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Original Article

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Development of a Correlation Model for Avian Botulism Outbreak in Sambhar Lake, Rajasthan, India

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Abstract: *Sambhar Lake, India's largest inland saline wetland and a Ramsar site, supports diverse migratory bird populations. In recent years, the lake has experienced significant environmental changes due to industrial activity, unregulated salt extraction, agricultural runoff, and wastewater inflow, altering key ecological parameters. These changes have led to recurrent outbreaks of avian botulism caused by Clostridium botulinum, resulting in large-scale bird mortality since 2019. Despite repeated incidents, there is a lack of predictive tools for outbreak assessment. This study based on data from Nawa region of Sambhar Lake develops a logistic regression-based correlation model to estimate outbreak probability and provide an early warning framework for effective management.*

Keywords: *Avian Botulism, Bird Mortality, Outbreak, Clostridium Botulinum, Sāmbhar Lake.*

INTRODUCTION

Sambhar lake spreads around 23000 hectares encompassing Deedwana-Kuchaman, Jaipur and Ajmer districts of Rajasthan, India. It is India's largest saline wetland and has been recognised as Ramsar site in 1990.The lake is fed by four seasons rivers namely Mendha, Rupangarh, Khariyan and Khandal forming a catchment of 5700 Km2.The legal status of Sambhar Lake is revenue area part of which has been leased out for salt making, accounting for 9% of the total salt production in India. Sāmbhar lake is rich in biodiversity and supports various local and migratory birds. Lesser and Greate flamingos are flagship species of the lake hosting several migratory birds in the winter. Arriving migratory birds use it as a stopover en-route or spend entire winter months there. A total of 83 waterfowl has been recorded in Sambhar.

The lake ecosystem attracts various migratory birds like Flamingos, Norther Shoveler and Common coot etc. Many of these migratory birds have become resident in the lake habitat. Adjoining Nawa (Deedwana-Kuchaman district) has become key hub of common salt producing industries. With access to canal water and new methods of water conservation techniques, agriculture activity has quite paced adjoining the lake area. Sāmbhar lake witnessed first reported mass outbreak of Avian botulism in migratory birds in year 2019 leading to a total casualty of around 19000.Avian botulism has spread due to growth of pathogen

Clostridium botulinum bacteria. Bird deaths due to Avian botulism have been reported in year 2024-25 and 2025-26 too.

FEATURES OF AVIAN BOTULISM SPREAD

Avian botulism is caused by bacteria named Clostridium botulinum. The bacteria produce botulinum neurotoxins (BoNTs) blocking neurotransmitter acetylcholine st synaptic junctions leading to paralysis affecting skeleton muscles of legs, wings neck, and death in migratory birds. Avian botulism is caused by ingestion of contaminated feed, water and litter and spreads in birds through consumptions of infected maggots. Clostridium botulinum is a soil bacterium. Its spores can survive in most environments and are very hard to kill. It is widely distributed in nature and can rapidly multiply in anaerobic conditions with optimum environmental conditions. Some of key limiting factors of its growth are:

Table 1: Table showing Clostridium botulinum growth conditions.

Parameter	Good growth	Complete inhibition
pH	6.5-8.5	<4.6,>9
Dissolved Oxygen	Anerobic	>2.5mg/L
Salinity (critical)	≤3.9-4.6%	~5.5-6.2%
Organic matter	Planktons, Nitrogen and phosphate presence leads to increased microbial respiration leading anoxic condition	

Avian botulism is recognized as a major cause of mass mortality events in wild bird populations worldwide, particularly among waterfowl. In North America, especially in wetland ecosystems and the Great Lakes, outbreaks have resulted in the death of over one million birds within a single year. Similar large-scale mortality events have been documented across Europe, Asia, Africa, and Australia, often associated with environmental disturbances such as heavy rainfall, fish die-offs, and the presence of shallow inland wetlands.

I. Anza *et al.* [1] established that in the Mediterranean region, susceptibility to Avian botulism intoxication varies considerably among species and habitats. This variability is quite reflected in waterfowl mortality data from Sambhar, indicating differential vulnerability linked to ecological and environmental conditions. The risk of Avian botulism increases substantially in wetlands receiving urban wastewater effluents. Elevated water temperatures, coupled with increased invertebrate biomass, can attract large congregations of waterbirds for feeding, thereby amplifying the likelihood of botulism outbreaks as reported by Ibone Anzaa *et al.* [2]. Kavita Singh *et al.* [3] reported that several environmental factors facilitate mass mortality events associated with avian botulism. These include low salinity, water temperatures exceeding 25°C, pH levels ranging between 7 and 9, dissolved oxygen concentrations below 4 mg/L, and the abundance of crustaceans and plankton, which contribute to toxin transmission within aquatic food webs.

