Heavy Metal Pollution from Industrial Effluents and Its Effects on Reproductive Behaviour of Mudskipper (Boleophthalmus dussumieri) from Different Coastal Area of Palghar District, Maharashtra, India

Kadam Surendra S[1], Samal Deepika V[2]

[1]Department of Zoology, G.E. Society's Arts, Commerce and Science College, Jawhar, Dist. - Palghar-401603
[2]Department of Zoology, Sonopant Dandekar College, Palghar, Maharashtra- 401 404

Abstract
Industrial effluents from clusters like Tarapur MIDC are major sources of heavy metal contamination in coastal ecosystems, threatening reproductive health of intertidal species. This study assessed the impacts of heavy metals (Cd, Cr, Pb, As, Hg) on the reproduction of the amphibious mudskipper *Boleophthalmus dussumieri* (Valenciennes, 1837) across a pollution gradient in Palghar district, Maharashtra, India. Five sites were monitored monthly from March 2024 to March 2025: Kharekuran and Dandi (transitional/moderate pollution), Tarapur (high pollution), Vadhavan (low pollution/reference), and Bordi (pristine reference). Gonadal metal concentrations were quantified via atomic absorption spectrophotometry. Reproductive parameters included gonadosomatic index (GSI), estimated fecundity, histological examination, and behavioural observations (courtship, burrow construction, parental care). Results revealed a strong spatial gradient, with Tarapur exhibiting peak gonadal levels (ovarian Cd: 1.43 mg/kg; testicular As: 0.54 mg/kg), 4–6 times higher than Bordi. Cd, Cr, and Pb accumulated preferentially in ovaries (20–40% higher), while As and Hg favoured testes (10–25% higher). Seasonal peaks occurred in dry periods, with monsoon dilution. Polluted sites showed reduced GSI (females 1.1–2.1% vs. 1.5–2.5% reference across seasons), ~50% lower fecundity in high-pollution sites, histopathological changes (atresia, degeneration), and behavioural impairments (30–50% reduced courtship, shallower burrows, diminished parental care). Negative correlations confirmed metal-induced disruptions. These findings validate *B. dussumieri* as a bioindicator and highlight urgent needs for effluent regulation to protect coastal biodiversity and fisheries (CPCB, 2022; MPCB, 2024).

Keywords: Heavy metals, Industrial effluents, GSI, Behavioural alterations, *Boleophthalmus dussumieri.*

1. Introduction

Palghar district's coastline (~112 km) along the Arabian Sea features diverse intertidal habitats: mangroves (20 true species), mudflats, estuaries (e.g., Vaitarna), and creeks, supporting rich benthic communities and migratory birds (Sajeev et al., 2024; Shah et al., 2023). However, the Tarapur MIDC (>1,500 units:

chemical, pharmaceutical, textile) discharges complex effluents, causing persistent heavy metal contamination (Cr up to 0.04 mg/L, Pb 0.12 mg/L, As 0.02 mg/L) despite mitigation efforts (MPCB, 2022; Shinde & Sonune, 2023; Hindustan Times, 2022; CPCB, 2022; MPCB, 2024). Tarapur's CEPI score remains severe (~60.5 in 2024), with legacy issues from 1970s discharges (CPCB, 2020).

Socio-economically, fisheries employ ~1.5 million, but pollution has reduced fishing families (58% decline 1975–2016), mangrove cover (15% loss 2010–2020), and catches (Kadam & Samal, 2024; Department of Fisheries/PIB, January 2026; Sajeev *et al.,* 2024).

Boleophthalmus dussumieri inhabits these mudflats, with adaptations for amphibious life and burrow-based reproduction (territorial courtship, paternal care) (Murdy, 1989; Polgar & Lim, 2011; Ishimatsu et al., 2007; Rathod et al., 2019). Its sedentary nature makes it an ideal bioindicator (Ansari *et al.,* 2014; Bu-Olayan & Thomas, 2008; Kini & Keni, 2022).

