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Ecological-Isotopic Evidences for Deglacial to Holocene Changes in Arabian Sea Denitrification and Oxygenation

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Abstract

The Arabian Sea hosts one of the most intense and perennial oxygen minimum zones (OMZs) in the world ocean, where water-column denitrification removes a substantial fraction of global marine fixed nitrogen. This review synthesizes ecological and isotopic evidence from bulk sedimentary nitrogen isotopes ($\delta^{15}N$), foraminifera-bounded nitrogen isotopes (FB-$\delta^{15}N$), benthic foraminiferal assemblages, and geochemical proxies to reconstruct changes in Arabian Sea denitrification and oxygenation from the Last Glacial Maximum (LGM- ~26.5 - 19 ka) through the Holocene (~11.7 ka to present). Multi-proxy evidence shows that the glacial Arabian Sea OMZ was moderately better oxygenated than present, with reduced water-column denitrification evidenced by low bulk $\delta^{15}N$ values and more diverse, oxic-tolerant benthic foraminiferal communities. The transition from the last glacial period was marked by a significant peak in $\delta^{15}N$, indicating increased denitrification due to enhanced monsoon-driven productivity and reduced ventilation of intermediate waters. Throughout the Holocene, the OMZ became more pronounced, as evidenced by consistently high $\delta^{15}N$ levels and low-diversity of benthic communities adapted to low-oxygen conditions. A significant ongoing discussion revolves around the interpretation of bulk sediment $\delta^{15}N$ compared to FB-$\delta^{15}N$ records, with the latter indicating similar denitrification rates during the LGM and late Holocene. We have identified two distinct oxygenation patterns over the last ~43,000 years: stable phases (LGM, Holocene) and unstable phases (MIS 3) characterized by centennial- to millennial-scale fluctuations, likely influenced by Dansgaard-Oeschger cycles and variations in the Atlantic Meridional Overturning Circulation.

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Keywords

Arabian Sea, Oxygen Minimum Zone, Denitrification, Nitrogen Isotopes, Benthic Foraminifera, Deglaciation, Holocene, Palaeoceanography

1. Introduction

The Arabian Sea holds a unique position in the global ocean biogeochemical landscape. Its intense, wind-driven monsoonal upwelling fuels some of the highest primary productivity rates in the open ocean. Combined with sluggish intermediate-water ventilation, this sustains a perennial oxygen minimum zone (OMZ) that ranks among the most severe in the world [1] [2]. In the Arabian Sea's OMZ, the concentration of dissolved oxygen drops below 5 μmol/kg, which is the critical level for denitrification to occur in the water column. This makes the Arabian Sea one of the three major oceanic zones where this process is observed, along with the eastern tropical regions of the North and South Pacific.

Denitrification within the water column serves as the primary process for the removal of fixed nitrogen (N) from the ocean, significantly affecting global marine productivity and the carbon cycle [3] [4]. This process tends to eliminate the lighter isotope ^{14}N in the form of N_2 gas, leading to an enrichment of ^{15}N in the remaining nitrate pool. The isotopic signature is then passed through the food web into sinking particulate organic matter and eventually into sediments, where it is preserved as an archive of past denitrification intensity [5] [6].

The late Quaternary period, which includes the Last Glacial Maximum (LGM, approximately 26.5 - 19 ka), the last deglaciation (Termination I, around 19 - 11.7 ka), and the Holocene (from about 11.7 ka to the present), serves as a natural setting for examining the sensitivity of OMZ to climate change. During this time, both orbital and suborbital climate disturbances led to significant alterations in monsoon intensity, intermediate water movement, sea levels, and atmospheric CO_2 factors that are pertinent to future climate predictions. Understanding how Arabian Sea denitrification and oxygenation reacted to these past climate variations is crucial for validating biogeochemical models and comprehending the ocean's nitrogen cycle under evolving boundary conditions.

In this review, published literature from 1994 to 2026 was systematically examined using Web of Science, Scopus, and Google Scholar, focusing on keywords associated with Arabian Sea denitrification, OMZ palaeoceanography, nitrogen isotopes, and changes from the deglacial to the Holocene period. The selection of studies was based on their temporal span (~40 - 0 ka), the presence of quantitative proxy data from accurately dated sediment cores, their geographical relevance to the Arabian Sea and its marginal basins, and the reliability of their age models. Conflicting proxy records were assessed by considering diagenetic stability, agreement among multiple proxies, and spatial replication. In cases where proxy signals differed, uncertainties and alternative interpretations were clearly addressed.

This review synthesizes extensive ecological and isotopic data gathered over thirty years of paleoceanographic studies in the Arabian Sea. Our emphasis is on proxy records from the deglacial to Holocene periods, combining nitrogen isotopes from both bulk samples and foraminifera, benthic foraminiferal faunal assemblages, and emerging geochemical indicators to create a comprehensive understanding of OMZ development. Additionally, we discuss ongoing debates, recent methodological improvements, and unresolved questions in the field.

