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Research Article

Assessment of Chromosomal Abnormalities in Hybrid Catfish in Reservoir Contaminated with Heavy Metals from Municipal Landfill

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Abstract

In this study, the concentrations of heavy metals (As, Cd, Cr and Pb) in water, sediment, and hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) as well as chromosomal abnormalities (CAs) from a reservoir affected by leachate from a municipal landfill were compared to those in an unaffected reservoir. Heavy metal concentrations were analyzed using inductively coupled plasma–optical emission spectrometry (ICP–OES). Chromosomes were prepared from kidney cells by direct methods. The As, Cd and Pb concentrations in the water and sediment from both reservoirs were within the Thailand water and soil standards. The concentrations of As and Cd in the water and the concentrations of As, Cd, Cr and Pb in the sediment and hybrid catfish significantly differed between the affected and unaffected reservoirs (p<0.05). The Pb concentration in hybrid catfish from the affected reservoir exceeded Thailand's food standard. Eight types of chromosomal abnormalities were detected in the hybrid catfish from the affected reservoir (centric fragmentation, centric gap, deletion, fragmentation, iso-chromatid break, iso-chromatid gap, single chromatid break, and single chromatid gap). The most common CA was deletion in the hybrid catfish from both reservoirs. The percentages of cells with CAs in hybrid catfish from the affected (22.00%) and unaffected reservoirs (8.60%) were significantly different (p< 0.05). These findings indicated that leachate from the municipal landfill has caused heavy metal contamination in the reservoir, leading to bioaccumulation and cytogenetic damage in hybrid catfish.

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Introduction

The Khon Kaen municipal landfill has been overused for more than 37 years. This overuse resulted in excessive residual solid waste on top of the landfill, posing potential risks to the nearby environment via leachate, including heavy metal contamination. When heavy metals from landfill leachate flow into reservoirs, they eventually dissolve into the water and precipitate in the sediment (Rakib et al., 2024). Heavy metals can accumulate in aquatic organisms through their feeding or breathing behavior, especially in fish species at relatively high trophic levels, via the biomagnification process (Aydin and Tunca, 2022). Previous studies have reported the quantity of heavy metals (As, Cd, Cr, Pb, and Hg) in water, sediment, and aquatic organisms in reservoirs near municipal landfills. The concentrations of As, Cd, Cr, Pb, and Hg in the water were 0.027 ± 0.007, 0.66 ± 0.32, 16.73 ± 1.32, 17.85 ± 4.28, and 0.0053 ± 0.0036 mg L^{-1}, respectively, which exceeded Thailand's water quality standards. As (8.616 ± 3.755 mg kg^{-1}) and Cd (2.60 ± 1.07 mg kg^{-1}) in the sediment exceeded Thailand's soil quality standards. Moreover, Cd, Cr, Pb, and Hg were detected in aquatic plants and animals that exceeded Thailand's food quality standards, including in *Oreochromis niloticus* (2.91 ± 1.49 mg kg^{-1}) and *Rasbora tornieri* (2.59 ± 1.72 mg kg^{-1}); Cr was detected

in *O. niloticus* (1.90 ± 0.99 mg kg^{-1}) and *Barbonymus gonionotus* (1.47 ± 0.88 mg kg^{-1}); Pb was detected in *O. niloticus* (0.90 ± 0.16 mg kg^{-1}), *R. tornieri* (0.60 ± 0.15 mg kg^{-1}), and *Anabas testudineus* (0.62 ± 0.15 mg kg^{-1}); and Hg was detected in *Channa striata* (0.133 ± 0.079 mg kg^{-1}) (Intamat et al., 2017; Inthuyod, 2020; Neeratanaphan et al., 2020; Phoonaploy et al., 2016; Promsid et al., 2015; Sriuttha et al., 2017; Thitiyan et al., 2021).

The hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) is a widely farmed species in Thailand. This fish species is known for its tolerance and high meat yield and is considered a predator at high trophic levels. Furthermore, their feeding behavior in sediment may cause hybrid catfish to accumulate high levels of heavy metals (Intramat, 2016). Previous studies have indicated that the toxic effects caused by heavy metal accumulation in organisms, including genotoxicity, can damage DNA and chromosomes (Bakare et al., 2013; Balali-Mood et al., 2021; Beyermann and Hartwig, 2008; Yadav and Trivedi, 2009). Thus, the aims of this study were to investigate the concentrations of heavy metals (As, Cd, Cr, and Pb) in the water, sediment, and hybrid catfish, including a chromosomal abnormality (CA) assessment of hybrid catfish (*C. gariepinus* x *C. macrocephalus*) in the affected reservoir near the municipal landfill compared with the unaffected reservoir with no heavy metal contamination from municipal landfill leachate.