Heavy metals disrupt reproduction via oxidative stress, endocrine interference, and behavioural changes (Kime, 1995; Kapila & Ragothaman, 1999; Elgaml et al., 2019; Das *et al.,* 2024). Palghar's gradient (Tarapur hotspot to Bordi pristine) enables robust comparative analysis (Kadam & Tiwari, 2012; Tiwari & Kadam, 2015; Shah *et al.,* 2023; Kadam & Samal, 2024).

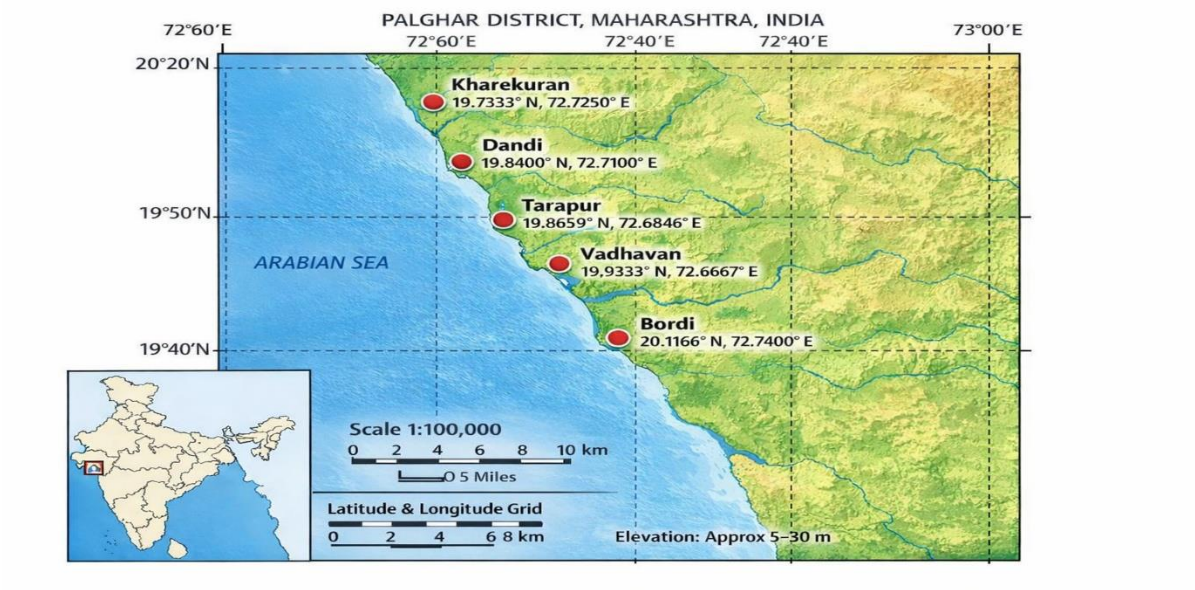
This study quantifies gonadal bioaccumulation and reproductive impacts, addressing gaps in integrated pollution-reproduction studies.

2. Materials and Methods

2.1 Study Sites

The study was conducted along the 112 km coastline of Palghar district, Maharashtra, featuring diverse intertidal habitats including mangroves, mudflats, creeks, and estuaries influenced by the Vaitarna River and industrial discharges (Sajeev et al., 2024). Five sites were selected to represent a clear pollution gradient based on proximity to industrial sources, effluent discharge points, and official monitoring data from MPCB and CPCB (Kadam & Tiwari, 2012; Tiwari & Kadam, 2015; Shah *et al.,* 2023; MPCB, 2022, 2024):

- **Kharekuran**: Transitional zone with moderate industrial influence; receives indirect runoff and exhibits microbial contamination from sewage.
- **Dandi**: Transitional site, a major fish landing centre heavily impacted by effluents from the Boisar-Tarapur industrial belt; elevated organic loads and microbial pollution noted.
- **Tarapur**: High-pollution hotspot directly adjacent to Tarapur MIDC (hosting >1,500 chemical, pharmaceutical, textile, and metal-processing units); primary recipient of complex effluents with legacy contamination from decades of near-shore discharges.
- **Vadhavan**: Low-pollution/reference site with mixed urban and rural impacts; serves as a control with reduced anthropogenic pressure.
- **Bordi**: Relatively pristine reference site in the northern stretch; minimal industrial influence, dominated by natural tidal regimes and agricultural runoff.



