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Heavy Metals in Wetland Ecosystem: Investigating Metal Contamination in Waterbirds via Primary Feathers and Its Effect on Population and Diversity

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Abstract: Wetlands are dynamic ecosystems that provide feeding and nesting grounds for diverse species of waterbirds. The quality of wetland habitat may have an impact on the density, diversity, and species richness of waterbirds. Toxic metal contamination is one of the most significant threats to wetland habitats. Feathers are a key indicator of heavy metal contamination in avian communities as a non-invasive method. We examined the levels of Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Lead (Pb), Nickel (Ni), and Zinc (Zn) using ICP-AAS and standards of digestion procedure from the primary feathers of 10 distinct species of waterbirds. The study was conducted at four wetlands, viz., Point Calimere Wildlife Sanctuary (Ramsar site); Pallikaranai Marshland (Ramsar site); Perunthottam freshwater lake (unprotected wetland), Tamil Nadu and the Pulicat Lake, Andhra Pradesh, (Ramsar site), India. The Large crested tern had higher concentrations of As, Co, Cr, and Ni. Cu was greater in the Indian pond heron, and Zn was higher in the Grey heron. The accumulation of metals differed among the waterbirds ($p < 0.05$), and the inter-correlation of metals found positive influences between the tested metals, i.e., Co was positively associated with As, Cr had a positive correlation with As and Co, and Ni was positively correlated with As, Co, Cr, and Cu. In contrast, Pb had a positive association with Cu and Ni. The Zn was associated with Co, Cr and Cu. The level of metals in waterbirds was Zn > Cu > Cr > Ni > Pb > Co > Cd > As. The results showed that metal levels in the primary feathers of waterbirds were greater than the other species of waterbirds examined across the world. Thus, the study emphasizes that managing wetlands and controlling pollution is crucial to saving waterbirds; otherwise, the population and diversity of waterbirds will decline and become a significant threat to waterbird communities.

Keywords: pollution; wetlands; heavy metals; feathers; waterbirds; impact and management

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1. Introduction

The abundance, distribution, and diversity of waterbirds are determined by the quality of their wetland habitat [1,2]. Indeed, wetlands support numerous species of waterbirds as feeding and breeding grounds [3]. However, globally, the diversity of waterbirds is declining due to various factors, and pollution is one of the major factors [4]. The water and soil quality parameters influence waterbirds' density, diversity, and species richness in a wetland habitat [5,6]. Studies reported that many vertebrates might be lost in the future due to anthropogenic pressures, especially due to heavy metals [7,8].

Heavy metals severely contaminate the environment, which poses intensive problems to humans and free-ranging animals [9,10]. Metal accumulation may affect the physiology and behaviour of waterbirds, for instance, their foraging behaviour, development (ontogeny), metabolic processes, breeding rates, moulting, memory, migration, and population size [11]. In the aquatic ecosystem, the soil sediments, water, crustaceans, mud-dwelling organisms, and fishes, as well as waterbirds' various organs (such as the liver, kidney, muscles, and feathers) and the embryonic development of their eggs, are severely damaged by the toxic metals [12,13]. Several studies have shown that heavy metals have intensive, serious physiological impacts on waterbirds, resulting in the deformation of several organs and metabolic disorders [14–16].

Evaluating metal contamination using free-ranging animals is a very contentious issue; the bioethical commission's standards forbid the slaughter of such species for biomonitoring or other scientific purposes [17]. Therefore, we aimed to use the primary feathers of waterbirds that were found dead in diverse aquatic environments in India to evaluate the metal levels in the birds' bodies. Several studies have concluded that examining feathers is simple and non-destructive biomonitoring technique for evaluating metals [18–21]. A study has explained the presence of metals in bird feathers through different mechanisms, i.e., digestion, forming of feathers, and releasing salt and oils from preen gland in waterbirds [22]. Furthermore, several investigations demonstrated that internal metal deposition occurred in feathers throughout their growth and development [18]. The present study focused on eight metals, As, Cd, Co, Cr, Cu, Pb, Ni, and Zn, because these metals are deeply involved in the food chain of aquatic organisms [23,24] and are severely damaging the physiology of plants and animals [25]. Numerous studies have revealed that these eight metals globally threaten the reproductive behaviour of several waterbirds [15,24].

Moreover, studies reported that As, Cd, Co, Cr, Cu, Pb, Ni and Zn have remarkable impacts on avian communities; for example, an excessive level of As can damage the DNA in birds [26]. A higher level of Cd in birds can damage their flying mechanisms and lead to poor development of bones [27]. Co is considered a significant element necessary for metabolism but can negatively affect birds in excessive concentrations [28]. The toxicity of Cr had several impacts on birds, including on embryo development and egg-hatching success in Mallard [29]. Cu is one of the major toxic elements that causes severe kidney issues in waterbirds when its concentration is beyond the threshold level [30]. Higher content of Pb could destroy birds' thermoregulation, growth of nestlings, and recognition of siblings [31]. Even in lower concentrations, Ni can affect the pigment colouring of feathers during feather moulting [32]. Severe reproductive failure and increased kidney toxicity have been reported in birds due to Zn poisoning [33].

