysopleuron*) suggested the potential dietary transfer and biomagnification of Hg in the storage pond (Fig. 2). Furthermore, the crab (*S. serrata*) showed the relative high Hg accumulation (Fig. 2), indicating the transport of sediment Hg contamination to benthic organisms (Cossa et al., 2021; Nyholt et al., 2022). Overall, the Hg bioaccumulation in fish observed in this study (1.10–8.54 mg/kg) are higher than that in other studies around the world, such as Argentina (< 0.22 mg/kg) (La Colla et al., 2019), China (<0.48 mg/kg) (Mao et al., 2021), and Iran (< 0.27 mg/kg) (Parang and Esmaeilbeigi, 2022). Due to the potential hazard of Hg contamination, corrective actions including institutional controls, engineering controls, and remediation, are implemented on the Hg-contaminated sediment to prevent the spread of pollution.

3.2. Decreased Hg concentration in the sediment of the polluted pond after corrective actions

The Hg concentration in the polluted sediment before and after corrective actions was further analyzed. The Hg concentration in the sediment before corrective measures ranged from 2.59 to 443 mg/kg, with the average concentration of 61 mg/kg (Fig. 3), which is higher than the upper limit of Taiwan's SQGs (0.87 mg/kg). The median of Hg concentration in the sediment was 68 mg/kg before the corrective actions and dropped to 18 mg/kg after the corrective actions (about 74% decrease) (Fig. 3). The significant decrease of Hg concentration after corrective actions was analyzed by Student's *t*-test ($p = 0.02$) (Fig. 3).

The Hg concentration measured in this study was higher than that of the Persian Gulf of Iran (Elsagh et al., 2021), the Coronel Bay of Chile (Chandia et al., 2022), and the Bohai Bay of China (Liu et al., 2019), which might be due to the dilution by flowing seawater. The Hg concentration reported in lagoons were relatively higher than that in open water (Rosati et al., 2020; Mancini et al., 2022), showing the potential higher accumulation of Hg in the sediment in close water. The present study observed much higher sediment Hg concentration than that in abovementioned studies (Fig. 3), suggesting an urgent need to implement corrective actions for reducing the Hg contamination. We found that after corrective actions were taken, the Hg concentration in the sediment of the storage pond decreased from 2.59–443 to 2.45–65.68 mg/kg, indicating the positive effects of corrective actions (Fig. 3).

3.3. Corrective actions decreased the pollution indices of Hg in the sediment of the polluted pond

To evaluate the accumulation level of Hg in the sediment, pollution indices such as CF and I-geo were used in the present study. The medians of CF of Hg in the sediment before and after corrective actions were 26 and 7, respectively. The CF before and after corrective actions were both classified as very high pollution contamination (Fig. 4A). In addition, the medians of I-geo of Hg in sediments decreased from 4 to 2 after corrective measures, which is from strongly to

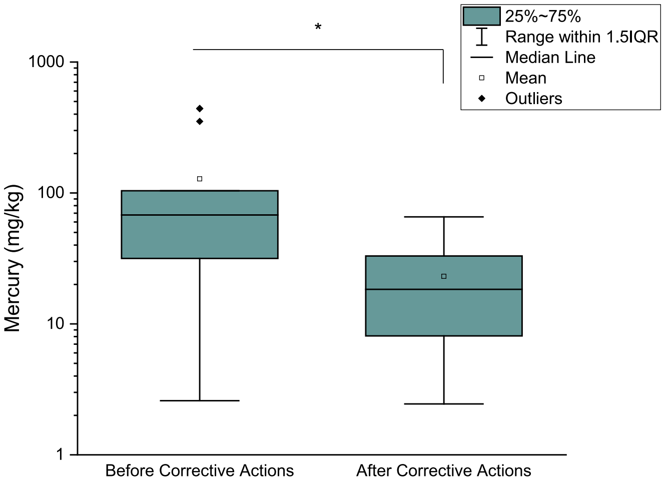

Fig. 3. The concentration of Hg in the sediment before and after corrective measures. The 14 sediment samples were obtained from the brine water storage before and after corrective actions. The Hg concentration in the sediment was analyzed using atomic absorption spectroscopy (wave length = 253.7 nm). The results were presented as boxplot. The statistical significance was determined by Student's t-test ($*p < 0.05$).

extremely polluted to moderately to strongly contaminated after corrective measures (Fig. 4B). Both CF and I-geo were significantly decreased after corrective actions ($p = 0.02$ and $p = 0.009$, Student's t-test).