2. The Modern Arabian Sea OMZ and Denitrification System

2.1. Hydrography and Oxygen Distribution

The modern OMZ in the Arabian Sea is vertically confined between depths of roughly 150 and 1250 m, with the lowest dissolved oxygen levels (<0.5 mL·L^{-1} or <22 μmol·kg^{-1}) concentrated at depths of 300 - 400 m [7] [8]. The intensity and spatial extent of OMZ result due to a mix of high surface productivity, spurred by seasonal upwelling along the Somali and Omani coasts, and restricted ventilation of intermediate waters [9]. Nutrients are introduced into the euphotic zone by the coastal upwelling systems of Somalia and Oman, which are activated by the southwest (summer) monsoon, leading to extensive phytoplankton blooms. The respiration of organic matter sinking into the thermocline and upper intermediate waters then depletes oxygen more rapidly than it can be replenished through physical transport.

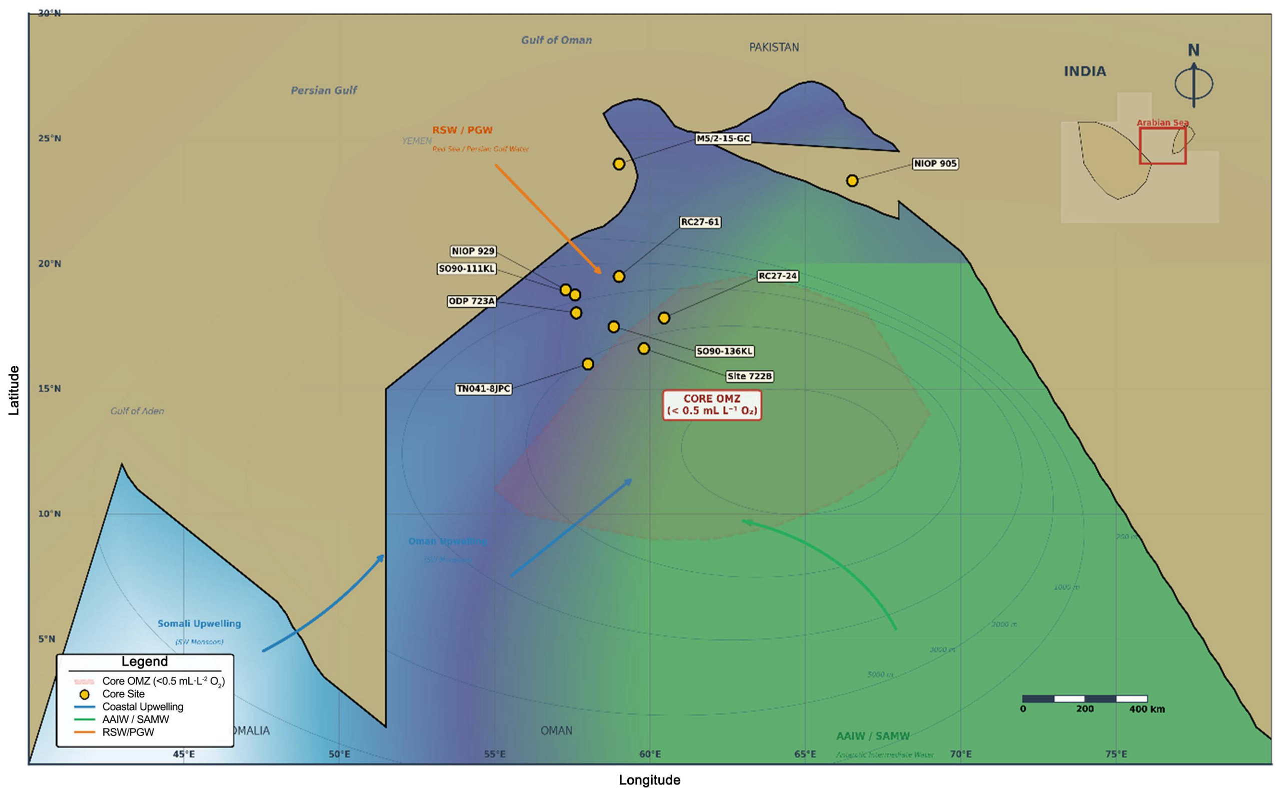

Figure 1. Conceptual map showing core sites, OMZ extent, upwelling zones (Somali, Oman), and water masses (AAIW/SAMW, RSW/PGW).