The level of metals in birds is severely affecting their physiology and behaviour by causing severe ailments. The current research aimed to evaluate the metal content of the primary feathers of 10 distinct waterbird species' dead carcasses from four wetland habitats in India, including the Point Calimere Wildlife Sanctuary, Pallikaranai Marshland, and Pulicat Lakes and Perunthottam Freshwater lake. These wetlands are Ramsar sites, except Perunthottam Freshwater lake and they support a greater diversity of waterbird species annually as feeding and breeding habitats [34–36]. However, studies revealed that waterbirds' density, diversity, and species richness drastically declined in the three wetland habitats (Ramsar sites) due to pollution, especially heavy metals. In order to understand the level of metals, this study also compared the concentration of metals in waterbirds with the results of metals examined from the birds investigated in other parts of the globe.

2. Materials and Methods

2.1. Study Area

The study was carried out at four wetlands, viz., (i) Point Calimere Wildlife Sanctuary, Kodikkarai, (ii) Perunthottam aquatic freshwater lake, (iii) Pallikaranai Marshland, Tamil Nadu, and (iv) Pulicat Lake, Andhra Pradesh, India, during 2019–2023 (Figure 1 and Table 1).

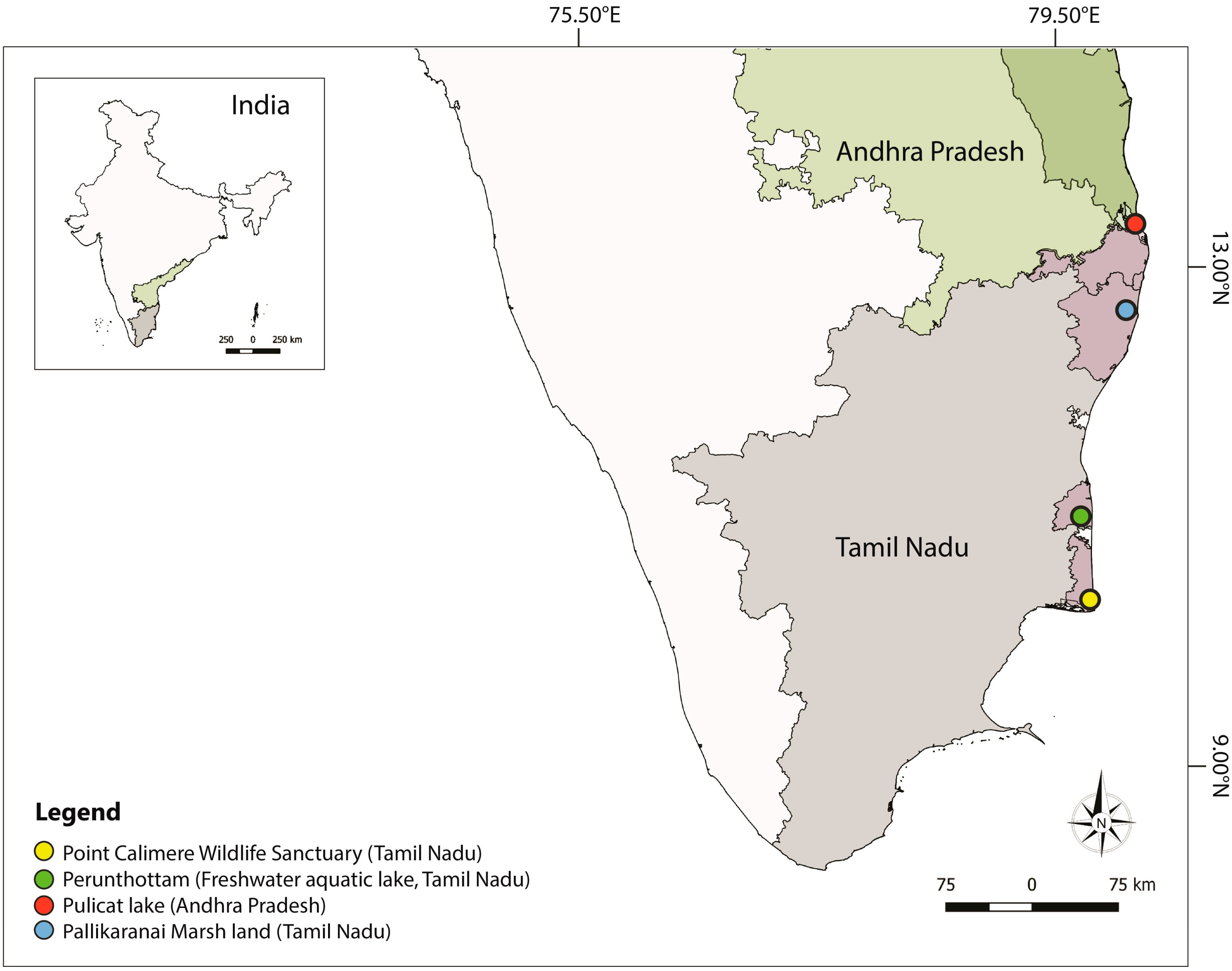

Figure 1. Map showing the locations of the four different wetlands, Tamil Nadu, and Andhra Pradesh, India.