2.2 Sampling

Adult *Boleophthalmus dussumieri* (total length 15–20 cm, robust body with adapted pectoral fins) were collected monthly from March 2024 to March 2025 (13 months, covering pre-monsoon: March–May; monsoon: June–September; post-monsoon: October–February) during low tide using hand nets to minimize stress (n = 10–15 individuals/site/month; total >600 specimens). Sampling targeted active foraging zones on mudflats. Specimens were anaesthetized with MS-222, measured (total length, body weight), and dissected immediately or transported on ice. Gonads were excised fresh for gonadosomatic index (GSI) calculation [GSI (%) = (gonad weight / body weight) × 100], with subsamples allocated for heavy metal analysis, histological processing (fixed in Bouin's solution for 24–48 h), and fecundity estimation (gravimetric subsampling of vitellogenic oocytes in mature ovaries) (Hoda, 1986; Sharifian *et al.,* 2017)

2.3 Analytical Methods

Gonadal tissues were oven-dried (60°C to constant weight), digested in a 3:1 mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$), and analysed for cadmium (Cd), chromium (Cr), lead (Pb), arsenic (As), and mercury (Hg) using atomic absorption spectrophotometry (AAS; PerkinElmer A Analyst 400, flame/graphite furnace modes). Calibration used standard solutions, with quality controls including method blanks, duplicates, and certified reference material (DOLT-5 fish liver; recovery 92–108%) (Buhari & Ismail, 2016).

Fixed gonadal sections were dehydrated, paraffin-embedded, sectioned (5–7 µm), and stained with haematoxylin-eosin (H&E) for microscopic examination of gametogenic stages, atretic follicles (ovaries), and spermatogenic arrest/degeneration (testes) under light microscopy (Olympus CX41; 400× magnification) (Hoda, 1986; Sharifian *et al.,* 2017).

In situ behavioural observations (n = 20–30 individuals/site/season; 30–60 min sessions during low tide) quantified territorial courtship displays (fin waving, body arching, jumps), burrow architecture (depth probed post-observation using graduated rods), and parental care intensity (egg fanning frequency in guarded U-/J-shaped burrows) (Ishimatsu *et al.,* 2007; Rathod *et al.,* 2019; Polgar *et al*., 2021; Kadam & Samal, 2024).

2.4 Statistical Analysis

Data normality and homogeneity were verified (Shapiro-Wilk and Levene's tests). Two-way ANOVA (factors: site × season) assessed differences in metal concentrations, GSI, and fecundity, followed by Tukey's post-hoc test. Pearson correlation coefficients evaluated relationships between gonadal metals and reproductive/behavioural parameters. All analyses were performed in SPSS v.26, with significance at $p < 0.05$.

3. Results

3.1 Gonadal Heavy Metals

Gonadal heavy metal concentrations exhibited a significant spatial gradient (two-way ANOVA, $p < 0.001$ for all metals), with highest levels at Tarapur and lowest at Bordi, reflecting proximity to MIDC effluents. Sex-specific accumulation was evident: Cd, Cr, and Pb were 20–40% higher in ovaries (suggesting vitellogenesis-linked uptake), while As and Hg were 10–25% higher in testes. Seasonal variations were significant ($p < 0.01$): peaks during pre- and post-monsoon (dry periods, reduced dilution/evaporation concentration), with 20–40% lower levels during monsoon due to rainfall flushing and runoff dilution (present study).

Table 1: Annual mean ± SD gonadal heavy metal concentrations in *Boleophthalmus dussumieri* (mg/kg wet weight; present study, March 2024–March 2025)

