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Impact of tropical monsoon forcing on foraminiferal distribution patterns within Chilika Lagoon

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Abstract

As biological proxies, benthic foraminifera are essential for interpreting environmental changes in coastal zones. Their community structure reflects a complex mix of salinity, oxygen, and hydrodynamic forces. Chilika Lagoon provides a prime example of a monsoon-dominated system where environmental boundaries are constantly shifting. This study synthesizes diverse datasets to test whether traditional lagoonal models hold true in such volatile tropical climates. The findings reveal that monsoon-induced salinity fluctuations and trophic forcing dictate species distribution. Meanwhile, the TROX model accurately explains how oxygen penetration and organic supply control sub-surface tiering. We also observed that discrepancies between living and dead shells are largely due to sediment reworking. Compared to temperate lagoons, monsoon-governed systems are defined by their rapid seasonal transitions. This has significant implications for monitoring, as natural "seasonal eutrophication" can often be mistaken for anthropogenic stress. This review establishes a robust basis for paleoenvironmental research in monsoonal regions and calls for more detailed time-series data to track ecosystem health amid a changing climate.

Keywords: Benthic Foraminifera; Chilika Lagoon; Monsoon-Dominated Lagoon; Environmental Proxies; TROX Model; Paleoenvironmental Reconstruction

1 Introduction

Marginal-marine settings rank among the most reactive sedimentary systems due to their position at the interface of terrestrial and oceanic influences. Within these dynamic habitats, benthic foraminifera function as reliable bioindicators because their brief life cycles and high fossilization potential are coupled with a sensitive "fingerprint" of specific environmental needs. [1] [2] [3] [4]. Because their composition is an integrated reflection of various environmental pressures, these assemblages offer a more holistic tool for modeling complex sedimentary environments than single-factor proxies[5] [6].

Current ecological models for lagoons often rely on data from mid-latitude regions. Consequently, these models reflect the steady hydrological states characteristic of temperate climates rather than more volatile systems [7] [8] [9]. Conversely, lagoons influenced by tropical monsoons experience dramatic seasonal shifts. These systems are defined by fluctuating levels of freshwater runoff, nutrient availability, and sediment deposits, alongside varying degrees of oceanic exchange [10] [11] [12]. Owing to its shifting inlet and massive seasonal freshwater pulses, Chilika Lagoon serves as a premier example of these highly fluid aquatic systems [13][14]

The primary objectives of this review are to synthesize existing ecological, sedimentological, and geochemical data regarding Chilika Lagoon to provide a comprehensive understanding of its current state. Building upon this synthesis, the study aims to identify the dominant environmental controls that dictate benthic foraminiferal distribution within

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the system. Furthermore, the review evaluates how effectively classical lagoonal models apply to monsoon-dominated environments, ultimately seeking to develop a process-based conceptual framework designed for both ongoing environmental monitoring and accurate paleoenvironmental reconstruction.