Materials and methods

1) Study area

The Khon Kaen municipal landfill is located in Kham Bon village, Khon Kaen Province, northeastern Thailand (Latitude of 16°35'48.4"N and longitude of 102°48'24.3"E) (Figure 1). The distance from the affected reservoir to the municipal landfill was approximately 200 meters. The unaffected reservoir was not affected by landfill leachate, which was 16 kilometers from the municipal landfill and located in Dong Pong village, Khon Kaen Province (Latitude of 16°28'34.0"N and a longitude of 102°53'31.3"E).

2) Sample collection

Five samples of water and sediment were collected from five random locations (Figure 1) in the affected and unaffected reservoirs. Five hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) samples (Weight range 740–1,020 g) were collected from the reservoirs affected and unaffected by the fishing net. The concentrations of heavy metals (As, Cd, Cr, and Pb) in water, sediment, and hybrid catfish were measured, and chromosomal abnormalities were assessed in the kidney cells of the hybrid catfish.

3) Heavy metal analysis

Water samples (20 mL) were digested with 1.25% HNO_3 on a hot plate. Air-dried sediment samples (1 g) were digested with 15 mL of HCl, 5 mL of HNO_3, and 10 mL of H_2O_2 on a hot plate. One gram of hybrid catfish muscle was digested with 7 mL of HNO_3 and 1 mL of H_2O_2 on a hot plate. The digested solutions of water, sediment, and hybrid catfish muscle were filtered and adjusted to 25, 50, and 25 mL, respectively, with deionized water (Chad et al., 2013; US EPA, 1996). The heavy metals (As, Cd, Cr, and Pb) in the final solutions were analyzed using inductively coupled plasma optical emission spectroscopy (ICP–OES). The limits of detection (LODs) for As, Cd, Cr and Pb were 0.001, 0.0001, 0.0002, and 0.001 mg L^{-1}, respectively (Wavelengths of 188.979, 226.502, 267.719, and 220.353 nm, respectively) (Chad et al., 2013; Roehrich, 2016).



Figure 1 Five random locations (yellow dots) in the affected reservoir near the Khon Kaen municipal landfill, Kham Bon village, Muang District, Khon Kaen Province.

4) Chromosome preparation and chromosomal abnormality assessment

Chromosomes were prepared from kidney cells by the direct method of Tanomtong et al. (2019) and Maneechot et al. (2016). The chromosome samples were stained with 20% Giemsa solution for 30 minutes. One hundred clear and well-spread metaphase cells were selected and photographed under a light microscope at a magnification of 1,000X for each sample to investigate the karyotype and chromosome abnormalities (Tanomtong et al., 2019).

5) Statistical analyses

The concentrations of heavy metals in the water, sediment and hybrid catfish, including the number and percentages of chromosomal abnormalities of the hybrid catfish from the affected and unaffected reservoirs, were analyzed using the Mann–Whitney U test at the 95% confidence level.

Results and discussion

1) Heavy metal concentrations in water and sediment

Tables 1 and 2 show the concentrations of heavy metals (As, Cd, Cr, and Pb) in water and sediment samples from the affected and unaffected reservoirs, which did not exceed Thailand's water and soil quality standards (National Environment Board, 1994; 2021). Statistical analysis revealed significant differences between the concentrations of As and Cr in the water and those of As, Cd, Cr and Pb in the sediment from the affected and unaffected reservoirs (p<0.05).

These results differ from those of previous reports (Inthuyod, 2020; Neeratanaphan et al., 2020; Thitiyan et al., 2021) that revealed that the concentrations of As, Cd, Cr and Pb in the water and of As and Cd in the sediment from the affected reservoir exceeded Thailand's water and soil quality standards. Nevertheless, the concentrations of As and Cr in the water and As, Cd, Cr and Pb in the sediment from the affected and unaffected reservoirs significantly differed (p<0.05) according to Phoonaploy et al. (2016), Neeratanaphan et al. (2020) and Thitiyan et al. (2021). These research findings demonstrate that heavy metal contamination in reservoirs is affected by leachate from municipal landfills.