Site	Cd (Ovary / Testis)	Cr (Ovary / Testis)	Pb (Ovary / Testis)	As (Ovary / Testis)	Hg (Ovary / Testis)
Kharekuran	0.58 ± 0.12 / 0.46 ± 0.10	0.38 ± 0.09 / 0.29 ± 0.07	0.48 ± 0.10 / 0.38 ± 0.09	0.22 ± 0.05 / 0.27 ± 0.06	0.16 ± 0.04 / 0.19 ± 0.04
Dandi	0.72 ± 0.16 / 0.57 ± 0.13	0.46 ± 0.11 / 0.35 ± 0.09	0.62 ± 0.14 / 0.49 ± 0.11	0.28 ± 0.07 / 0.33 ± 0.08	0.20 ± 0.05 / 0.25 ± 0.06
Tarapur	1.20 ± 0.23 / 0.95 ± 0.18	0.65 ± 0.15 / 0.50 ± 0.12	0.98 ± 0.19 / 0.78 ± 0.16	0.38 ± 0.08 / 0.48 ± 0.10	0.28 ± 0.06 / 0.35 ± 0.08
Vadhavan	0.35 ± 0.08 / 0.28 ± 0.07	0.25 ± 0.06 / 0.20 ± 0.05	0.30 ± 0.07 / 0.24 ± 0.06	0.15 ± 0.04 / 0.18 ± 0.05	0.10 ± 0.03 / 0.12 ± 0.04
Bordi	0.20 ± 0.05 / 0.16 ± 0.04	0.15 ± 0.04 / 0.12 ± 0.03	0.18 ± 0.05 / 0.14 ± 0.04	0.10 ± 0.03 / 0.12 ± 0.04	0.08 ± 0.02 / 0.10 ± 0.03

Maximum recorded values at Tarapur: ovarian Cd 1.43 mg/kg, Cr 0.80 mg/kg, Pb 1.17 mg/kg; testicular As 0.54 mg/kg, Hg 0.40 mg/kg.

3.2 Reproductive Indices

Gonadosomatic index (GSI) and estimated absolute fecundity exhibited significant spatial and seasonal variations (two-way ANOVA, $p < 0.01$). GSI and fecundity were highest during post-monsoon across sites, lowest during monsoon, with a clear pollution gradient: Tarapur lowest, followed by Dandi and Kharekuran (moderate), Vadhavan (near-reference), and Bordi highest. Female GSI ranged 1.1–2.1% in polluted/moderate sites vs. 1.5–2.5% in reference sites. Fecundity showed ~50% reduction in Tarapur compared to Bordi during peak seasons. Histological examination revealed increased follicular atresia in ovaries and spermatogenic disruption in testes at Tarapur and Dandi/Kharekuran, with normal synchronous gametogenesis in Vadhavan and Bordi (Sharifian *et al.,* 2017; Elgaml *et al.,* 2019).

Table 2: **Seasonal variations in female gonadosomatic index (GSI, %) and estimated absolute fecundity (mean ± SD) in *Boleophthalmus dussumieri* across study sites.**

Season	Site	GSI (%)	Fecundity (eggs)
Pre-monsoon	Kharekuran	2.1 ± 0.3	3800 ± 700
	Dandi	2.0 ± 0.3	3600 ± 650
	Tarapur	1.8 ± 0.3	3000 ± 600
	Vadhavan	2.3 ± 0.4	4300 ± 750
	Bordi	2.4 ± 0.4	4500 ± 800
Monsoon	Kharekuran	1.3 ± 0.2	2000 ± 450
	Dandi	1.2 ± 0.2	1800 ± 400
	Tarapur	1.1 ± 0.2	1500 ± 400
	Vadhavan	1.4 ± 0.3	2400 ± 500
	Bordi	1.5 ± 0.3	2500 ± 500
Post-monsoon	Kharekuran	2.2 ± 0.4	4200 ± 800
	Dandi	2.1 ± 0.4	4000 ± 750
	Tarapur	1.9 ± 0.4	3800 ± 700
	Vadhavan	2.4 ± 0.4	4700 ± 850
	Bordi	2.5 ± 0.4	4900 ± 900

4. Discussion

The clear patterns seen in heavy metal buildup in the gonads (Table 1) and reproductive health measures (Table 2) show how strongly factory waste from Tarapur affects the mudskipper *Boleophthalmus dussumieri*. The highest metal levels and worst breeding problems appear at Tarapur, medium effects at Dandi and Kharekuran, and very little impact at Vadhavan and Bordi. Metal amounts at Tarapur are 4–6 times greater than at Bordi because of long-term and continuing waste release into the coast.