Table 1. The details of waterbirds collected from the four different wetlands, Andhra Pradesh, and Tamil Nadu, India, during 2019–2023.

S.No.	Name of the Waterbirds	Name of the Wetlands
1.	Purple heron (*Ardea purpurea*)	Point Calimere Wildlife Sanctuary, Tamil Nadu (Ramsar site)
2.	Northern Shoveler (*Spatula clypeata*)	
3.	Large egret (*Ardea alba*)	Perunthottam (Freshwater aquatic lake) Tamil Nadu (Unprotected wetland)
4.	Pond heron (*Ardeola grayii*)	
5.	Grey heron (*Ardea cinerea*)	

Table 1. *Cont.*

S.No.	Name of the Waterbirds	Name of the Wetlands
6.	Striated heron (*Butorides striata*)	Pulicat Lake, Andhra Pradesh (Ramsar site)
7.	Spot-billed pelican (*Pelecanus philippensis*)	
8.	Heuglin's gull (*Larus heuglini*)	Pallikaranai Marshland, Tamil Nadu (Ramsar site)
9.	Brown headed-gull (*Chroicocephalus brunnicephalus*)	
10.	Large crested tern (*Thalasseus bergii*)	

The Point Calimere Wildlife Sanctuary (PCWLS), Kodikkarai, is located on the east coast of southern India, Tamil Nadu. The PCWLS was declared a Ramsar site in India in August 2002 since it is a globally significant wetland that supports and provides suitable habitats for migratory, resident migratory, and resident species of waterbirds annually [34–36]. The PCWLS receives water from the Bay of Bengal and rainwater during the monsoon season [35]. The Chemplast and small-scale saltpans are functioning in and around the PCWLS.

The Perunthottam Lake is a unprotected fresher-water wetlands, and the lake supports numerous species of waterbirds seasonally, including common and near-threatened species of waterbirds. Heronries are the lake's largest population, and the birds use this lake as a suitable feeding and breeding habitat (Unpublished data). Water from the Cauvery River fills the Perunthottam lake and irrigates the fields that run beside the river's bundh.

The Pallikaranai wetland is a globally important marshlands and has recently been declared Ramsar site. The wetland covers 700 acres, and it is located in the metropolitan city of greater Chennai Corporation of Tamil Nadu, India. According to research, several species of waterbirds use the Pallikaranai as a breeding and roosting site [37]. The Pulicat Lake is the second greatest saline waterbody lagoon and one of the Ramsar sites on the east coast of southern India. The lake provides critical support to various species of migratory and resident migratory waterbirds, functioning as feeding and breeding grounds during their migration. The lake receives water through various river systems, including the Araani and Kalangi rivers, which pass through various agricultural and industrial areas.

The Pulicat lake has a larger population and richer diversity of species over each season [38]. Moreover, numerous small, medium, and large-scale factories, industries, refineries, distilleries, battery companies, fertilizer companies, and national highways are located adjacent to the wetlands, and oil spills (through fishing vessels), discharges of effluents, and sewage water are the major sources of pollution in the wetlands.

2.2. Collection of Bird Feathers

Feathers were collected from four select wetland habitats; the details of the feathers are presented in Table 1. Primary feathers were collected from each species of waterbird (dead carcasses), such as the Purple heron, Northern Shoveler, Large egret, Pond heron, Grey heron, Striated heron, Spot-billed pelican, Heuglin's gull, Brown headed-gull, and Large crested tern, to assess them for metals. The Spot-billed pelican is in the Near Threatened Category (NT), and the other nine species of waterbirds are in the Least Concern (LC) category (IUCN, 2023). Though we collected more than three specimens for each species, we used only three specimens for the metal analysis to meet the statistical exploration. The primary feathers of birds are extensively used for assessing metal pollution [14,39]. The primary feathers of birds are the outermost wing feathers, which are protected by minute bones. There are generally ten primary feathers present in every species of bird. Additional inner primary feathers are also found in birds, but the outer primary feathers or flight feathers were employed for the current study [21].

2.3. Digestion of Bird Feather Samples

The feathers were washed in distilled water to remove any accumulated contaminants (external) on their surface. Washed feathers dried for 24 h using a hot air oven at 60 °C until constantly dehydrated (dry mass), and the feathers were weighed to the nearest 0.001 g [14]. The feathers were digested using a microwave digestion process using 10 mL of HNO_3 (69%) for five minutes, 1 mL of $HClO_4$ (70%) for five minutes, and 5 mL of H_2O_2 (30%) for ten minutes at 250 W magnetron power settings. Filter paper was used to filter the digested samples, which were made into 25 mL by using (MP) H_2O. The samples were kept in polythene tubes in the deep freezer until metal analysis [14].