2) Heavy metal concentrations in hybrid catfish

Table 3 shows the concentrations of As, Cd, Cr and Pb in hybrid catfish samples from the affected and unaffected reservoirs, which did not exceed Thailand's food standards (Ministry of Public Health, 2003), except for the Pb concentration in fish from the affected reservoir. Statistical analysis revealed that the concentrations of As, Cd, Cr and Pb in the hybrid catfish significantly differed between the affected and unaffected reservoirs (p<0.05).

Previous studies have reported that the concentration of Cr in hybrid catfish from affected reservoirs exceeds food standards (Neeratanaphan et al., 2020). However, the concentrations of As, Cd and Pb in the hybrid catfish from the affected reservoir were detected in this study and in a previous study. Significant and standard-exceeding concentrations of heavy metals were detected in the hybrid catfish in this study, along with similar reports on the standard-exceeding concentrations of heavy metals in other fish species: Cd in *Oreochromis niloticus* and *Rasbora tornieri*; Cr in *O. niloticus* and *Barbonymus gonionotus*; Pb in *O. niloticus*, *R. tornieri*, and *Anabas testudineus*; and Hg in *Channa striata* (Promsid et al., 2015; Sriuttha et al., 2017; Thitiyan et al., 2021). These findings demonstrate that heavy metals accumulate in the fish species from the affected reservoir near the municipal landfill. These results are consistent with those of previous studies that reported high levels of heavy metals in reservoirs near municipal landfills.

Table 1 As, Cd, Cr and Pb concentrations in water from the affected and unaffected reservoirs

Heavy metals ($mg\ L^{-1}$)	Study areas		Standard*
	Affected reservoir	Unaffected reservoir	
As	0.0047±0.0012[a]	0.0020±0.0000[b]	0.01
Cd	0.0056±0.0005	ND	0.05
Cr	0.0073±0.0025[a]	0.0005±0.0002[b]	0.05
Pb	0.0027±0.0021	0.0010±0.0000	0.05

Remark: ND = not detected,
*Notification of the National Environment Board Re: Surface Water Quality Standards (National Environment Board, 1994).
[a, b] Different values in the same row indicate significant differences ($p<0.05$)

Table 2 As, Cd, Cr and Pb concentrations in sediment from the affected and unaffected reservoirs

Heavy metals ($mg\ kg^{-1}$)	Study areas		Standard*
	Affected reservoir	Unaffected reservoir	
As	1.4467±0.3156[a]	0.5267±0.0971[b]	25.00
Cd	1.3000±0.2646[a]	0.1367±0.0153[b]	762.00
Cr	16.6900±1.8917[a]	5.5033±0.3837[b]	212.00
Pb	24.2333±3.8223[a]	4.5200±1.1344[b]	800.00

Remark: *Notification of the National Environment Board Re: Soil Quality Standards (National Environment Board, 2021).
[a, b] Different values in the same row indicate significant differences ($p<0.05$).

Table 3 As, Cd, Cr and Pb concentrations in hybrid catfish from the affected and unaffected reservoirs

Study areas	Heavy metals (mg kg^{-1})			
	As	Cd	Cr	Pb
		Affected reservoir		
Individual 1	0.634	0.063	0.410	0.397
Individual 2	1.298	0.067	0.390	0.379
Individual 3	1.180	0.043	0.470	0.289
Individual 4	0.680	0.065	0.450	0.330
Individual 5	0.790	0.057	0.370	0.329
Mean± SD	0.9164±0.3028[a]	0.0590±0.0097[a]	0.4180±0.0415[a]	0.3448±0.0432[a]
		Unaffected reservoir		
Individual 1	0.103	0.012	0.280	0.124
Individual 2	0.068	0.021	0.430	0.149
Individual 3	0.112	0.015	0.390	0.153
Individual 4	0.093	0.017	0.240	0.137
Individual 5	0.087	0.019	0.370	0.139
Mean± SD	0.0926±0.0167[b]	0.0168±0.0035[b]	0.3420±0.0792[b]	0.1404±0.0113[b]
Standard*	2.00	1.00	1.00	0.30

Remark: *Standard for contaminants in food according to the Notification of the Ministry of Public Health No. 414 (Ministry of Public Health, 2003).
[a, b] Different values in the same column indicate significant differences ($p<0.05$).

