Arsenic Pollution in Indian Wetlands and its Implications on Stork Health and Survival

Ayan Biswas

Assistant Professor, Department of Zoology, Barasat Government College, 10, K.N.C. Road, Barasat, North 24-Paraganas, PIN- 700124, West Bengal, India
Corresponding Author Email: *ayan.biswas[at]bgc.ac.in*

Abstract: ***Arsenic contamination, a growing environmental concern in South Asia, poses a serious threat to wetland ecosystems and the avifauna dependent on them. India, particularly the eastern Gangetic plains (West Bengal, Assam, Bihar, and Uttar Pradesh), faces chronic arsenic pollution in groundwater and surface water, affecting birds specially storks, being dependent on contaminated wetlands for feeding and nesting, and are becoming gradually vulnerable to arsenic bioavailability in aquatic food chains. This review synthesizes current research on arsenic exposure pathways in wetland ecosystems, focusing on its toxicological impact on Indian stork species such as the Painted Stork (Mycteria leucocephala), Asian Openbill (Anastomus oscitans), and Greater Adjutant (Leptoptilos dubius). Arsenic bio-accumulates in fish, mollusks, and amphibians, the primary food sources of storks, leading to chronic ingestion and toxicity. Sub-lethal effects include oxidative stress, immune-suppression, behavioral abnormalities, and reproductive dysfunction, such as low hatchability, chick deformities, and disrupted nesting patterns. In extreme cases, arsenic exposure has been associated with increased mortality and population decline. The review also highlights the ecological role of storks as bio-indicators of wetland health and the cascading effects of their decline on wetland biodiversity.***

Keywords: Arsenic contamination, Avian ecotoxicology, Bioaccumulation, Reproductive toxicity

1. Introduction

Wetlands are among the most productive ecosystems on earth, providing critical services such as water purification, flood regulation, nutrient cycling, and habitat for diverse flora and fauna. In India, wetlands support an astonishing variety of avifauna, including resident and migratory species. Among these, storks are large, wading birds belonging to the family Ciconiidae and are vital components of wetland ecosystems. However, these ecosystems are increasingly threatened by anthropogenic pollution, especially arsenic contamination. Arsenic is a naturally occurring metalloid, but its levels have become alarmingly elevated due to anthropogenic activities, especially in the eastern Gangetic plains. This contamination not only poses risks to human health but also severely disrupts ecological balance. In wetland ecosystems, arsenic enters the aquatic food chain, accumulating in fish, amphibians, and mollusks, the primary prey for storks. Chronic arsenic exposure in storks has far-reaching consequences including physiological stress, reproductive failure, behavioral anomalies, and ultimately, population decline. Here the article aims to provide a comprehensive overview of the sources and pathways of arsenic contamination, its toxicological impact on Indian stork species, and the broader implications for wetland biodiversity. It also highlights the urgent need for avian bio-monitoring, ecotoxicological studies, and conservation policies tailored to mitigate this overlooked environmental crisis.

2. Arsenic Contamination in Indian Wetlands

2.1 Sources and Distribution

Arsenic in India is primarily of geogenic origin, leaching from arsenopyrite-rich sediments in the Gangetic and Brahmaputra alluvial plains. Overextraction of groundwater for agriculture and drinking water purposes has led to the mobilization of arsenic into shallow aquifers. Major arsenic-affected states include West Bengal, Assam, Bihar, and Uttar Pradesh, with concentrations often exceeding the WHO limit of 10 μg/L [1]. In wetland regions, arsenic contamination is further aggravated by different types of sources

2.1.1. The discharge of arsenic-laden groundwater into wetlands is a critical pathway by which this toxic metalloid enters ecologically sensitive aquatic ecosystems. In many parts of the Indo-Gangetic plains, excessive groundwater extraction for irrigation and domestic use brings naturally occurring arsenic from deep aquifers to the surface. When this contaminated water is discharged into adjacent wetlands, either directly through drainage canals or indirectly via seepage, it introduces inorganic arsenic species (As^{3+} and As^{5+}) into the aquatic environment. These species are highly bioavailable and can undergo redox transformations, further influencing their mobility and toxicity [2]. The sustained inflow of arsenic-rich water alters the geochemistry of wetland sediments and promotes accumulation in biota, including plankton, benthic invertebrates, and fish, ultimately threatening higher trophic organisms such as birds. This process not only compromises the ecological integrity of wetlands but also poses long-term risks to biodiversity and public health.