Furthermore, a significant positive association has been observed between the number of bird carcasses recorded during botulism outbreaks and the mean temperature in July in the Mediterranean region as reported by Dolors Vidal *et al.* [4] Key environmental determinants influencing outbreak dynamics include temperature, substrate salinity, pH, and redox potential, all of which play critical roles in the proliferation of Clostridium botulinum and toxin production [5].

AVIAN BOTULISM OUTBREAK IN SAMBHAR LAKE

Adjoining places of the Sambhar lake region has undergone massive industrialization of common salt-based industries. Many of these salt industries get saline water from illegal borewells in the lake. Massive unregulated salt water extraction from the lake has detrimental effect on lake ecosystem. Municipal drainage and industrial discharge have increased organic overload of the lake [6]. Use of fertilizers rich of Nitrate and Phosphate in nearby agriculture fields added with excessive rainfall has led to mixing nutrient rich water in lake which has in turn created conditions of eutrophication, plankton growth and thus increasing biotic load in form of phytoplankton and fishes which has creates conditions of anerobic growth conditions of Clostridium botulium [7]. High rainfall years of 2019 ,2024 and 2025 lead to reduced salinity of the lake. Added with optimum temperature conditions, optimum serile conditions got created for growth of Clostridium botulinum.

High rainfall years, low salinity, higher organic load and high temperature conditions provide ideal conditions for outbreak of Avian botulism. For example, in year 2025, Sambhar lake region received excessive rainfall and flooding. It led massive mixing of organic and nutrient in the lake which led to growth of planktons and fishes. In high temperature of October, the water evaporation started leading to increase in salinity and lower dissolved oxygen conditions aggravated by bacterial respiration leading to anaerobic conditions and growth of Clostridium botulinum.

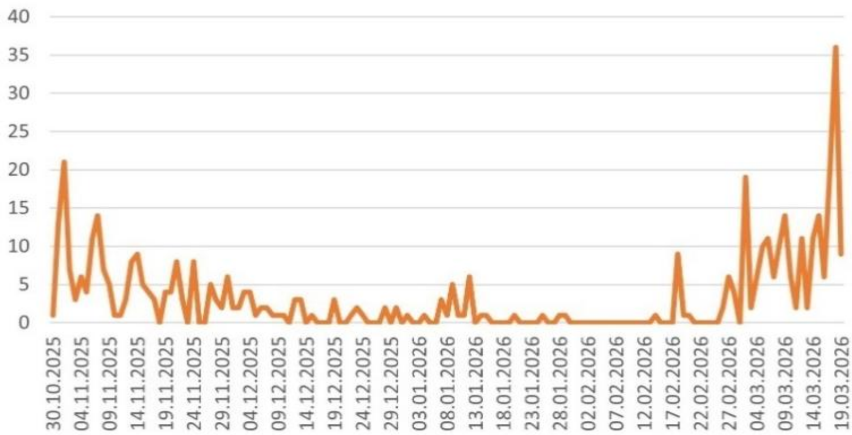

Figure 1: Represents waterbird deaths in Sambhar Lake Year 2025-26.

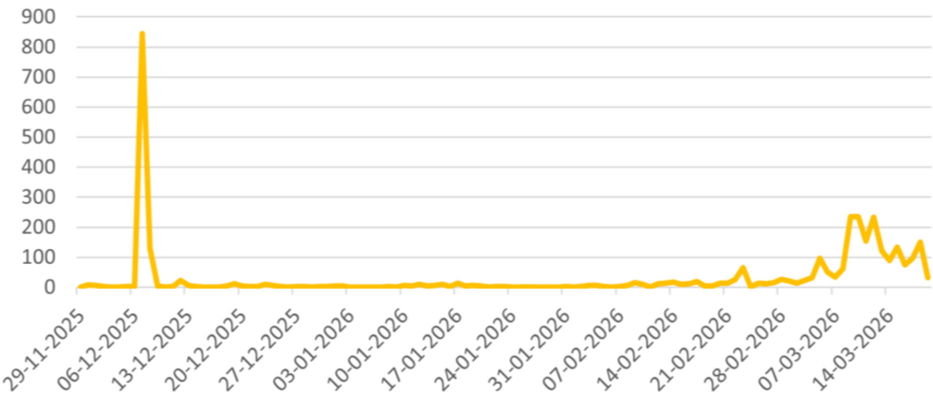

Figure 2: Represents fish deaths in Sambhar Lake Year 2025-26.