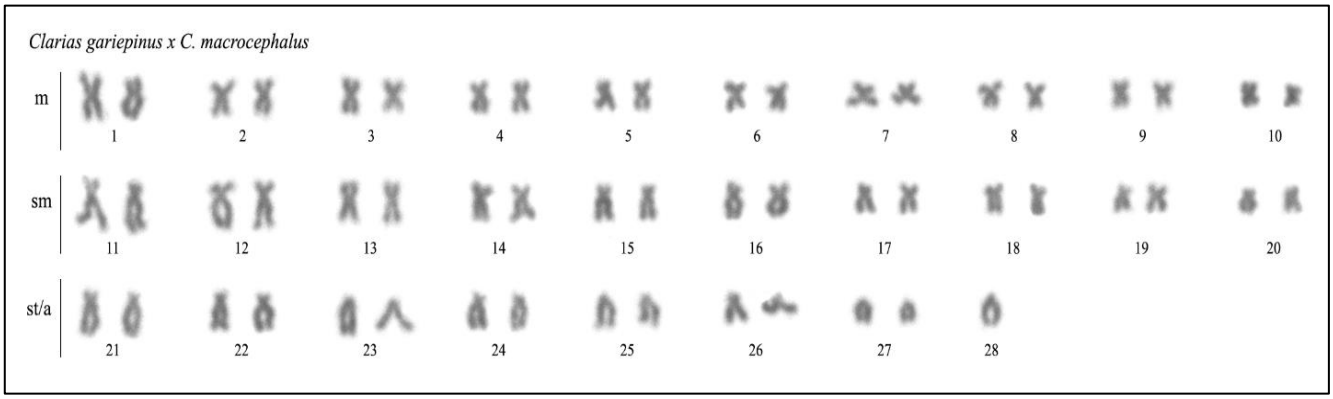


Figure 2 Karyotype of the hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) in the affected and unaffected reservoirs showing a diploid chromosome number (2*n*) = 55.

With respect to the heavy metal concentrations in water, sediment and hybrid catfish from the affected and unaffected reservoirs, the concentrations of As, Cd, Cr and Pb were highest in the sediment, followed by those in the hybrid catfish and then those in the water. These results are consistent with those of previous studies by Phoonaploy et al. (2016), Sriuttha et al. (2017), Intuyot (2020) and Thitiyan et al. (2021) because heavy metals in water can precipitate and bind with sediment particles, which results in a significant accumulation of heavy metals in the sediment over the duration of contamination. Similarly, aquatic organisms, particularly fish, are exposed to heavy metals through dermal contact, respiration, filter-feeding, or benthic foraging behaviors over highly contaminated sediment, such as the hybrid catfish, leading to the uptake of heavy metals through bioaccumulation. Consequently, aquatic organisms exhibit significant levels of heavy metal accumulation in their bodies, followed by the sediment (Rakib et al., 2024).

3) Hybrid catfish karyotype

The diploid chromosome number (2*n*) of the hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) in the affected and unaffected reservoirs was 2*n* = 55. The karyotype of the hybrid catfish consists of 10 metacentric, 10 submetacentric, and 7 acrocentric chromosome pairs and 1 acrocentric chromosome (Figure 2). These findings are consistent with a previous karyotype report (2*n* = 55) on hybrid catfish species by Maneechot et al. (2016).

4) Chromosome abnormality assessment

Eight types of chromosome abnormalities (CA) were identified in the hybrid catfish in the affected reservoir, arranged from highest to lowest frequency: deletion (D), centric gap (CG), single chromatid gap (SCG), single chromatid breaks (SCB), centric fragmentation (CF), isochromatid gap (ISCG), fragmentation (F), and iso-chromatid break (ISCB) (Figure 3), whereas six types were observed in the hybrid catfish in the unaffected reservoir. The most common and second most common chromosomal abnormalities (CAs) were deletions (D) and centric gaps (CG) in the hybrid catfish from both reservoirs. The total CAs, the total cells with CAs, and the percentage of cells with CAs in the hybrid catfish in the affected and unaffected reservoirs were 318.00, 110.00, and 22.00% and 67.00, 43.00, and 8.60%,

respectively (Table 4). Statistical analysis revealed significant differences between the total CAs, the total cells with CAs, and the percentage of cells with CAs in the hybrid catfish in the affected and unaffected reservoirs (p<0.05).