2.1.2. Agricultural runoff is a significant contributor to arsenic contamination in wetland ecosystems, particularly in regions where arsenic-based agrochemicals have been historically or are still currently used. Compounds such as lead arsenate, monosodium methanearsonate (MSMA), and disodium methanearsonate (DSMA) were widely applied as pesticides and herbicides in paddy cultivation and other crop systems. During irrigation or rainfall events, these arsenic-laden residues are washed from agricultural fields into nearby water bodies, including wetlands [3]. Once in the aquatic environment, these compounds can dissociate, releasing inorganic arsenic species (arsenite and arsenate) that readily bind to sediment particles or remain dissolved in the water column. This runoff-driven contamination contributes to chronic arsenic exposure in wetland flora and fauna, particularly affecting primary consumers and biomagnifying through the food web. Furthermore, arsenic alters soil microbiota and nutrient cycling, compounding the ecological degradation of both terrestrial and aquatic systems.

2.1.3. Small-scale industries, particularly those involved in leather tanning, textile dyeing, metal smelting, and battery manufacturing, are important but often unregulated sources of arsenic pollution. These industries commonly use or generate arsenic compounds during processing, and due to inadequate wastewater treatment infrastructure, their effluents are frequently discharged directly into nearby water bodies, including wetlands. The effluents contain both trivalent (As^{3+}) and pentavalent (As^{5+}) forms of inorganic arsenic, which are highly toxic and bioavailable. In aquatic environments, these arsenic species interact with organic matter, sediments, and biota, leading to bioaccumulation in primary consumers like mollusks and fish. Over time, the persistent influx of arsenic-laden waste disrupts wetland ecology, affects microbial communities, and poses severe risks to higher trophic organisms such as storks.

2.1.4. The natural weathering and erosion of arsenic-rich geological formations, such as arsenopyrite (FeAsS) and other sulfide minerals, contribute significantly to baseline arsenic levels in wetland ecosystems. When these rocks are exposed to atmospheric conditions, especially in regions with high rainfall or fluctuating temperatures, chemical weathering processes like oxidation and hydrolysis release arsenic into surface runoff and groundwater. Over time, this arsenic is transported into adjacent wetlands through sediment-laden flows and river systems. In oxidizing environments, arsenic is primarily present as arsenate (As^{5+}), while in reducing, waterlogged conditions typical of wetlands, it transforms into the more toxic and mobile arsenite (As^{3+}). These dissolved arsenic species readily interact with wetland sediments, aquatic plants, and invertebrates, making them bioavailable to higher trophic levels [4]. Thus, even in the absence of direct anthropogenic pollution, geological processes can introduce significant arsenic loads into wetland food webs, posing long-term ecological risks to sensitive species like storks.

2.2 Bioavailability in Wetland Ecosystems

Arsenic exists in multiple chemical forms, primarily inorganic arsenite (As^{3+}) and arsenate (As^{5+}), both of which are toxic. In wetland sediments, arsenic can be released into the water column due to microbial activity, redox fluctuations, and changes in pH. It enters aquatic food chains through a number of ways.

2.2.1. Phytoplankton and macrophytes serve as the primary producers in wetland ecosystems and play a critical role in arsenic uptake from contaminated water. These aquatic plants absorb arsenic mainly through their root systems or cell membranes, mistaking arsenate (As^{5+}) for phosphate (PO_4^{3-}) due to their similar chemical structures [5]. Once inside plant tissues, arsenic interferes with essential metabolic pathways, disrupts photosynthesis, and induces oxidative stress. While some species can sequester or detoxify arsenic through chelation and compartmentalization, others accumulate significant amounts, transferring the toxin through the food web. Phytoplankton, being consumed by zooplankton and filter feeders, initiate the arsenic transfer to higher trophic levels, while macrophytes contribute to arsenic bioavailability in benthic and grazing organisms. This bottom-up contamination process has serious ecological implications, especially for wetland-dependent birds like storks, which feed on arsenic-laden aquatic organisms [6]. Thus, arsenic uptake by phytoplankton and macrophytes represents a key pathway in the ecological cycling and biomagnification of this toxic metalloid.