2.4. Quality Control and Analytical Procedure

A quality control (QC) sample was injected for every six samples to assess the instrument's stability. In addition, for better accuracy, blank and standard samples were run in a set of three (triplicate) for each analytical course [14]. Regarding the accuracy of the systematic procedure in the metal analysis, the relative standard deviation (RSD) was obtained at the 5–10% range, and the RSD was calculated from the STD/mean values. For each metal, separate calibration curves were prepared at 0.5, 1.0, 2.0, 5.0, and 10 ppm. The working solution was also prepared every day to analyse the different metals by making a stock solution with the mixture of 65% (v/v) HNO_3, 30% (v/v) H_2O_2, and H_2O ($v/v/v$ = 1:1:3) ratios [40]. The instrument was set to zero concentration for every sample set using a blank solution. The results of each metal were determined using (triplicate) samples. All glassware was rinsed with distilled water before use, soaked in nitric acid (30%) overnight, and air-dried before being used to analyse metals. Analyses were performed using ICP-MS. The results are expressed as ppm [14,40,41].

2.5. Data Analysis

The descriptive statistics were completed for each metal that was assessed from the various waterbird species collected from the four wetlands. The values are given as a mean of ±SE (ppm). Shapiro–Wilk has also been tested to ascertain the normality of the data for further analysis. One-way variance analysis (ANOVA) has explored the variations of metal load among the waterbird species collected at different wetlands. We completed inter-correlation analysis to understand the sources and relationships among the metals examined to the different wetlands based on the feathers of various species of waterbirds. The analysis was conducted by using SPSS 25.0 software (South Asia Private Limited, Bangalore, India), and the outcomes are represented using the interpretations described by Sokal and Rohl [42].

3. Results

Metals were assessed from the primary feathers of 10 distinct species of waterbirds from four different wetlands (Figures 2–9). Arsenic (As) was higher in Large crested tern (0.1 ± 0.002 ppm) than the other metals examined. The cadmium (Cd) concentration was high in Purple heron (0.10 ± 0.030 ppm). The Cobalt (Co) and Chromium (Cr) concentrations were detected at higher levels (0.02 ± 0.053) and (1.29 ± 0.406 ppm), respectively, in the Large crested tern. Higher levels of Copper (Cu) (1.28 ± 0.012) and Lead (Pb) (1.10 ± 0.321 ppm) were found in the Indian Pond heron. Nickel (Ni) concentration was higher in the Large crested tern (3.511 ± 0.130 ppm). In the Grey heron, the Zinc (Zn) level was dominant, with 14.79 ± 0.408 (ppm) compared to the other species of waterbirds studied. The metals, viz., As, Cd, Co, Cr, Cu, Ni, Pb, and Zn showed differences among the various species of waterbirds examined in the wetlands (Figures 2–9). The concentrations of the eight different metals in the primary feathers of the 10 distinct species of waterbirds were Zn> Cu > Cr > Ni > Pb > Co > Cd > As.

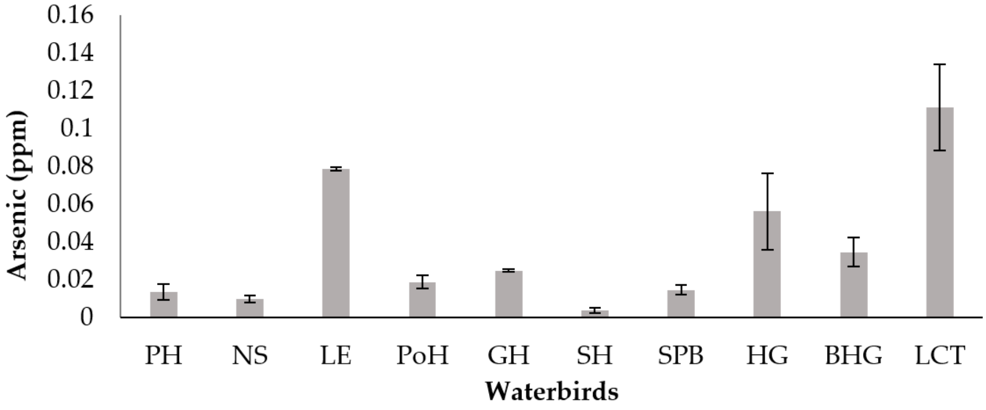

Figure 2. Level of Arsenic (As) accumulated in the feathers of the different waterbirds studied in various wetlands in India. [PH = Purple heron; NS = Northern Shoveler; LE = Large egret; PoH = Pond Heron; GH = Grey heron; SH = Striated heron; SPB = Spot-billed pelican; HG = Heuglin's gull; BHG = Brown-headed gull; LCT = Large-crested tern]. (Bar indicates the mean value and the line indicates the standard error values).