These results are similar to those of previous studies in the affected reservoir in the Khon Kaen municipal landfill area by Promsid et al. (2015) and Inthuyod (2020), which revealed four and seven types of significant CAs in snakehead fish (*Channa striata*), respectively, whose Hg concentration exceeded the food standard. The most common CAs in the two studies were single chromatid breaks (SBs) and centric fragmentation (CF), which are different from those in this study.

Structural CAs have been reported in fish affected by heavy metals in laboratory and polluted environments. Yadav and Trivedi (2009) reported that CAs were significantly increased in snakehead fish (*C. punctata*) exposed to Hg, As, and Cu for longer durations and at higher concentrations. Khamlerd et al. (2019) and Phoonaploy et al. (2019) reported five and eight types of significant CAs, respectively, in snakehead fish (*C. striata*) in reservoirs near e-waste dumping areas and industrial factories with significant Cd, Cr, Fe, Mn, and Ni contamination. Tengjaroenkul et al. (2017), Neeratanaphan et al. (2019) and Soulivongsa et al. (2020) reported seven types of CAs in fish (*Monopterus albus*, *Osteochilus vittatus* and *R. tornieri*) in reservoirs near a gold mine area with significant As, Cd, Cr, Fe, Mn, Ni and Pb contamination. These studies revealed that the eel species *M. albus* and the hybrid catfish exhibited the most feeding behavior on sediment surfaces with the highest concentration of heavy metals due to precipitation. However, each study did not report the same type of most common CA, which requires further investigation on the effects of heavy metals on each specific CA type.