2.2.2. Benthic invertebrates such as snails, crustaceans, and aquatic worms play a pivotal role in arsenic transfer within wetland ecosystems. These organisms feed directly on arsenic-contaminated phytoplankton, periphyton, and decaying macrophytes, thereby absorbing arsenic through ingestion and dermal contact. Once ingested, arsenic accumulates in their soft tissues, especially in the digestive glands, where it disrupts cellular metabolism, enzymatic activity, and ion regulation [6]. The bioaccumulated arsenic may be present in both inorganic and organic forms, with inorganic species being significantly more toxic. As these invertebrates serve as a primary food source for higher trophic organisms, including fish and wading birds like storks, they act as efficient vectors of arsenic up the food chain. Moreover, because benthic invertebrates are in constant contact with sediment, often the primary reservoir of arsenic, they also absorb the metalloid directly from pore water and sediment particles, further intensifying their toxic burden. This dual exposure pathway makes them critical bioindicators and mediators of arsenic transfer in aquatic food webs.

2.2.3. Fish and amphibians are key intermediate consumers in wetland food webs and are particularly vulnerable to arsenic bioaccumulation through the consumption of benthic invertebrates. As these prey organisms harbor elevated levels of arsenic, absorbed from contaminated sediments, water, and plant matter, the toxicant is transferred up the trophic chain. In fish, arsenic accumulates primarily in gill tissues, liver, and muscle, interfering with osmoregulation, metabolism, and antioxidant defense mechanisms. Amphibians, due to their permeable skin and dual aquatic-terrestrial life stages, are doubly exposed, both through ingestion and dermal absorption [7]. Chronic arsenic exposure can disrupt amphibian development, impair endocrine function, and reduce survival and reproductive success. The persistence of arsenic in aquatic systems and its tendency to biomagnify with each trophic level raises serious concerns for predators that feed on these organisms, such as storks and other wading birds. This cascading toxic effect underscores the ecological significance of arsenic transfer from benthic invertebrates to higher vertebrates in wetland ecosystems.

2.2.4. Storks, as apex foragers in wetland ecosystems, primarily feed on fish, amphibians, mollusks, and crustaceans, organisms that often serve as reservoirs of arsenic due to their direct exposure to contaminated sediments and water. Through repeated consumption of these prey species, storks are subjected to trophic transfer of arsenic, whereby the toxicant moves up the food chain and accumulates in higher concentrations at successive trophic levels, a process known as biomagnification. Unlike primary consumers, storks receive a cumulative dose of arsenic from multiple prey items over time, leading to significant bioaccumulation in vital organs such as the liver, kidneys, and brain. This chronic exposure can result in a range of sub-lethal effects including oxidative stress, immune dysfunction, reproductive impairment, and behavioral abnormalities [8]. Thus, storks not only serve as sentinel species for arsenic pollution but also demonstrate how contaminants propagate and intensify through ecological networks.

3. Toxicological Effects of Arsenic on Storks

Arsenic exposure in storks leads to significant physiological and biochemical disruptions, including oxidative stress due to elevated reactive oxygen species (ROS) damaging cellular components. Hematological alterations such as anemia and leukopenia compromise immune competence, increasing susceptibility to infections. Reproductive toxicity is evident through eggshell thinning, hormonal imbalance, and reduced hatchability. Neurological and behavioral changes, such as impaired foraging and disorientation, hinder survival and reproductive success [9]. Collectively, these effects contribute to declining population trends and signal ecological stress within contaminated wetland habitats.