Ventilation of intermediate waters in the Arabian Sea is a complex process influenced by several distinct water masses. From the south, Antarctic Intermediate Water (AAIW) and Sub-Antarctic Mode Water (SAMW) bring oxygen-rich waters to mid-depths [10]. Conversely, in the northern Arabian Sea, Red Sea Water (RSW) and Persian Gulf Water (PGW) introduce warmer, saltier waters with lower oxygen content, which can hinder ventilation [11]. The interplay between these water masses and the oxygen consumption due to remineralization affects the strength and vertical extent of the OMZ (Figure 1).

2.2. The Nitrogen Cycle and Denitrification

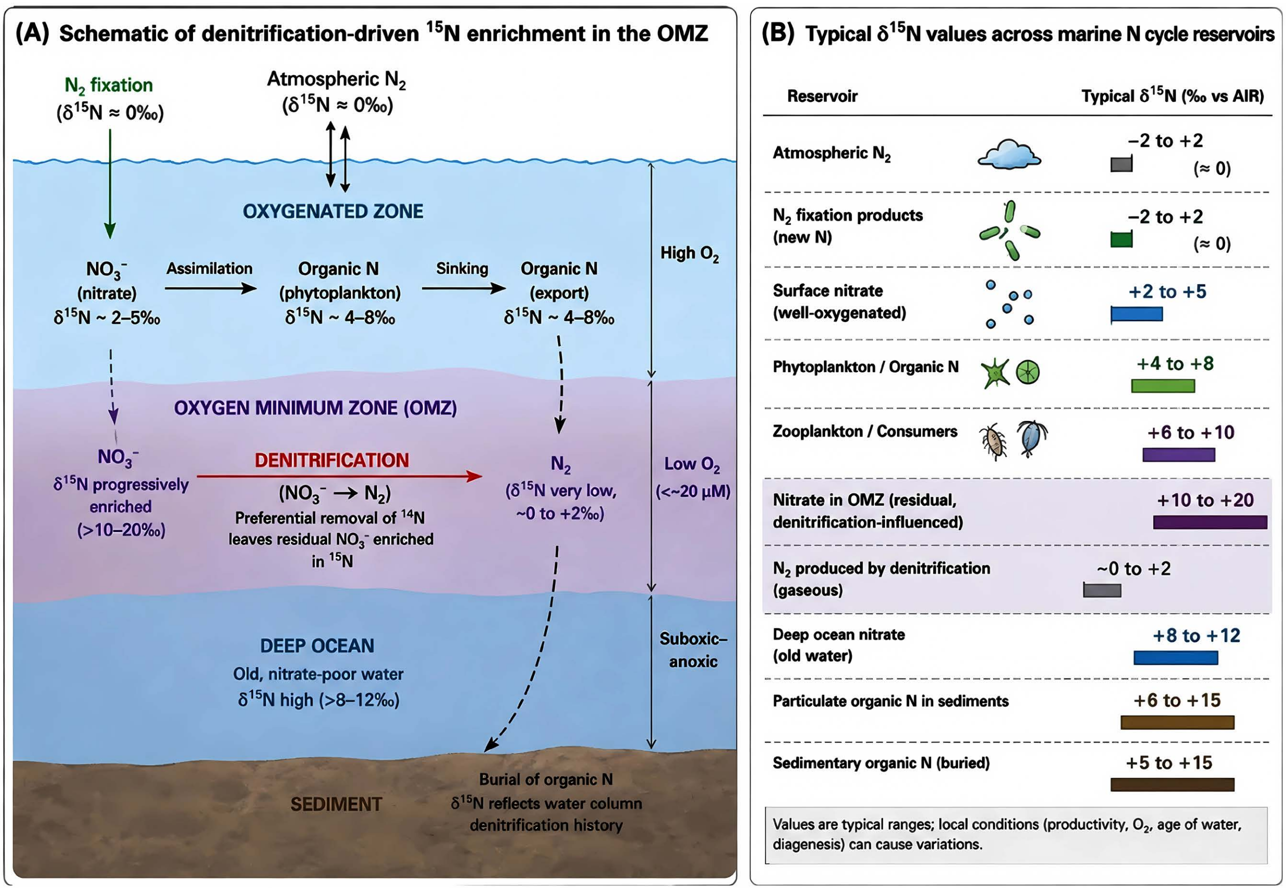

Figure 2. (A) Conceptual diagram of nitrogen isotope fractionation during water-column denitrification in the Arabian Sea OMZ. The preferential removal of ^{14}N as N_2 gas enriches residual nitrate in ^{15}N, which is recorded in sinking particulate organic matter and sediments. (B) Typical $\delta^{15}N$ values for key reservoirs in the marine nitrogen cycle, illustrating the isotopic contrast between weakly and strongly denitrified systems.