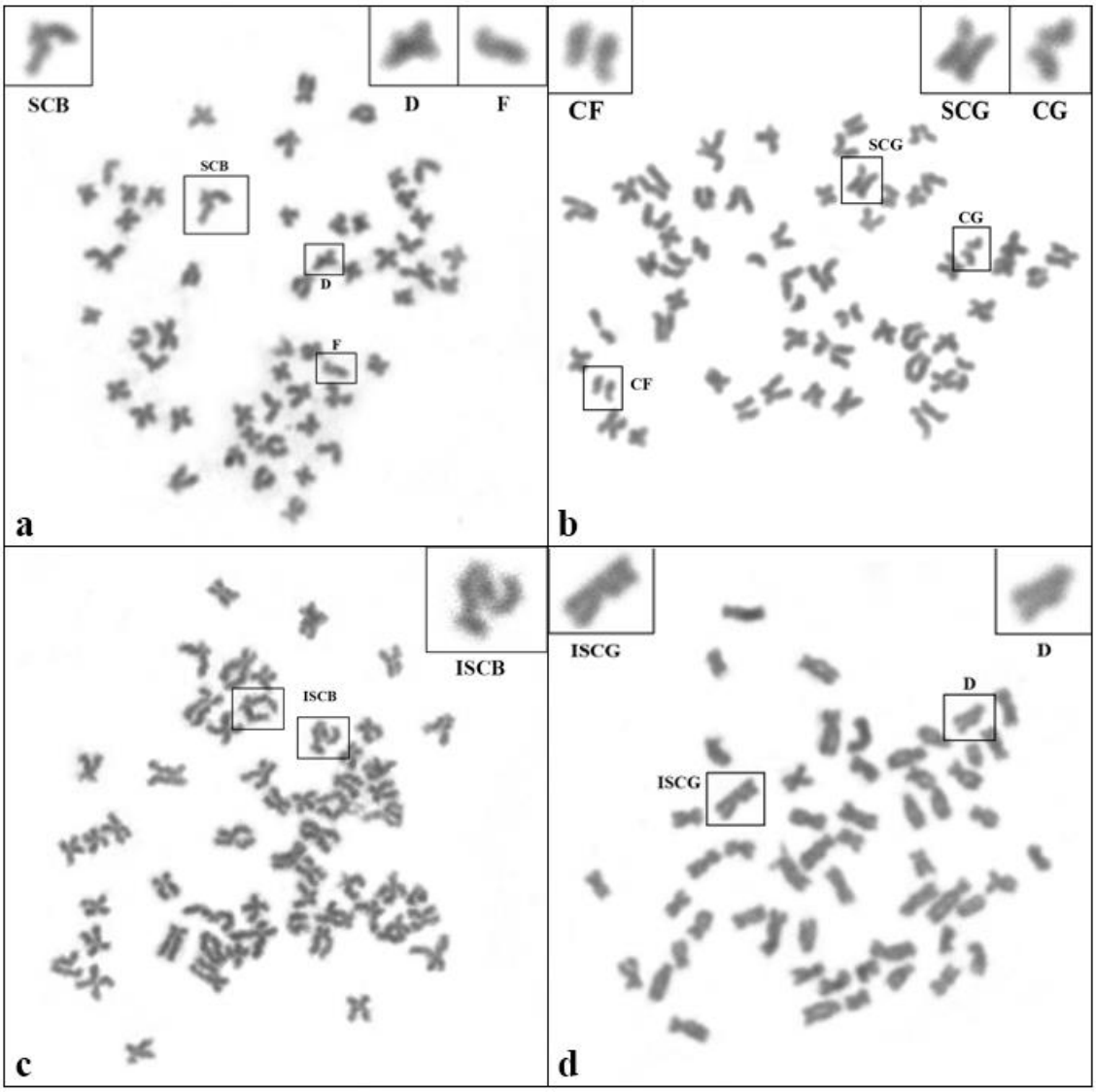


Figure 3 Eight types of chromosomal abnormalities of the hybrid catfish (*Clarias gariepinus x C. macrocephalus*) in the affected and unaffected reservoirs: centric fragmentation (CF), centric gap (CG), deletion (D), fragmentation (F), iso-chromatid break (ISCB), iso-chromatid gap (ISCG), single chromatid breaks (SCB), and single chromatid gap (SCG) (a–d).

Table 4 Number and percentage of chromosomal abnormalities of the hybrid catfish (*Clarias gariepinus* x *C. macrocephalus*) in the affected and unaffected reservoirs

C. gariepinus x *C. macrocephalus*	Chromosome abnormalities (CAs)								Total CAs	Total cells with CAs	% of cells with CAs
	CF	CG	D	F	ISCB	ISCG	SCB	SCG			
Affected reservoir											
Individual 1	1	4	18	2	6	6	9	7	53	21	21.00
Individual 2	4	7	28	2	0	6	6	12	65	21	21.00
Individual 3	7	25	22	4	1	2	5	3	69	18	18.00
Individual 4	4	10	38	2	0	2	2	5	63	24	24.00
Individual 5	3	18	27	5	2	2	3	8	68	26	26.00
Total/Average	19	64	133	15	9	18	25	35	318	110	22.00
Unaffected reservoir											
Individual 1	0	2	4	0	0	0	3	1	10	7	7.00
Individual 2	0	2	7	1	0	0	0	0	10	6	6.00
Individual 3	0	4	4	1	0	1	0	0	10	8	8.00
Individual 4	0	8	11	1	0	1	1	2	24	13	13.00
Individual 5	0	7	5	1	0	0	0	0	13	9	9.00
Total/average	0	23	31	4	0	2	4	3	67	43	8.60
p value									0.01*	0.01*	0.01*

Remarks: [a, b] Different values in the same column indicate significant differences ($p < 0.05$).
CF = centric fragmentation, CG = centric gap, D = deletion, F = fragmentation, ISCB = iso-chromatid break, ISCG = iso-chromatid gap, SCB = single chromatid breaks, and SCG = single chromatid gap.

Previous studies have emphasized the toxic effects of heavy metal contamination on aquatic organisms. Heavy metals, especially As, Cd, Cr and Pb, can induce oxidative stress in cells, which triggers oxygen species (ROS) production, causing lipid, protein, and DNA damage (Balali-Mood et al., 2021; Beyermann and Hartwig, 2008). Furthermore, heavy metals can bind to proteins and DNA structures, preventing those structures from functioning properly, replicating, and repairing themselves, eventually leading to damage to DNA and chromosomes (Bakare et al., 2013).