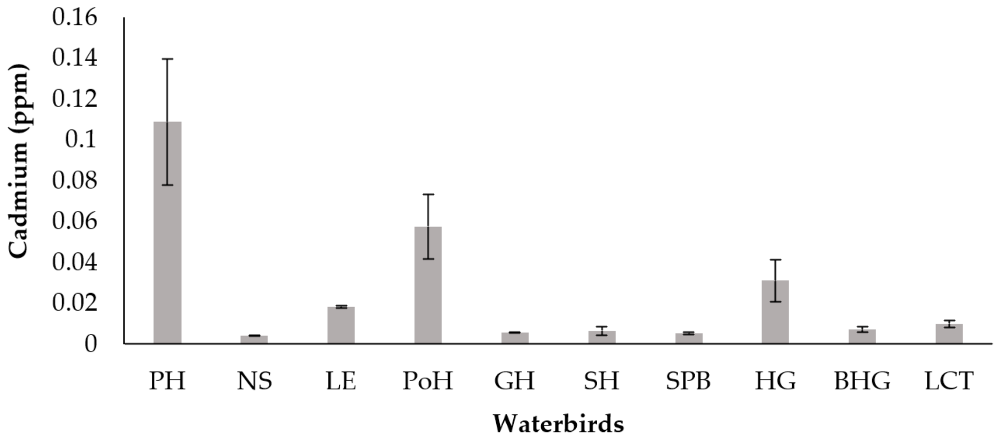

Figure 3. Level of Cadmium (Cd) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

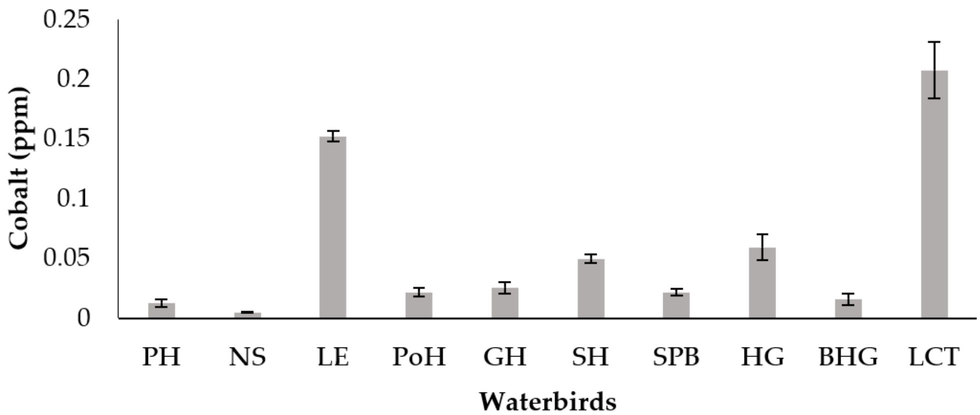

Figure 4. Level of Cobalt (Co) accumulated in the feathers of the different waterbirds studied in different wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

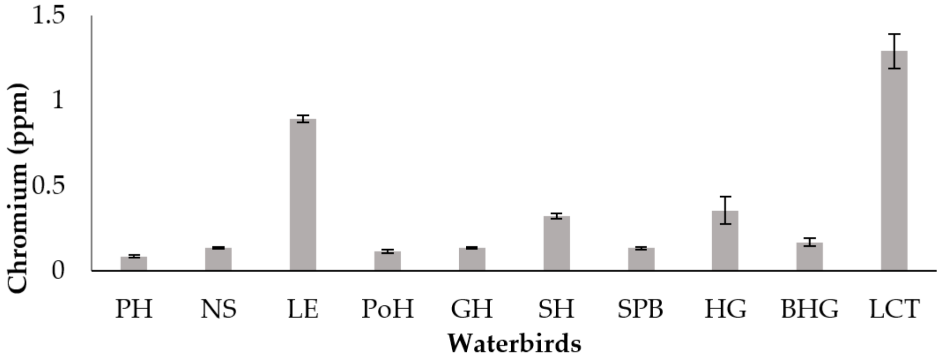

Figure 5. Level of Chromium (Cr) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

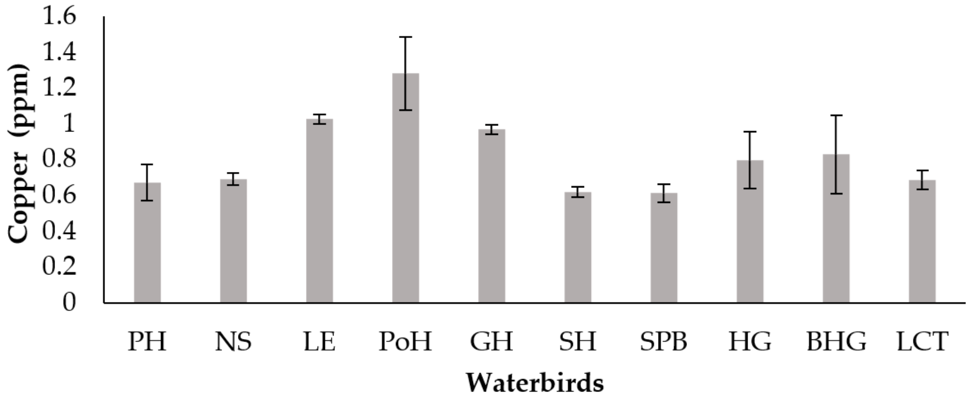

Figure 6. Level of Copper (Cu) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