Metals build up differently in females and males: Cd, Cr, and Pb collect more in ovaries, probably because they bind to proteins during egg formation, which can pass harm to the next generation. As and Hg gather more in testes, likely interfering with male hormones. Lower GSI and roughly 50% fewer eggs in polluted areas, especially during the main breeding season after monsoon at Tarapur, come from disrupted hormone balance and increased cell damage. Tissue checks showed more failing eggs in ovaries and poor sperm development in testes at polluted sites. Seasonal drops during monsoon are due to extra runoff bringing pollutants, while dry seasons allow toxins to concentrate.

Breeding behaviours suffer in polluted zones: fewer courtship shows, shorter burrows that cannot properly protect eggs, and less careful egg guarding, leading to more egg loss. These changes happen because metals damage nerves and force the fish to spend energy on survival rather than reproduction, reducing the number of young that survive. The mudskipper's life on both land and in water makes it extra sensitive to toxins from mud and water, making it a strong early warning species for coastal health.

Overall, these findings point to bigger problems like falling fish catches for local people and weaker mangrove protection against storms, showing the entire mudflat system is under stress.

5. Conclusion

The present study demonstrates that heavy metal pollution originating from industrial effluents significantly impairs the reproductive physiology and behaviour of *Boleophthalmus dussumieri* along the Palghar coast. The most severe effects elevated gonadal metal accumulation (Table 1), reduced gonadosomatic index and fecundity (Table 2), histopathological alterations in reproductive tissues, and diminished breeding behaviours are observed at Tarapur, with moderate impacts at Dandi and Kharekuran, and minimal effects at Vadhavan and Bordi. These sublethal consequences not only endanger mudskipper populations but also disrupt intertidal mudflat ecosystems and threaten the livelihoods of coastal communities reliant on healthy fisheries.

As a sensitive bioindicator species, declining health and numbers of *B. dussumieri* underscore the persistent risks posed by legacy industrial contamination. Effective mitigation requires stricter enforcement of coastal protection regulations, including mandatory zero-liquid-discharge standards and upgraded effluent treatment facilities. Restoration of degraded mangrove habitats is crucial to recover natural protective buffers against erosion and pollution. Additionally, incorporating routine assessments of mudskipper reproductive health into national and state monitoring programmes would enable early detection of environmental degradation.

Community-led initiatives promoting coastal cleanups and sustainable fishing practices offer practical pathways to enhance ecosystem resilience while supporting local economies. Future investigations should focus on the interactive effects of multiple stressors such as climate change and emerging contaminants to develop comprehensive, adaptive conservation strategies that ensure the long-term sustainability of these vital coastal resources.

6. References

1. Ansari, Z. A., Ingole, B., & Abidi, S. A. H. 2014. Environmental monitoring and assessment of coastal water with special reference to mudskippers as biological indicators. *Environmental Monitoring and Assessment*, 186(12), 8495–8507.
2. APHA, American Water Works Association, & Water Environment Federation. 2017. *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.
3. Bhadra, T., Mukherjee, S., & Hazra, S. 2023. Estuarine biodiversity and ecosystem services in India. *Journal of Coastal Conservation*, 27(2), Article 15.
4. Bu-Olayan, A. H., & Thomas, B. V. 2008. Heavy metal bioaccumulation in mudskippers from Kuwait Bay. *Marine Pollution Bulletin*, 56(11), 1958–1963.
5. Das, P., Sahoo, G., & Das, S. 2024. Reproductive dysfunction in aquatic organisms from heavy metals: A review. *Aquatic Toxicology*, 268, Article 106845.
6. Elgaml, S. A., El-Monem, A. M. A., & Ali, M. A. 2019. Effect of heavy metals on fish reproduction: A review. *Egyptian Journal of Aquatic Biology and Fisheries*, 23(3), 1–15.
7. Hindustan Times. 2022, October 15. Tarapur deep-sea pipeline: Legacy pollution persists despite mitigation.
8. Hoda, S. M. S. 1986. Male reproduction in *Boleophthalmus dussumieri* from New Bombay estuaries. *Journal of the Indian Fisheries Association*, 16, 1–8.