Under the scenario, a correlation model of probability of Avian botulism can developed.

AVIAN BOTULISM OUTBREAK CORRELATION MODEL

Factors affecting growth of Clostridium botulinum bacteria are functions of rainfall, temperature, organic/fish load present in the lake at any moment of time [8]. Under the case, the Logistical regression model fits the case. The best fit logistical regression model can be used to estimate Avian botulism outbreak probability as follows:

$$\mathrm{P}(outbreak) = 1/\left(1 + e^{(-\mathrm{Zt})}\right) \quad \ldots (1)$$

Where as:

$$\mathrm{Z_t} = \beta 0 + \beta 1 R_t + \beta 2 F_t + \beta 3 T_t + \beta 4 R_t F_t + \beta 5 P_{t-1} \quad \ldots (2)$$

Where,

- P_t: Probability of outbreak in month 't'
- R_t: Rainfall (mm, monthly)
- F_t: Fish/biomass mortality index (0-1: low mortality; 1-2: moderate decay; 2-3: severe dieoff/toxin amplification)
- T_t: Temperature (°C)
- P_{t-1}: Previous month outbreak probability (carry-over effect as the toxin build up and carcass decay happen over time)

The coefficients β can be found using Maximum Likelihood Criteria as per:

$$Pi = 1/1 + e^{-Zi} \quad \ldots (3)$$

$$\text{Where, } Z_i = \beta 0 + \beta 1 X_{1i} + \ldots + \beta_k X_{ki} \quad \ldots (4)$$

For binary output Y_i belonging to (0,1)

$$\text{Likelihood functions is } L(\beta) = \prod_{k=1}^{n} P_k{}^{y}{}_{i} (1-P_i)^{1-yi} \quad \ldots (5)$$

$$=> \frac{\partial log(L(\beta)}{\partial \beta j} = \sum_{i=0}^{n} (Yi - Pi) X_{ij} = 0 \quad \ldots (6)$$

With that iteration using Newton-Raphson method, it leads to:

$$Z_t = -2.90 - 0.036 R_t + 1.76 F_t + 0.081 T_t + 0.044 R_t F_t + 0.65 P_{t-1} \quad \ldots (7)$$

Now with normalized data for year 2024-25 and 2025-26 the joint outbreak probability can be best fit as per Table 2.

Table 2: Table showing $P_{outbreak}$ against various parameters.

Month	R_t	T_t	F_t	$P_{outbreak}$
August	220	28	0.9	0.48
September	10	30	0.8	0.41
October	5	32	1.5	0.67
November	2	28	2.3	0.78
December	0	24	2.0	0.74
January	0	20	1.6	0.66
February	0	24	1.8	0.69
March	0	30	2.4	0.81

With $P_{outbreak}$ in mind monthly risk curve for year 2024-25 and 2025-26 fits well with the proposed model Figure 3.