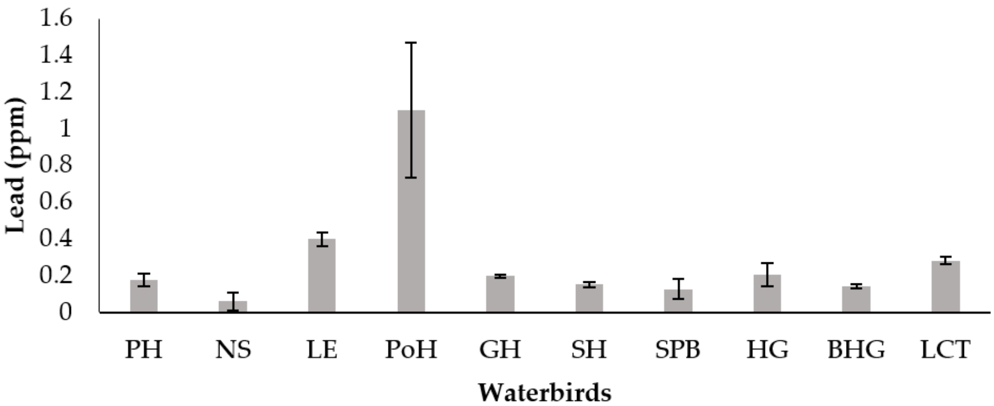

Figure 7. Level of Lead (Pb) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

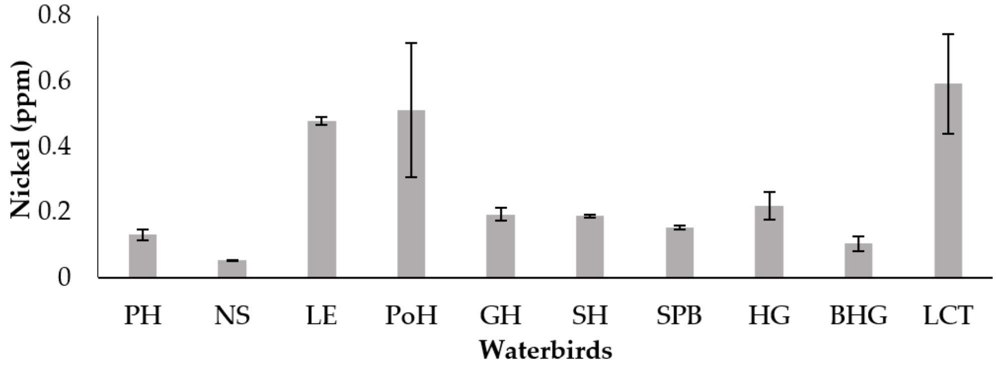

Figure 8. Level of Nickel (Ni) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

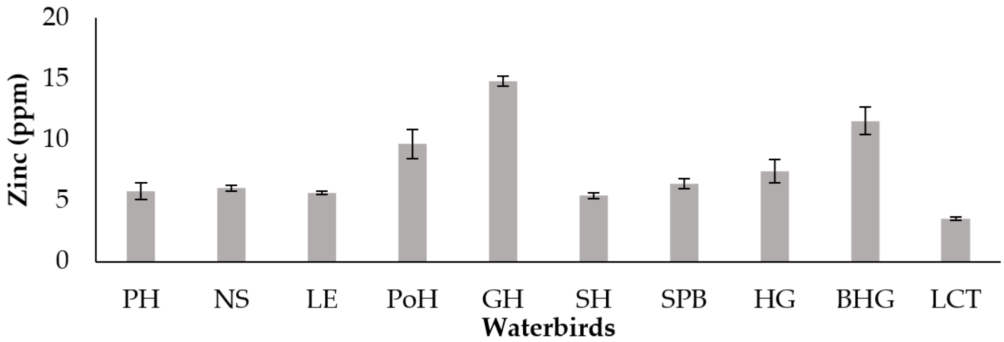

Figure 9. Level of Zinc (Zn) accumulated in the feathers of the different waterbirds studied in diverse wetlands in India. (Bar indicates the mean value and the line indicates the standard error values).

The inter-correlation of metals showed positive correlations among the metals examined in the 10 different species of waterbirds. A positive association was predicted between Co and As (r = 0.910; $p < 0.01$); Cr also showed similar results with As and Co (r = 0.901 and 0.991; $p < 0.01$). Ni exhibited absolute relationships with As (r = 0.680; $p < 0.01$), Co (r= 0.739; $p < 0.01$), Cr (r =0.711; $p < 0.01$), and Cu (r = 0.557; $p < 0.01$). Pb showed a positive correlation with Cu (r = 0.729; $p < 0.01$) and Ni (r = 0.686; $p < 0.01$). Zn was correlated with Co (r = 0.422; $p < 0.05$), Cr (r = 0.427; $p < 0.05$) and Cu (r = 0.532; $p < 0.01$) (Table 2).

Table 2. Inter-correlation of metals examined from the 10 different species of waterbirds studied from the four different wetlands, Andhra Pradesh, and Tamil Nadu, India, during 2019–2022.