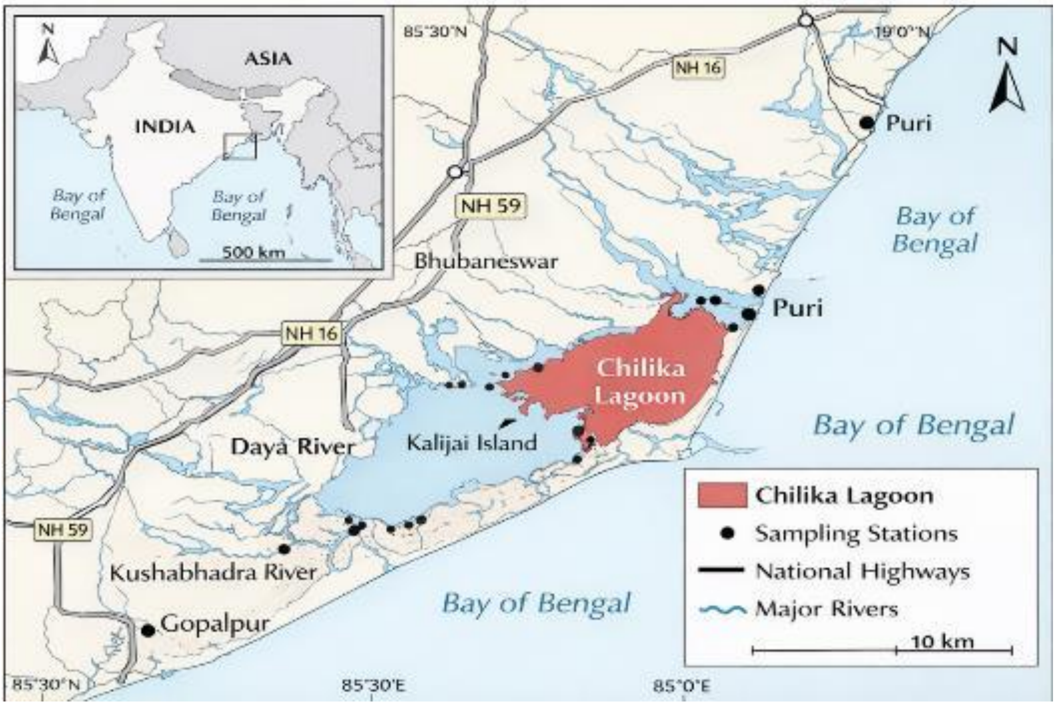

Figure 1 Location map of Chilika Lagoon along the east coast of India**.**

1.1 Study Area

Chilika Lagoon, situated along the east coast of India in the state of Odisha, is a sprawling brackish water ecosystem and the largest coastal lagoon in Asia. As shown in the provided map, the system is situated between latitudes 19°28' N and 19°54' N and longitudes 85°05' E and 85°38' E. The lagoon is a highly complex transition zone between terrestrial and marine environments. It is bordered by the Bay of Bengal to the east and receives significant continental input from several major river systems.

The hydrology, salinity variability and sediment distribution of Chilika Lagoon have been described in several earlier investigations [15] [16] [17]. Remote sensing and geomorphological studies demonstrate the long-term instability of the tidal inlet and its role in controlling lagoonal circulation and ecological zonation [18] [19] [20].

The remainder of this paper is organized as follows. Section 2 details the literature review. Section 3 describes the proposed methodology and experimental setup. Section 4 presents and discusses the experimental results. Section 5 concludes the study and outlines future research directions.

2 Methodology and Data Synthesis

This review synthesizes existing research on Chilika Lagoon's ecology, hydrodynamics, and geochemistry. We also examined similar monsoon-driven coastal environments. Using Web of Science, Scopus, and Google Scholar, we sourced relevant papers through targeted keyword searches. These terms included "benthic foraminifera," "monsoon variability," and "environmental proxies." Our criteria were strict: we only included studies that offered solid quantitative or semi-quantitative data. The selected literature includes peer-reviewed journal articles, monographs and authoritative technical reports. Data were evaluated in terms of salinity range, sediment texture, total organic carbon, dissolved oxygen, species composition and diversity, living-dead assemblage relationships. A process-based interpretative approach was adopted in which faunal patterns were analysed in relation to environmental gradients rather than as isolated distributional records.

2.1 Data Standardization and Selection Bias

To ensure a robust meta-analysis, we implemented a rigorous standardization protocol to address potential sources of error in foraminiferal data comparison.

A primary challenge in synthesizing lagoonal datasets is the inconsistency in sieve fractions, specifically the use of 63 μm vs. 125 μm mesh sizes. The 63 μm fraction often captures smaller, opportunistic species like *Ammonia* juveniles or certain *Bolivinids* that are missed by the 125 μm sieve. To mitigate this bias, we categorized the selected studies into two sub-groups based on their processing methodology. Where quantitative comparisons were made across the entire lagoon, we focused on the relative abundance (%) of major taxa rather than absolute density, as the dominant trends in assemblage shifts are generally preserved across both size fractions in these high-energy monsoonal settings.