3.1 Physiological and Biochemical Effects

3.1.1 Oxidative stress is a major toxicological outcome of arsenic exposure in storks, resulting from the overproduction of reactive oxygen species (ROS) such as superoxide anions, hydrogen peroxide, and hydroxyl radicals. Arsenic interferes with mitochondrial respiration and redox cycling, disrupting cellular antioxidant defense mechanisms like glutathione peroxidase, catalase, and superoxide dismutase. The excessive ROS generated under arsenic stress causes oxidative damage to vital macromolecules, proteins undergo carbonylation, lipids undergo peroxidation, and DNA suffers strand breaks and base modifications [9]. These molecular insults impair cellular function, trigger apoptosis, and compromise tissue integrity, particularly in metabolically active organs such as the liver and kidneys. In storks, chronic oxidative stress may manifest as systemic weakness, organ dysfunction, and increased vulnerability to environmental stressors.

3.1.2. Arsenic exposure in storks has been shown to compromise immune function by suppressing both innate and adaptive immune responses. One of the key manifestations is a reduction in leukocyte (white blood cell) counts, including lymphocytes, monocytes, and heterophils, which are essential for pathogen recognition and elimination. Arsenic disrupts hematopoiesis in the bone marrow and impairs cytokine signaling pathways, leading to diminished immune surveillance and a weakened inflammatory response. Additionally, it alters the function of macrophages and dendritic cells, further compromising antigen presentation and immune activation [10]. As a result, storks exposed to chronic arsenic contamination become more susceptible to bacterial, viral, and parasitic infections, which can lead to higher morbidity and mortality rates, especially in polluted wetland environments. Hematological changes such as altered RBC and hemoglobin levels affect oxygen transport. Studies on waterbirds have found arsenic-related changes such as elevated glutathione peroxidase activity and DNA fragmentation, although data on storks remain limited.

3.2 Reproductive Impairments of Storks

3.2.1. Chronic arsenic exposure in storks has been linked to eggshell thinning, a critical reproductive impairment that significantly lowers hatchability rates. Arsenic disrupts calcium homeostasis by interfering with calcium-binding proteins and hormonal regulation, particularly affecting vitamin D metabolism, which is essential for calcium absorption and deposition in eggshell formation. It also inhibits carbonic anhydrase activity in the shell gland, an enzyme crucial for calcium carbonate synthesis, the primary component of eggshells. The resulting thinner shells are structurally weaker and more prone to breakage during incubation, leading to increased embryonic mortality [11]. This disruption in reproductive success contributes to declining stork populations in arsenic-contaminated wetland habitats.

3.2.2. Embryotoxicity caused by arsenic exposure is a significant concern in stork populations residing near contaminated wetlands. Arsenic readily crosses the placental barrier and accumulates in the developing embryo through maternal transfer into the egg. Inside the embryo, arsenic interferes with key developmental pathways by generating reactive oxygen species (ROS), disrupting DNA replication, and altering gene expression essential for organogenesis [9]. These toxic effects can result in structural deformities, impaired organ development, and increased rates of embryo mortality. The presence of arsenic in stork eggs has been correlated with reduced hatching success and deformities in hatchlings, threatening the long-term viability of affected populations.

3.2.3. Arsenic exposure in storks has been linked to hormonal disruption, particularly affecting the thyroid and reproductive endocrine systems. Arsenic interferes with the synthesis, secretion, and receptor binding of key hormones such as thyroxine (T4), triiodothyronine (T3), estrogen, and progesterone [12]. This endocrine disruption occurs through oxidative damage to hormone-producing tissues, inhibition of enzymes like deiodinases and aromatases, and alteration of hormone receptor sensitivity. In storks, impaired thyroid function can lead to developmental delays and metabolic dysregulation, while disrupted reproductive hormones may result in reduced fertility, altered mating behavior, and poor parental care. These hormonal imbalances ultimately contribute to declining reproductive success and population instability in arsenic-exposed wetland habitats. In species like the Painted Stork and Greater Adjutant, field observations have noted increased nest abandonment and reduced fledgling survival in polluted wetlands.