Metals	As	Cd	Co	Cr	Cu	Ni	Pb	Zn
As	1							
Cd	0.083	1						
Co	0.910 **	0.158	1					
Cr	0.901 **	0.182	0.991 **	1				
Cu	0.205	0.163	0.077	0.043	1			
Ni	0.680 **	0.017	0.739 **	0.711 **	0.557 **	1		
Pb	0.073	0.220	0.070	0.026	0.729 **	0.686 **	1	
Zn	0.208	0.056	0.422 *	0.427 *	0.532 **	0.119	0.206	1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

4. Discussion

The presence of metal pollutants in aquatic environments has been found to have a negative impact on waterbird communities, resulting in reduced abundance, distribution, diversity, and species richness. This is due to the effects of the pollutants on the reproductive physiology and behaviour of these avian species. Numerous studies have indicated that the presence of diverse pollutants, particularly metals, can have an impact on the well-being and longevity of waterbird populations in terms of their fitness and sustainability [23]. The current study examined the metals that are directly associated with trophic structures [24]. The study revealed critical results on the concentration of metals in waterbirds examined. Zinc (Zn) was highest (14.79 $\pm$ 0.408 ppm) in the Grey heron and lowest in the Large crested tern (3.51 $\pm$ 0.130). The Pond heron had the highest Copper (Cu) and Lead (Pb) when compared to other waterbirds that were studied from the four wetlands (Figures 2–9). Zn was higher in the Grey heron; this may have occurred because this bird mainly feeds on fish species, but can also prefer to consume aquatic invertebrates when the distribution and abundance of fish species are low in their foraging grounds [14]. Numerous reports describe that Zn occurred at a higher level in fish [16,43,44]; since the Grey heron's preferred and principal diet is fishes, this may have influenced the level of Zn in their primary feathers, which was higher in the present study.

Cu and Pb were higher in the Pond heron. The Pond heron is a carnivorous bird that forges on various prey species in the aquatic habitat, such as fishes, molluscs, crustaceans, insects, and other mud-dwelling organisms (occasionally). The birds that feed on those prey species might have accumulated more Cu and Pb [15]. Youssef et al. [45] reported that crustaceans and fishes showed higher amounts of Cu and Pb. Similarly, another study described the extensive accumulation of Cu and Pb in fishes and crustaceans through their feeding preferences [46]. Battley et al. [47] reported that top predators in an aquatic ecosystem, including heronries, showed maximum Cu and Pb because waterbird species feed on fishes, amphibians, crustaceans, and molluscs. Consequently, it is verified that the quality of the ecosystem may affect the accumulation of metals in predators, such as waterbirds.

This study also found that the highest level of Zn was in Grey heron, and Cu and Pb were highest in Pond heron. The dead specimen of Grey heron and Pond heron were collected from the Perunthottam freshwater wetland, which is one of the unprotected wetlands. The lake gets water from the Cauvery River, which covers more than 600 km from its source in Talai-Cauveri, Kodagu District, Karnataka State, to its mouth at the east coast of Tamil Nadu, southern India. The Cauvery River not only loads fresh water from the natural sources of Western Ghats, it is also the outlet for various pollutants from agricultural farmlands, tanneries, as well as small, medium and large scale factories, municipal and corporation wastes, sewages of distilleries companies, oil leaks, etc., from locations all along the Cauvery basin. Therefore, the lake is loaded with various pollutants through the river water; this can affect the waterbirds since they are using the lake as feeding and breeding grounds. In addition, the current study witnessed that the level of Zn was higher in the feathers of Grey heron, and Cu and Pb were higher in the feathers of the Pond heron. In fact, Zn is a vital element for animals, but a surplus level of Zn will affect its the metabolic and vital physiological systems [10,48].

Moreover, the results of the present study revealed that most of the waterbird species showed 4–6 times higher concentrations of Zn compared to other species of waterbirds studied globally, such as Spotted Redshank (2.1 $\pm$ 0.20), Black-winged stilt (2.559 $\pm$ 0.35), Common redshank (2.041 $\pm$ 0.29), and Painted stork (1.5 $\pm$ 0.12) [48,49]. The highest mortality has been reported in terrestrial and wetland birds due to Zn poisoning; ducks and a few species of Columbiformes showed severe physiological effects with a higher level of Zn concentration [50,51]. Indeed, the high amount of Cu and Pb in avian communities has been linked to several health problems and tissue abnormalities [52,53], and problems with reproductive behaviour, thermoregulation, movement, poor growth and survival of nestlings, and kin recognition have been reported in birds with Pb poisoning [52]. In addition, memory loss was also reported in migratory birds due to the heavy load of Cu and Pb [52–54]. In fact, a greater level of Cu was reported in the Red knot, Sanderling, and Semipalmated sandpiper [53] and Pb in the Red knot (484 ppm), Sanderling (367 ppm), and Semipalmated sandpiper (411 ppm), than in the current study [53].