We differentiated between Living (Rose Bengal stained) and Total (Dead + Living) assemblages to account for varying temporal resolutions.

- Living assemblages were utilized to interpret modern, seasonal responses to monsoonal pulses (e.g., immediate freshening).
- Total assemblages were used to provide an integrated signal of the annual cycle and to account for the impact of taphonomic processes and sediment transport. By analyzing these separately, we avoided the common error of treating "snapshot" living data as a representative long-term environmental proxy.

To minimize selection bias, we excluded studies that relied solely on qualitative descriptions. We prioritized research that provided concurrent environmental data (salinity, TOC, and dissolved oxygen). Furthermore, to account for "publication bias" (where only significant results are published), we included datasets from gray literature and regional reports from the Chilika Development Authority (CDA), ensuring the synthesis reflects the lagoon's full spatial variability rather than just "hotspots" of high diversity.

3 Methodology flow chart

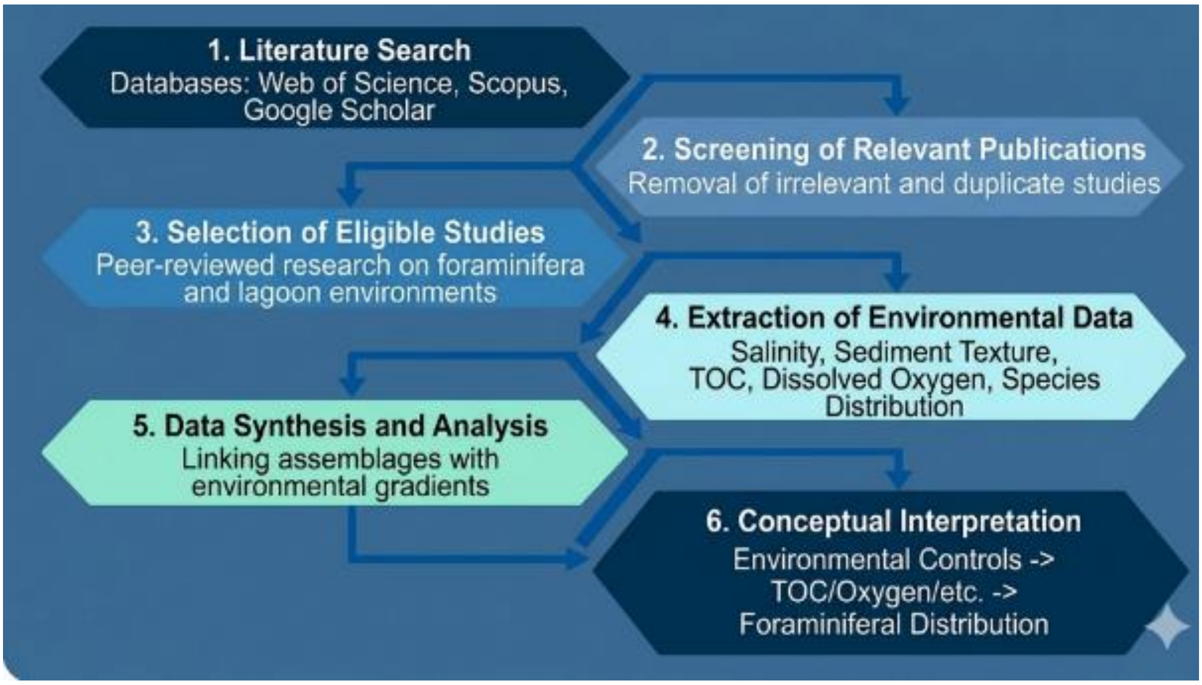

Figure 2 Methodological workflow illustrating the literature screening, data extraction and synthesis process used to evaluate environmental controls on benthic foraminiferal assemblages in Chilika Lagoon