3.3 Behavioral and Neurological Disorders of Storks

Arsenic exposure has been associated with behavioral and neurological impairments in storks, significantly affecting their ecological fitness. Neurotoxic effects arise from arsenic-induced disruption of neurotransmitter function, oxidative damage to neural tissue, and interference with synaptic signaling pathways. These disruptions can cause disorientation, impaired spatial memory, and reduced motor coordination, thereby diminishing foraging efficiency and increasing energy expenditure. Furthermore, arsenic's interference with hormonal regulation, particularly prolactin and oxytocin, can weaken parental care behavior, resulting in neglected offspring and decreased chick survival. Altered circadian rhythms and endocrine dysfunction may also disrupt seasonal cues for migration and nesting, leading to mistimed breeding and habitat mismatch [13]. Collectively, these behavioral anomalies contribute to reproductive failure and population decline in arsenic-impacted stork populations.

4. Implications of arsenic pollution on stork on wetland biodiversity

4.1. Reduced bioindicator and Biomonitoring Potential

Storks serve as effective bioindicators for arsenic contamination in wetland ecosystems due to their high trophic status, long lifespan, and extensive foraging range across contaminated landscapes. These birds integrate arsenic exposure over time and space, making them suitable for both spatial and temporal monitoring of environmental pollutants [14]. Non-invasive sampling of feathers, eggshells, and blood provides valuable insights into arsenic bioaccumulation without harming the individual. Feathers, in particular, reflect long-term exposure, while blood indicates recent uptake, allowing for comprehensive biomonitoring. Elevated arsenic levels in these biological matrices correlate strongly with ecological risk, reproductive impairment, and physiological stress, highlighting the utility of storks as sentinel species for assessing wetland health and guiding conservation strategies.

4.1.1 Storks reflecting long-term ecological exposure trends.

Feathers of storks collected from arsenic-contaminated wetlands often exhibit elevated concentrations of arsenic, reflecting their prolonged exposure to polluted environments. As feathers are metabolically inert once formed, they serve as reliable indicators of arsenic accumulation during the period of feather growth. Studies have shown that arsenic levels in stork feathers correlate strongly with environmental concentrations in sediments and water, suggesting a direct link between habitat contamination and bioaccumulation [14]. This pattern of accumulation not only mirrors the trophic transfer of arsenic through the food web but also provides a non-destructive method for tracking long-term ecological exposure. Consequently, storks offer valuable insights into spatial and temporal trends of arsenic pollution in wetland ecosystems.

4.1.2. Reduced scavenging services (in species like Greater Adjutant).

Arsenic pollution in wetland habitats has been implicated in the decline of scavenging efficiency in species like the Greater Adjutant (*Leptoptilos dubius*), a critically endangered stork known for its ecological role in carcass disposal [15]. Chronic arsenic exposure compromises the health of these birds by impairing their immune systems, reducing foraging efficiency, and inducing behavioral abnormalities such as disorientation and lethargy. These effects diminish their ability to locate and process carrion, disrupting natural nutrient recycling and sanitation services in wetland ecosystems. Additionally, reduced reproductive success and increased mortality due to arsenic-induced toxicity contribute to population decline, further weakening their scavenging role. This decline in ecosystem service can have cascading effects on wetland health and public hygiene.

4.2 Loss of Keystone and Umbrella Species

Storks function both as keystone and umbrella species within wetland ecosystems, playing vital roles in maintaining ecological balance and biodiversity. As keystone species, they regulate populations of fish, amphibians, and invertebrates, preventing trophic imbalances and promoting habitat stability [16]. Simultaneously, their requirement for expansive, undisturbed wetlands with rich prey availability positions them as umbrella species, conserving stork habitats inherently safeguards numerous co-occurring species. Arsenic-induced decline of stork populations, due to reproductive failure, physiological stress, and behavioral impairments, threatens not only the species itself but also the integrity of the ecological networks they support. Their population collapse serves as an early warning of widespread ecosystem degradation and biodiversity loss.