The high values of CF and I-geo of Hg in the sediment suggested the potential anthropogenic input and accumulation in the sediment of storage pond. Previous studies have shown that high Hg concentration in sediment might originate from anthropogenic activity (Ranjbar Jafarabadi et al., 2020; Wang et al., 2020c; Aguilar et al., 2021; Elsagh et al., 2021), which is in agreement with our results. Despite the relative high value of CF and I-geo after corrective actions, the significant reduction of CF and I-geo showed that the corrective actions have decreased the pollution level of Hg in the sediment. Therefore, further implementation of corrective actions for longer time could be expected to lower the Hg pollution to an acceptable level.

3.4. Lower ecological risk of Hg in the sediment of the polluted pond after corrective actions

We further assess the RI and RQ to understand the effects of corrective actions on the ecological risk and biological toxicity. The median of RI values before and after corrective measures were 1049 and 300, respectively, which were classified into very high risk (Fig. 5A). The median of RQ before corrective measures was 1699, and dropped to 459 after corrective actions (Fig. 5B). Although both RI and RQ indicated high ecological risk after corrective actions, the significant decrease of RI ($p = 0.03$) and RQ ($p = 0.03$) still underscores the effectiveness of corrective actions on lowering the risk of Hg.

The Er calculated based on Hg was greater than others including Ni, Pb, and Cd in the sediment from the Gulf of Tunis, showing the higher contribution of Hg pollution to the sediment RI than other metals in their study area (Ben Mna et al., 2021). Similarly, the Er and corresponding RI of sediment Hg in Southern Mediterranean Sea were also higher compared with other heavy metals (El Zrelli et al., 2021). Other research reported that Hg in the wetland sediment in Iran showed considerable ecological risk, which higher than other potential toxic metals (Vahidipour et al., 2022). Therefore, the risk posed by Hg pollution is globally significant among other heavy metals in the sediment. Our study also showed the high ecological risk of Hg in the sediment of polluted pond (Fig. 5). It has been suggested that remedial actions could lower the Hg body burden of fish in the contaminated sites (Eckley et al., 2020). Herein, we further analyzed the ecological risk of Hg in the sediment and found that the corrective actions could help decrease the risk of Hg (Fig. 5). To sum up, after the implementation of corrective actions for 3 years, the concentration, accumulation, and biological risk of Hg in the sediment have been reduced. Although the indices were still high after corrective actions, keeping implementing the remedial measures and restoration will help further ameliorate the environmental impacts of sediment Hg in the polluted pond, and ultimately reduce the risk to the stakeholder's acceptable level.

3.5. Corrective actions and further application

The institutional control of corrective actions such as removal of aquatic organisms in the pond was to prevent consumption of Hg-contaminated animals and water by people, lowering the probability of human exposure and health risk of Hg pollution. Similarly, engineering control such as constructing fences and monitoring was to avoid people approaching the Hg-contaminated pond. The significant reduction of Hg concentration, accumulation, and ecological risk