3.1 Environmental controls on foraminiferal distribution

Although salinity has traditionally been regarded as the primary controlling factor, several studies have demonstrated the importance of organic-matter flux and substrate character[21], [22]. The dominance of *Ammonia beccarii* in finegrained, organic-rich sediments reflects eutrophic and oxygen-deficient conditions [23], [24] . *Elphidium* species are typically associated with moderately energetic mixing zones [25], [26]. Agglutinated taxa characterise low-salinity, restricted environments [27], [28], [29].

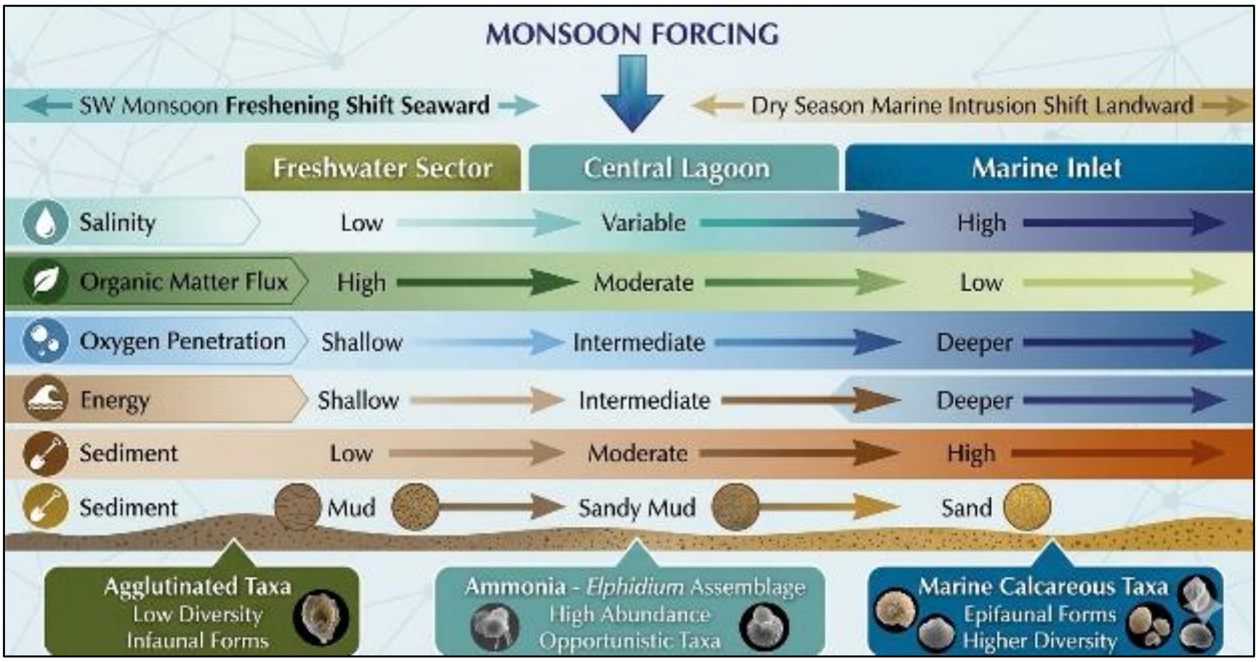

Figure 3 Conceptual model illustrating monsoon- driven environmental gradients in Chilika Lagoon and their control on benthic foraminiferal distribution

Table 1 Environmental controls on benthic foraminiferal assemblages in Chilika Lagoon.