Therefore, the high concentrations of As, Cd, Cr and Pb in water, sediment, and hybrid catfish, as well as CAs found in hybrid catfish from affected reservoir near the Khon Kaen municipal landfill, indicate heavy metal contamination and bioaccumulation. This bioaccumulation may have genetic effects, such as CAs, in hybrid catfish. However, reports on heavy metal contamination and genetic effects are limited to specific fish species. Therefore, studying CAs in various fish species affected by heavy metals from municipal landfill leachate is necessary.

Conclusions

The concentrations of As, Cd, Cr and Pb in the water and sediment from the affected and unaffected reservoirs did not exceed the Thailand water and soil standards. The concentration of Pb in the hybrid catfish from the affected reservoir exceeded Thailand's food standard. The concentrations of As and Cd in the water, as well as those of As, Cd, Cr and Pb in the sediment and hybrid catfish, significantly differed between the affected and unaffected reservoirs. Eight types of chromosomal abnormalities were detected in the hybrid catfish from the affected reservoir near the municipal landfill, which significantly differed from those in the unaffected reservoir. Most chromosomal abnormalities were deletions. These findings indicated that leachate from the municipal landfill has caused heavy metal contamination in the reservoir, leading to bioaccumulation and subsequent genetic damage in hybrid catfish. Therefore, enhanced environmental monitoring and proper management strategies should be implemented in affected areas, along with raising community awareness regarding heavy metal contamination and its potential health and ecological risks in this reservoir.

Data availability statement

Information and data used in the study will be disclosed upon request.

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Manop Sriuttha: Conceptualization, Methodology, Resources

Lamyai Neeratanaphan: Conceptualization, Validation, Writing – Original draft, Writing – Review & editing, Supervision, Project administration

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

References

Aydin, M., & Tunca, E. (2022). Ecological risk assessment of elemental accumulation under the impact of gold mine. *International Journal of Environmental Science and Technology*, *19*, 7093–7112.

Bakare, A. A., Alabi, O. A., Gbadebo, A. M., Ogunsuyi, O. I., & Alimba, C. G. (2013). In vivo cytogenotoxicity and oxidative stress induced by electronic waste leachate and contaminated well water. *Challenges*, *4*(2), 169–187.

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, *12*, 643972.

Beyermann, D., & Hartwig, A. (2008). Carcinogenic metal compounds: Recent insight into molecular and cellular mechanisms. *Archives of Toxicology*, *82*(8), 493–512.

Chad, V., & Prasad, S. (2013). ICP-OES assessment of heavy metal contamination in tropical marine sediments: A comparative study of two digestion techniques. *Microchemical Journal*, 111, 53–61.

Intamat, S., Buasriyot, P., Sriuttha, M., Tengjaroenkul, B., & Neeratanaphan, L. (2017). Bioaccumulation of arsenic in aquatic plants and animals near a municipal landfill. *International Journal of Environmental Studies*, *74*(2), 303–314.

Inthuyod, M. (2020). *Evaluation of chromosome aberrations in snakehead fish* (*Chana striata*) *affected by landfill leachate in aquaculture* [MSc Thesis, Khon Kaen University].

Intramat, P. (2016). Hybrid catfish (2nd ed.). Bangkok: Kaset Siam Press.

Khamlerd, C., Tenjaroenkul, B., & Neeratanaphan, L. (2019). Abnormal chromosome assessment of snakehead fish (*Channa striata*) affected by heavy metals from a reservoir near an industrial factory. *International Journal of Environmental Studies*, *76*(4), 648–662.

Maneechot, N., Yano, C. F., Bertollo, L. A., Getlekha, N., Molina, W. F., Ditcharoen, S., Tengjaroenkul, B., Supiwong, W., Tanomtong, A., & de Bello Cioffi, M. (2016). Genomic organization of repetitive DNAs highlights chromosomal evolution in the genus Clarias (*Clariidae, Siluriformes*). *Molecular Cytogenetics*, 9, 4.

Ministry of Public Health. (2003). Standard of contaminants in food. Notification of the Ministry of Public Health No. 414. Royal Thai Government Gazette, Vol. 137, Special Part 118 D, pp. 10–18. Bangkok: Ministry of Public Health.