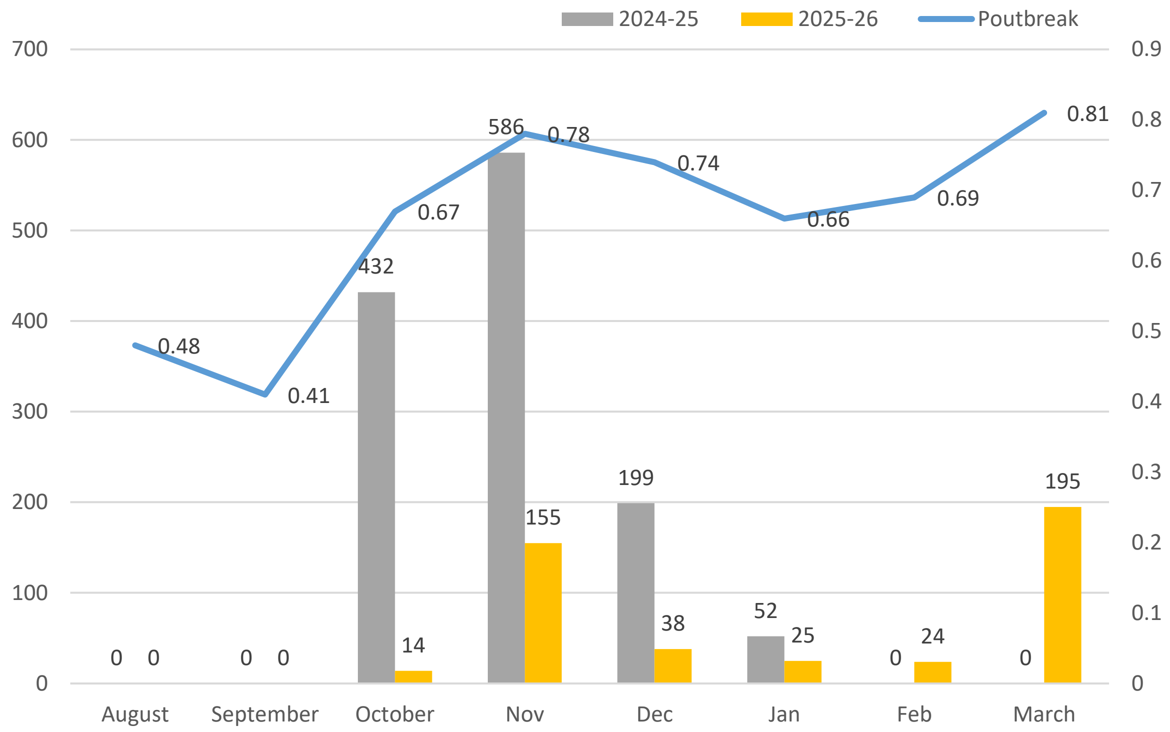

Figure 3: Shows waterbird death in Sambhar Lake vs $P_{outbreak}$ curve.

Month	$P_{outbreak}$	Risk level	Key driver
September	0.41	Moderate	Rainfall stops, start of decay and early exposure and arrival of migratory birds
October	0.67	High	Excess heat, decay of organic and biotic load leading to oxygen depletion
November	0.78	Very high	Peak toxin amplification by rapid growth of Clostridium botulinum
December	0.74	Very high	Sustained anaerobic conditions and toxin amplification
January	0.66	High	Residual toxin recycling, carcass leading to maggots and bird cycle fully active
February	0.69	High	High temperature and sustained anaerobic conditions. carcass leading to maggots and bird cycle fully active
March	0.81	Extreme	Maximum stress, sustained anaerobic conditions and outmigration of birds

Key Management Lessons

Whenever, $P_{outbreak}$ crosses 0.5, bird death is being reported in successive years. Hence an early action strategy is as follows:

Table 4: Table showing actionable strategy outcome in various months.

Month	Action
September	Start surveillance of the lake immediately, periphery to be segmented and teams to be formed
October	Deployment of dead bird carcass removal teams, early and immediate removal of carcass to stop maggot formation and birds feeding on them
November	Full emergency response of carcass removal process to break the maggot cycle, fishes to be removed on priority as dead fishes become new host
December	Full emergency response of carcass removal process to break the maggot cycle, fishes to be removed on priority as dead fishes become new host
January	Monitoring extreme toxicity and fishes to be removed on priority as dead fishes become new host
February	Full emergency response of carcass removal process to break the maggot cycle, fishes to be removed on priority as dead fishes become new host
March	Full emergency response of carcass removal process to break the maggot cycle, fishes to be removed on priority as dead fishes become new host

CONCLUSION

The derived correlation model establishes the probability of Avian botulism outbreak in Sambhar Lake with environmental parameters like temperature, rainfall and fish mortality index. It comes out with a handy prediction tool for field managers and stakeholders engaged in Avian botulism management in Sambhar Lake. Rajasthan state Sambhar Wetland and Management Authority has come out with Standard Operating Procedures for management of Avian botulism. However, the Standard Operating Procedure need to take various environmental factors into account for better management strategies. The established correlation model and probability outbreak index may serve in enhanced management of Avian botulism outbreak in Sambhar Lake.

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