Environmental parameter	Lagoon sector	Sediment / water characteristics	Dominant taxa / assemblage	Microhabitat	Environmental interpretation
Very low salinity (<10 PSU)	Inner lagoon	Clay-silt, high TOC	Ammobaculites, Trochammina [30], [31]	Infaunal	Restricted circulation
Fluctuating salinity (10-25 PSU)	Central lagoon	Muddy sand, nutrient-rich	Ammonia-Elphidium [32][22]	Shallow infaunal	Eutrophic, unstable
Marine salinity (>25 PSU)	Outer channel	Sand, low TOC	Miliolids, rotaliids [22] [33]	Epifaunal	Marine exchange
High organic flux	Inner lagoon	Organic-rich mud	Ammonia beccarii [22]	Infaunal	Dysoxic (TROX)
Low hydrodynamic energy	Sheltered sector	Fine sediment	Agglutinated taxa[30]	Infaunal	Low circulation
High hydrodynamic energy	Tidal inlet	Coarse sand	Marine calcareous taxa [33]	Epifaunal	Strong tidal currents

TOC = Total organic carbon.

The observed relationship between environmental gradients and benthic foraminiferal assemblages in Chilika Lagoon. The distribution pattern reflects monsoon-driven salinity variability, organic-matter flux, oxygen availability and hydrodynamic exchange as shown in Table 1.

4 Microhabitat tiering and oxygen dynamics

The vertical distribution of benthic foraminifera is controlled by the balance between food supply and oxygen penetration [34][35][36][9]. The TROX model predicts a shift from epifaunal to infaunal taxa with increasing organic flux [37] [32] [38]. Similar relationships have been observed in monsoon-influenced environments [39]. These relationships demonstrate that microhabitat distribution in monsoon-dominated lagoons is governed by seasonal shifts in organic-matter flux and bottom-water ventilation rather than by static bathymetric zonation.

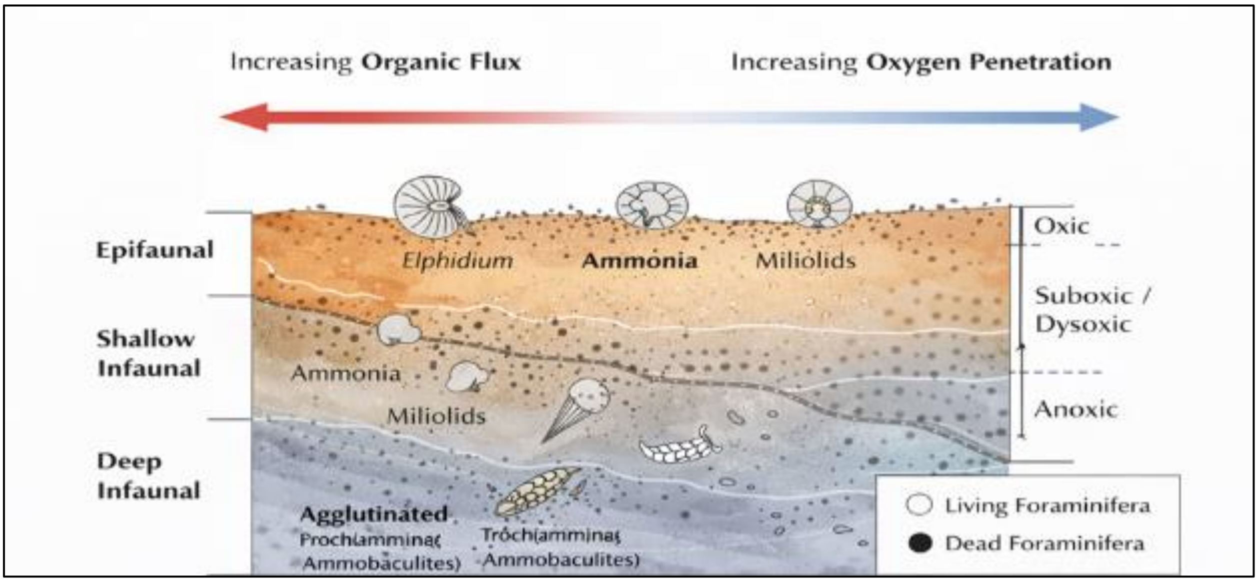

Figure 4 TROX **-** based microhabitat tiering of benthic foraminifera in relation to organic flux and bottom- water oxygenation

5 Taphonomy and hydrodynamic connectivity

Transport and reworking of tests are common in lagoonal systems affected by tidal exchange and inlet migration[13] [40]. The relationship between living and dead assemblages therefore provides a reliable proxy for hydrodynamic connectivity and sediment redistribution [41] [42].