Moreover, As, Co, Cr, and Ni were higher in Large-crested tern (Figures 2, 4, 5 and 8). The concentration level of As was lower in waterbirds studied than in the other species of birds examined, i.e., *Calidris canutus* (446 ± 42 ng/g), *Calidris alba* (311 ± 64 ng/g), and *Calidris pusilla* (842 ± 101 ng/g), which were discussed at Delaware Bay, USA [53]. In fact, a higher level of cobalt was reported in the *Alectoris chukar* (1.2 ppm), *Ammoperdix griseogularis* (5.4 ppm), and *Columba livia* (1.3 ppm) compared with those from the current study [55]. Co is important for various metabolic activities; however, higher cobalt accumulation in waterbirds influences enzymes that are essential for several physiological activities [30,54]. In addition, a higher concentration of Cr was reported from various species of birds than in the present study [29,52,56]. Above 1.8 ppm of Cr has shown adverse effects in birds, but the present study did not observe harmful levels of Cr [29,52,57]. Compared to other studies worldwide, the level of Ni in the waterbirds studied was lower [58,59]. Studies have reported that Ni could affect the pigmentation in feathers and moulting mechanisms when the Ni concentration is exceeded in birds [15–17].

The dead Large-crested tern examined in this study was found at Pallikaranai marshland, one of the largest marshland in the urban ecosystem of Tamil Nadu, India. One study described that the Pallikaranai lake supports numerous species of avian communities by providing necessary prey species, i.e., 46 fish species, five species of crustaceans, nine molluscs, and 10 species of amphibians [60]. However, research found higher concentrations of As, Co, Cr, and Ni in Pallikaranai lake water [61], and the results stressed that the contamination of the lake was largely due to the dumping of solid and liquid wastes from the Chennai metropolitan city and the emergence of a new building in and around the lake. This might be why the Large crested tern shows a higher level of As, Co, Cr and Ni in its feathers. The chief prey for the Large crested tern is fish and prawn species [62]. A study reported that reported that the accumulation of Co and Cr was greater in fishes and prawn species [16]. Terns mostly feed on fishes and prawn species, which could be a reason that Co and Cr are greater in the Large crested tern.

The Purple heron and Northern shoveler carcasses were collected from the Point Calimere Wildlife Sanctuary. The dead Striated heron and Spot-billed pelican were collected at Pulicat lake, Andhra Pradesh, India. These four species showed lower concentrations of metals in their feathers when compared to the other six species of waterbirds. However, if the number of samples was increased, we could shed more light on the concentration of metals from the feathers of these species of waterbirds. Studies have reported that the water, sediment, and prey species, as well as several species of waterbirds in the Point Calimere Wildlife Sanctuary and Pulicate lake are contaminated with metal load [12,63–65].

The inter-correlation of metals showed a positive correlation among the metals ($p < 0.01$ and $p < 0.05$). Co was positively correlated with As, Cr showed a positive correlation with As and Co, and Ni positively correlated with As, Co, Cr, and Cu. In contrast, Pb is positively associated with Cu and Ni. Zn was linked to Ni, which showed that the metals have a close association with each other, which is one of the driving forces behind the accumulation of metals in biological organisms, especially top predators. Similarly, several studies have shown the accumulation of metals in top predators through their prey or environment [15–17]. Indeed, the uptake of toxic metals in waterbirds may occur through their feeding behaviour, which involves water, soil, and prey species. A study reported that metals enter the waterbirds' bodies through water and soil while they are searching, pecking, probing, catching, swallowing, etc. [66]. The accumulation of metals in the waterbirds could also occur through their prey species [67,68].

The results of the present study showed that the waterbirds carry more significant levels of toxic metals in their body than other species of birds examined elsewhere. However, globally, several studies reported that waterbirds' abundance, composition, density, diversity, and species richness has declined [14,16,34,35]. In fact, certain species of waterbirds are critically endangered, for example, the white-bellied heron, spoon-billed sandpiper, and social lapwing. Moreover, the white-headed duck, white-winged wood duck, great knot, greater adjutant, black-bellied heron, and black-bellied tern are endangered (IUCN 2023). These species of waterbirds have not been observed recently on the east coast of southern India. The reason for this is unknown, but it may be due to pollution of the wetlands [14]. Moreover, studies have also indicated that refuel sites have been degraded through pollution, and thus, migratory waterbirds are facing critical consequences during their migration [69]. Studies also state that heavy metals influence 19% of the physiological activities of bird communities, along with other pollutants, such as pesticides, oil, noise, light, plastic, air, and pharmaceutical and radioactive pollution [70–72]. Toxic metals threaten the wetlands habitats and various species of fauna and flora, depending on the wetlands [73].

5. Conclusions

The current study showed the variations of metal accumulation in waterbirds; these variations may occur because different species use different hunting techniques and consume different foods. Moreover, the age of the birds and their principal and preferred prey also could directly influence the accumulation of metals, but the study did not investigate the feeding and habitat selection for waterbirds used in the current study. In addition, the pollution in aquatic habitats in the study area comes from various sources, which could also influence the metal load in the waterbirds studied. The load of metals in the waterbirds come not only from the wetlands studied, but also where the birds are moving and using other wetlands as feedings grounds, which could also facilitate the accumulation of metals in the waterbirds. Overall, the study emphasises that the waterbirds accumulate toxic metals from their feeding and breeding habitats through different sources. Therefore, the study cautioned that we must monitor and manage the wetlands as pollution-free habitats because the metals not only affect the waterbird communities, they also influence the health of human society. Nutritious foods, such as fishes, molluscs and crustaceans, are collected from the wetlands and consumed by human society, which could damage human health.

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