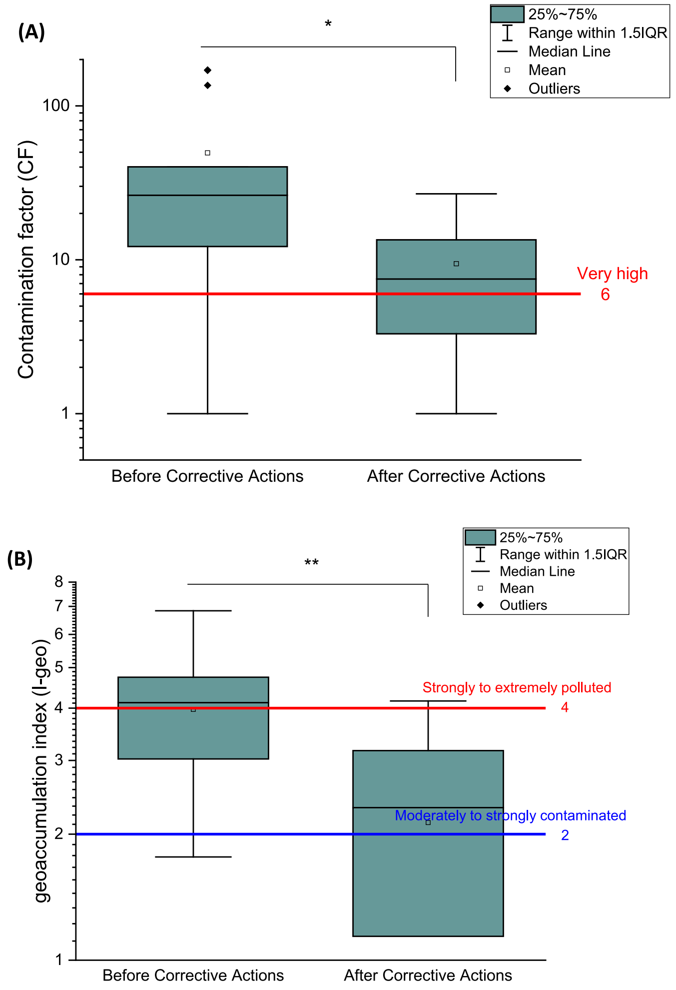

Fig. 4. Decreased pollution indices of Hg in the sediment of the brine water storage pond. (A) The CF showed the increased Hg concentration compared with the background value. The red line indicated the highest degree of the index (CF = 6). **(B)** The I-geo was calculated based on the background concentration. The red line indicated the strongly to extremely degree of the index (I-geo = 4), the blue line indicated the moderately to strongly degree of the index (I-geo = 2). The results were presented as boxplot. The statistical significance was determined by Student's t-test ($^{*}p < 0.05$, $^{**}p < 0.01$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was mostly contributed from the construction of high dike and sediment curtain (engineering control), and the remediation. The high dike and sediment curtain successfully minimized the potential runoff from Hg-contaminated soil and Hg pollution interchange in the sediment. Further remediation including suction dredging without sediment disturbing and resuspension, and thermal desorption/condensation recovery of Hg significantly decreased the Hg concentration in the sediment.

Since the accumulation level and ecological risk of Hg pollution in the sediment of the storage pond were relatively high, further prohibition of fishing, recreation, or draining water for aquaculture is still required to prevent the spread of Hg. In addition, the transport of Hg through ground water, soil runoff, sediment resuspension might raise the concern about Hg pollution in the vicinity. Therefore, the frequency of Hg monitoring in the nearby regions such as soil, groundwater, and biota needs to be increased. Taken together, further control to avoid the human exposure of Hg pollution in the storage pond, more frequent environmental monitoring of Hg for early warning, and more intense implementation of remediation are still warranted.

This study provided the positive results of corrective actions including institutional/engineering control and remediation for decreasing Hg pollution in sediment. We found that 3-year implementation of corrective actions could not lower the ecological risk of Hg pollution in the sediment to negligible risk. However, the significant decrease of Hg accumulation and risk indices still demonstrated the feasibility of corrective actions for decreasing the pollution in the future. The ultimate minimization of environmental impacts if we keep implementing the corrective actions is reasonably expected. The median of RQ decreased by 73% after 3-year corrective action. If the intensity of remediation such as the amount of suction dredging and the capacity thermal desorption with Hg recovery could be largely increased. It