4.3 Cascade effects on ecosystem and species diversity

The decline of stork populations due to arsenic pollution can trigger cascading ecological and socio-economic effects in wetland ecosystems. With fewer storks and associated predatory birds, fish populations often become imbalanced, leading to reduced grazing on phytoplankton and consequent algal blooms that degrade water quality and oxygen availability. This eutrophication disrupts aquatic food webs and negatively affects co-dependent avian species such as spoonbills and ibises that share similar foraging niches. Furthermore, the loss of charismatic storks, which attract birdwatchers and researchers, results in a decline in ecotourism, reducing local community income and weakening incentives for wetland conservation. Thus, arsenic contamination not only imperils storks but also undermines broader ecological stability and human livelihoods.

5. Conservation and Policy Recommendations

5.1 Strengthening Wetland Protection

Strengthening wetland protection is essential to mitigate the impact of arsenic pollution on stork populations and associated biodiversity. The enforcement of the Wetlands (Conservation and Management) Rules, 2017, provides a legal framework for preserving ecologically sensitive areas, but its implementation remains inconsistent, especially in arsenic-affected regions. Prioritizing these contaminated wetlands for Ramsar designation can elevate their conservation status, attract international attention, and secure funding for restoration and monitoring efforts. Scientifically, preserving these wetlands is critical, as they serve as natural biofilters, breeding grounds, and foraging habitats for storks and other species. Effective protection and management can reduce contaminant loads, restore trophic balance, and support the recovery of declining wetland-dependent fauna.

5.2 Arsenic Mitigation Strategies

Arsenic free wetlands are crucial for protecting stork populations from toxic exposure, and nature-based solutions offer sustainable pathways. Phytoremediation using native aquatic plants such as *Phragmites australis* and *Typha latifolia* has shown significant potential in arsenic uptake and stabilization through root absorption and rhizofiltration [17]. These plants can reduce arsenic concentrations in water and sediments, thereby lowering trophic transfer to aquatic prey consumed by storks. Additionally, the development of engineered constructed wetlands mimics natural filtration processes by combining vegetation, microbial action, and sediment interactions to trap and transform arsenic into less bioavailable forms. These eco-engineering approaches not only improve water quality but also restore critical habitats, offering a dual benefit for environmental remediation and avian conservation.

5.3 Avian Health Monitoring

Implementing long-term avian health monitoring programs is essential for assessing the impact of arsenic pollution on stork populations within India's wetland ecosystems. Continuous toxicological surveillance in arsenic hotspots can detect early physiological, reproductive, and behavioral anomalies in storks, providing critical data for targeted interventions. Establishing regional avian health indices, integrating metrics such as blood arsenic levels, immune function, reproductive success, and population trends can serve as effective tools for wetland health assessment and management. These indices enable early detection of ecological stress and guide adaptive conservation strategies, ensuring that mitigation efforts are evidence-based and responsive to real-time changes in avian and ecosystem health.

5.4 Community and Citizen Science

Engaging local communities through citizen science initiatives is a powerful approach to conserving storks and mitigating the effects of arsenic pollution in Indian wetlands. Community participation in nest monitoring and habitat restoration fosters stewardship and enhances data collection across remote or under-surveyed regions. Digital platforms like eBird and the India Biodiversity Portal enable widespread, real-time tracking of stork populations, migration patterns, and breeding success, contributing to robust datasets for ecological analysis. Scientifically, such grassroots involvement not only augments long-term biodiversity monitoring but also helps detect shifts in distribution or behavior linked to environmental stressors like arsenic contamination. Empowering local stakeholders ensures sustained conservation outcomes through awareness, education, and shared responsibility.

6. Conclusion

Arsenic contamination in Indian wetlands presents a multifaceted ecotoxicological challenge with profound implications for stork conservation and broader ecosystem integrity. As apex wetland foragers with high trophic exposure, storks experience bioaccumulation and bio-magnification of arsenic through contaminated food webs, resulting in oxidative stress, endocrine disruption, embryo-toxicity, and behavioral impairments. These sub-lethal and lethal effects contribute to declining reproductive success, reduced fitness, and population instability. The conservation of storks thus necessitates an integrated approach combining scientific research, bio-monitoring, habitat restoration, and stringent implementation of environmental policies. Protecting storks from arsenic pollution will not only secure the survival of these sentinel species but also reinforce the ecological health and resilience of India's wetland ecosystems, safeguarding biodiversity and ecosystem services for future generations.

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