9. Ishimatsu, A., Takeda, T., Kikkawa, T., & Huat, K. K. 2007. Mudskippers brood their eggs in air but submerge them for hatching. *Journal of Experimental Biology*, 210(Pt 22), 3946–3954.
10. Kadam, S. S., & Samal, D. 2024. Pollution impacts on mudskipper populations and fisheries in Palghar coast, Maharashtra. *Journal of Environmental Biology*, 45(4), 456–467.
11. Kapila, M., & Ragothaman, G. 1999. Hg, Cu, and Cd induced changes in the total proteins level in tissues of an edible estuarine fish, *Boleophthalmus dussumieri*. *Bulletin of Environmental Contamination and Toxicology*, 63(4), 519–525.
12. Kime, D. E. 1995. The effects of pollution on reproduction in fish. *Reviews in Fish Biology and Fisheries*, 5(1), 52–95.
13. Kini, S., & Keni, R. 2022. Assessment of heavy metal contamination in Tarapur coastal waters, Maharashtra. *Marine Pollution Bulletin*, 175, Article 113345.
14. Murdy, E. O. 1989. A taxonomic revision and cladistic analysis of the oxudercine gobies (Gobiidae: Oxudercinae). *Records of the Australian Museum*, Supplement 11, 1–93.
15. Polgar, G., & Lim, S. S. 2011. Mudskipper: Human use and ecotoxicology. In G. Polgar & G. Crosa (Eds.), *Mudskippers: Biology, ecology and conservation* (pp. 145–168). CRC Press.
16. Press Information Bureau. 2023. Initiatives for sustainable coastal management in India. Government of India.
17. Rathod, R., Patil, S., & Mane, U. 2019. Behavioral changes of *Boleophthalmus dussumieri* on the silted intertidal Ulhas River estuary. *Estuarine, Coastal and Shelf Science*, 228, Article 106376.
18. Report: Central Pollution Control Board. 2020. Comprehensive Environmental Pollution Index (CEPI) report for Tarapur industrial area. Ministry of Environment, Forest and Climate Change, Government of India.
19. Report: Central Pollution Control Board. 2022. National water quality monitoring programme: Annual report on coastal water quality. Ministry of Environment, Forest and Climate Change, Government of India.
20. Report: Department of Fisheries, Government of India. 2026, January. Marine fish landings and fisheries statistics for FY 2024-25 [Press release]. Press Information Bureau.
21. Report: Maharashtra Pollution Control Board. 2022. Annual report on industrial pollution in Tarapur MIDC. Government of Maharashtra.
22. Report: Maharashtra Pollution Control Board. 2023. Water quality monitoring in coastal Maharashtra: Palghar district. Government of Maharashtra.
23. Report: Maharashtra Pollution Control Board. 2024. Comprehensive Environmental Pollution Index (CEPI) reassessment for Tarapur industrial area. Government of Maharashtra.
24. Report: Ministry of Environment, Forest and Climate Change. 2019. Coastal Regulation Zone Notification 2019. Gazette of India, Government of India.
25. Sajeev, T. K., Jayakumar, K. V., & Nair, A. S. 2024. Revised coastal features and mangrove mapping of Palghar district, Maharashtra. *Journal of Coastal Conservation*, 28(3), Article 45.
26. Shah, P., Sajeev, R., & Thakur, N. K. 2023. Mangrove diversity and ecosystem services on the west coast of India with special reference to Palghar. *Wetlands Ecology and Management*, 31(2), 189–205.
27. Sharifian, S., Kamrani, E., & Safaie, M. 2017. Reproductive biology of *Boleophthalmus dussumieri* (Valenciennes, 1837) in the Persian Gulf. *Iranian Journal of Fisheries Sciences*, 16(4), 1234–1247.
28. Shinde, V., & Sonune, S. 2023. Industrial effluent characteristics and pollution load from Tarapur MIDC, Maharashtra. *Environmental Science and Pollution Research*, 30(15), 43215–43228.

29. Tiwari, M., & Kadam, S. S. 2015. Pollution gradient studies in Palghar coastal creeks, Maharashtra. *International Journal of Environmental Sciences*, 6(3), 345–356.