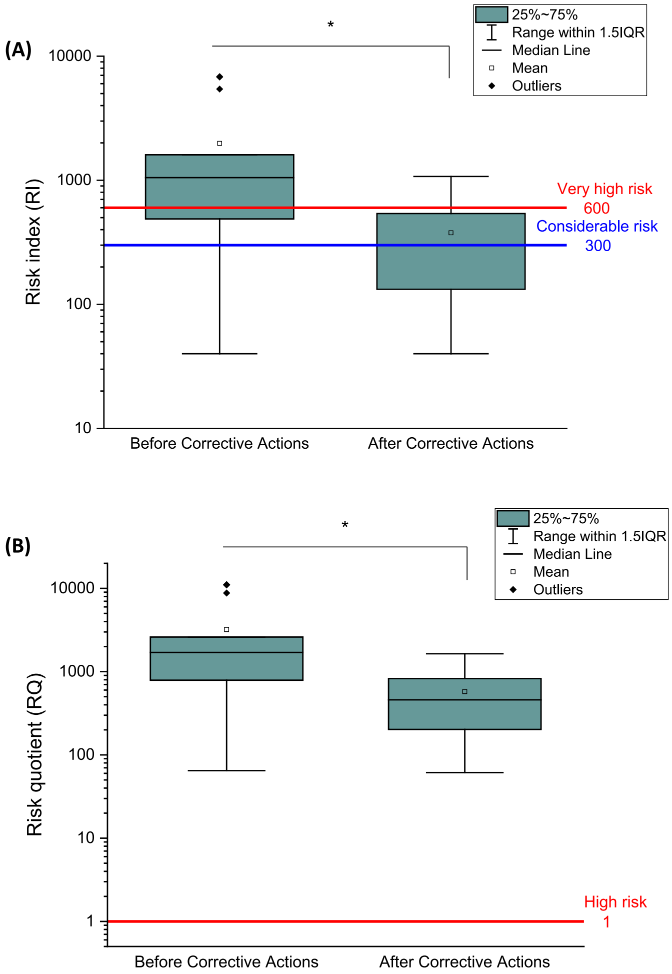

Fig. 5. Decreased risk indices of Hg in the polluted sediment of the brine water storage pond. (A) The RI reflected the potential ecological risk, and calculated by the toxic response factor and the CF. The red line indicated the highest degree of the index (RI = 600), the blue line indicated the considerable risk degree of the index (RI = 300). **(B)** The RQ was calculated by the Hg concentration and PNEC (predicted no effect concentration). The values above red line indicated the high risk (RQ > 1). The results were presented as boxplot. The statistical significance was determined by Student's *t*-test ($^*p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

might be able to lower the ecological risk of sediment Hg to negligible risk (RQ = 459 to RQ <1) after about 10-year implantation. In addition, to prevent sediment disturbing and resuspension, we suggested future application and research conducting suction dredging and *ex-situ* process and assessing the remedial results. Moreover, the sediment curtain and totally enclosed pollution area to prevent further potential Hg transportation are required. Our results provide evidence of corrective actions lowering the Hg accumulation and environmental risk for future studies about corrective actions for other pollutants.

4. Conclusion

The present study found the high Hg accumulation in the sediment and biota in the brine water storage pond of a closed alkali-chlorine factory in southern Taiwan. We then carried out a 3-year corrective actions including institutional/engineering control and remediation to improve the sediment quality and reduce the potential hazards caused by Hg in the sediment. It was shown that the pollution and risk indices such as CF, I-geo, RI, and RQ in the polluted sediment were significantly decreased after corrective actions. Although the value of these indices suggested the high ecological risk and high pollution in the sediment after corrective actions, the corrective actions were effective in lowering the accumulation and risk of Hg in the sediment. With the obvious decline of all indices, it shows that the corrective actions have a reducing effect on the Hg pollution in the sediment. Therefore, corrective measures should be continuously implemented to reduce the level of risk in all aspects to a level acceptable to stakeholders.

CRediT authorship contribution statement

Wen-Yen Huang: Methodology, Investigation, Writing – original draft. **Chi-Wei Huang:** Investigation, Visualization, Writing – original draft. **Yi-Lin Li:** Methodology, Investigation, Visualization. **Tsung-Po Huang:** Methodology, Investigation, Visualization. **Chitsan Lin:** Conceptualization, Resources, Writing – review & editing, Supervision. **Huu Hao Ngo:** Conceptualization, Resources. **Xuan-Thanh Bui:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2022.103003.

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