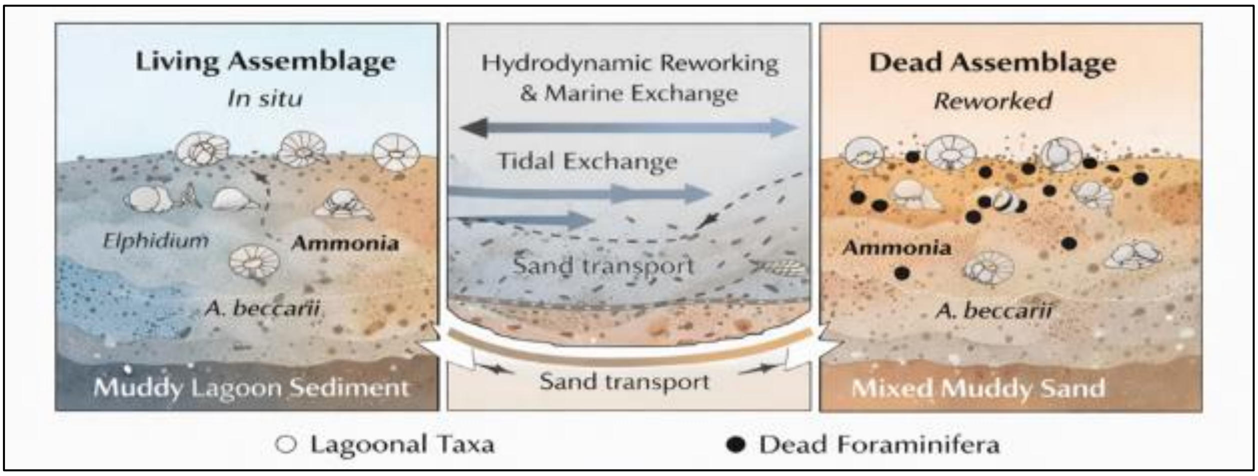

Figure 5 Conceptual model illustrating the relationship between living and dead foraminiferal assemblages in mobile lagoonal settings

6 Chilika lagoon in the context of global lagoonal models

Comparative studies indicate that tropical lagoons differ significantly from temperate systems in terms of salinity variability, trophic structure and oxygen dynamics [43] [44] [45]. Seasonal flushing and inlet migration produce time-transgressive ecological gradients that are rarely observed in permanently open lagoons[46] [47]. The Chilika system therefore represents a dynamic end-member in which ecological gradients are time-transgressive and seasonally reorganised.

Table 2 Comparison of Chilika Lagoon with global lagoonal systems

Environmental aspect	Temperate lagoons	Open tropical lagoons	Chilika Lagoon (monsoon-dominated)
Hydrology	Stable [48]	Marine dominated [49]	Seasonally reversing[50] [51]
Salinity	Persistent zonation	Near-marine	Highly fluctuating
Organic flux	Moderate	Low-moderate	Seasonal pulses [52]
Dominant assemblage	Marsh taxa	Calcareous marine	Ammonia- Elphidium [22]
Taphonomy	Autochthonous	Mostly autochthonous	Mixed assemblages [53]
Sea-level reconstruction	Reliable [24]	Reliable	Hydrodynamically overprinted

Comparison of environmental controls on benthic foraminiferal distribution in Chilika Lagoon with temperate and permanently open tropical lagoonal systems, highlighting the distinctive influence of monsoon-driven hydrological variability as shown in Table 2.