National Environment Board. (1994). Notification of the National Environment Board Re: Surface water quality standards. No. 8, B.E. 2537. Royal Thai Government Gazette, Vol. 111, Part 16 D. Bangkok: Ministry of Natural Resources and Environment.

National Environment Board. (2021). Notification of the National Environment Board Re: Soil quality standards. Royal Thai Government Gazette, Vol. 138, Special Part 54 D, pp. 20. Bangkok: Ministry of Natural Resources and Environment.

Neeratanaphan, L., Kanjanakunti, A., Intamat, S., & Tengjaroenkul, B. (2019). Analysis of chromosome abnormalities in the Asian swamp eel (*Monopterus albus*) affected by arsenic contamination near a gold mine area. *International Journal of Environmental Studies*, *77*(5), 815–829.

Neeratanaphan, L., Kamollerd, C., Suwannathada, P., Suwannathada, P., & Tengjaroenkul, B. (2020). Genotoxicity and oxidative stress in experimental hybrid catfish exposed to heavy metals in a municipal landfill reservoir. *International Journal of Environmental Research and Public Health*, *17*(6), 1980.

Phoonaploy, U., Intamat, S., Tengjaroenkul, B., Sriuttha, M., Tanomtong, A., & Neeratanaphan, L. (2016). Evaluation of abnormal chromosomes in rice field frogs (*Fejervarya limnocharis*) from reservoirs affected by leachate with cadmium, chromium and lead contamination. *EnvironmentAsia*, *9*(2), 26–38.

Phoonaploy, U., Tengjaroenkul, B., & Neeratanaphan, L. (2019). Effects of electronic waste on cytogenetic and physiological changes in snakehead fish (*Channa striata*). *Environmental Monitoring and Assessmen*t, 191, 363.

Promsid, P., Neeratanaphan, L., Supiwong, W., Sriuttha, M., & Tanomtong, A. (2015). Chromosomal aberration of snakehead fish (*Channa striata*) in affected reservoir by leachate with lead and mercury contamination. *International Journal of Environmental Research*, *9*(3), 897–906.

Rakib, M. R. J., Sarker, A., Nahida, Z. T., Islam, A. R. M. T., Mia, M. Y., Rahman, M. N., & Malafaia, G. (2024). A critical review on heavy metal contamination in aquatic food webs by edible fish species: A special case concerning Bangladesh. *Environmental Monitoring and Assessment*, *196*(12), 1175.

Roehrich, A. M. (2016). *ICP guide: ICP-OES detection limit*s. www.perkinelmer.com/atomicspectroscopy

Soulivongsa, L., Tengjaroenkul, B., & Neeratanaphan, L. (2020). Effects of contamination by heavy metals and metalloids on chromosomes, serum bioche-

mistry and histopathology of the bonylip barb fish near Sepon gold-copper mine, Lao PDR. *International Journal of Environmental Research and Public Health*, *17*(24), 9492.

Sriuttha, M., Tengjaroenkul, B., Intamat, S., Phoonaploy, U., Thanomsangad, P., & Neeratanaphan, L. (2017). Cadmium, chromium, and lead accumulation in aquatic plants and animals near a municipal landfill. *Human and Ecological Risk Assessment: An International Journal*, 23(2), 350–363.

Tanomtong, A., Pintong, K., & Patawang, I. (2019). Cytogenetics. Bangkok: Chulalongkorn University Press.

Tengjaroenkul, B., Intamat, S., Boonmee, S., & Neeratanaphan, L. (2017). Chromosomal aberration assessment of silver rasbora fish (*Rasbora tornieri*) living near gold mine area with heavy metal contamination. *Human and Ecological Risk Assessment: An International Journal*, *23*(5), 1140–1152.

Thitiyan, T., Pongdontri, P., Tengjaroenkul, B., & Neeratanaphan, L. (2021). Bioaccumulation and oxidative stress in *Barbonymus gonionotus* affected by heavy metals and metalloid in municipal landfill reservoir. *International Journal of Environmental Studies*, *79*(1), 98–113.

United States Environmental Protection Agency (USEPA). (1996). *Acid digestion of sediment, sludges and solids: 3050 Method B*. USA: Office of Water.

Yadav, K. K., & Trivedi, S. P. (2009). Chromosomal aberrations in a fish, *Channa punctata* after in vivo exposure to three heavy metals. *Mutation Research*, *678*(1), 7–12.