7 Environmental stress and ecosystem recovery

Reduced diversity and dominance of opportunistic taxa are widely used as indicators of pollution [54] [55] [56]. However, seasonal faunal recovery in Chilika Lagoon suggests that low diversity may represent natural monsoon-driven eutrophication rather than persistent anthropogenic stress [57]. This distinction is critical for environmental assessment programmes because misinterpretation of naturally stressed assemblages may lead to overestimation of anthropogenic impact.

8 Paleoenvironmental and sea-level implications

Modern foraminiferal assemblages are widely used for reconstructing Holocene sea-level change [58]. In monsoon-dominated lagoons, however, hydrodynamic reorganisation may produce vertical faunal successions that mimic sea-level signals [13].

9 Climate change relevance

Projected changes in monsoon intensity, river discharge and nutrient loading are likely to modify carbonate saturation, organic-carbon burial efficiency and the agglutinated-to-calcareous ratio in lagoonal sediments, thereby altering the long-term preservation potential of environmental proxy records [53] [21]

10 Discussion

- Contradicting the Temperate Paradigm
- The TOC Burial Contrast: Chilika vs. Temperate Systems

While temperate lagoons like the Venice Lagoon (Italy) or Pamlico Sound (USA) are often characterized by stable, long-term accumulation of Total Organic Carbon (TOC), the monsoon-dominated Chilika system operates under a “pulse-and-flush” regime. In temperate settings, TOC burial is typically a function of high primary productivity and slow, anaerobic degradation. However, in Chilika, the massive seasonal freshwater discharge acts as a scouring mechanism.

This leads to a distinct geochemical signature;

Temperate Lagoons: Exhibit steady-state TOC burial with predictable foraminiferal colonization based on organic enrichment.

Monsoonal Lagoons: Experience episodic "export" of organic matter to the Bay of Bengal.

Consequently, foraminiferal assemblages in Chilika are not just reflecting the amount of available food, but rather the residence time of that organic matter, which is strictly controlled by the monsoonal clock. This suggests that in tropical systems, TOC as a proxy must be interpreted through the lens of hydrodynamic energy rather than just productivity.

10.1 Critical Evaluation of the Ammonia-Elphidium (A-E) Index

The Ammonia-Elphidium index, a standard proxy for hypoxia and paleosalinity in temperate estuaries, faces significant challenges when applied to monsoonal settings. In the stable salinity gradients of the North Atlantic, a shift toward Ammonia dominance often signals anthropogenic eutrophication or increasing restriction.

In contrast, our synthesis indicates that in Chilika:

- **Salinity Extremes**: The "freshening shift" during the SW Monsoon can drop salinity to near-zero, favoring agglutinated taxa over both *Ammonia* and *Elphidium*.
- **Opportunistic Spikes**: *Ammonia* blooms in Chilika often represent a rapid response to "natural" seasonal nutrient pulses rather than persistent human-induced stress.

Using the A-E index without adjusting for these monsoonal "shocks" would lead to an overestimation of environmental degradation. Therefore, we propose that in monsoonal systems, the A-E index must be supplemented by the **Agglutinated-to-Calcareous ratio** to accurately capture the transition between freshwater-dominated and marine-dominated phases.

11 Conclusions

Chilika Lagoon demonstrates that foraminiferal distribution in monsoon-dominated coastal systems is controlled by seasonally mobile environmental gradients rather than by fixed ecological zonation. Salinity variability, organic-matter flux and episodic marine connectivity represent the primary drivers of assemblage composition, while microhabitat tiering follows the TROX model. The living-dead relationship reflects hydrodynamic reworking and provides a proxy for lagoonal connectivity. These characteristics distinguish monsoonal lagoons from temperate systems and require region-specific environmental calibration. The process-based framework developed here enhances the reliability of both modern environmental assessment and paleoenvironmental reconstruction in marginal-marine successions formed under strongly seasonal climatic regimes.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

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