Under the suboxic conditions (<5 μmol·kg^{-1} O_2) prevailing within the Arabian Sea OMZ core, microbial denitrification converts nitrate (NO_3^-) to gaseous N_2, representing a major leak in the marine N budget. Estimates suggest that the Arabian Sea accounts for roughly one-third of global water-column denitrification [8] [12]. The isotopic fractionation associated with denitrification enriches the residual nitrate $\delta^{15}N$ by 20‰ - 30‰ relative to the substrate [13]. This enriched nitrate is upwelled into the surface ocean and incorporated into phytoplankton biomass, creating a strong isotopic signal that propagates through the food web and is ultimately recorded in sediments [5]. In addition to water-column denitrification, sedimentary denitrification occurs within suboxic porewaters across the Arabian Sea margin. Although sedimentary denitrification also fractionates N isotopes, the effect is typically smaller, and the signal is more susceptible to diagenetic alteration [14]. Distinguishing between water-column and sedimentary denitrification signals in the sedimentary archive remains a key challenge in paleoceanographic interpretation (**Figure 2(A)**, **Figure 2(B)**).

3. Paleoceanographic Proxies for Denitrification and Oxygenation

A variety of proxy have been used to study past changes in denitrification and oxygen levels in the Arabian Sea. These proxies fall into three main categories: isotopic, ecological (faunal), and geochemical. Each proxy has its own strengths and weaknesses, and reliable reconstructions of past ocean conditions increasingly depend on using multiple methods together (**Table 1** and **Table 2**).

Table 1. Comparison of proxy methods for reconstructing Arabian Sea denitrification and oxygenation.

Proxy	Target	Typical Resolution	Key Advantages	Main Limitations	References
Bulk sediment $\delta^{15}N$	Integrated water-column + sedimentary denitrification; N cycle dynamics	~100 - 500 yr	Long records available; direct link to N cycle	Diagenetic alteration; terrestrial OM mixing; integrates multiple N loss pathways	[6] [15] [16]
FB-$\delta^{15}N$	Surface ocean nitrate $\delta^{15}N$; water-column denitrification	~200 - 1000 yr	Diagenetically robust; species-specific; direct surface ocean signal	Limited by foraminifera abundance; analytical complexity; fewer long records	[17]-[19]
Benthic foraminifera (BFOI/EBFOI)	Bottom-water oxygenation; ecological stress	~100 - 500 yr	Independent of geochemistry; quantitative BWO estimates; high resolution	Taxonomic expertise required; taphonomic bias; species-specific depth habitats	[20]-[22]
I/Ca (planktonic foraminifera)	Upper-ocean oxygenation	~500 - 2000 yr	Semi-quantitative; archives upper water column	Diagenetic sensitivity; species-dependent uptake; limited calibration data	[23]-[25]
Mn/Ca	Redox changes in water column/sediment	~500 - 2000 yr	Complementary to other proxies	Non-unique redox response; diagenetic overprinting	[25]
U/Ba, UEF	Bottom-water oxygenation	~500 - 2000 yr	Effective in oxic-suboxic transition; quantitative	Limited to >50 µM O_2 range; requires normalization	[26]
Benthic porosity	Bottom-water O_2 concentration	~200 - 1000 yr	Direct morphological response; quantitative calibration	Species-specific; taphonomic effects; limited species applicability	[27] [28]

Continued

$\Delta\delta^{13}C$ (epi-infaunal)	Porewater organic matter remineralization intensity	~200 - 1000 yr	Integrates productivity and oxygenation	Requires paired species; metabolic effects; limited calibration	[28]
Lycopane/alkane ratios	Bottom-water redox conditions	~500 - 2000 yr	Independent lipid biomarker; specific to anoxia	Source uncertainty; diagenetic alteration; limited quantitative calibration	[29]

Table 2. Key study sites and sediment cores in the Arabian Sea with deglacial-Holocene proxy records.

Core/Site	Latitude	Longitude	Water Depth (m)	Region	Key Proxies	Primary References
RC27-24	17˚51'N	60˚27'E	~650	Western Arabian Sea (core OMZ)	FB-$\delta^{15}N$, bulk $\delta^{15}N$	[15]
RC27-61	19˚30'N	59˚00'E	~800	Western Arabian Sea (core OMZ)	FB-$\delta^{15}N$, bulk $\delta^{15}N$	[30]
ODP Hole 723A	18˚03'N	57˚37'E	~808	Northwestern Arabian Sea (Oman margin)	Benthic foraminifera, TOC, biomarkers	[22]
TN041-8JPC	~15˚N	~58˚E	~1250	Western Arabian Sea	U/Ba, UEF, benthic foraminifera	[27]
SO90-111KL	18˚46'N	57˚35'E	~730	Oman margin	Bulk $\delta^{15}N$, TOC, benthic foraminifera	[16] [31]
SO90-136KL	17˚30'N	58˚50'E	~585	Oman margin	Bulk $\delta^{15}N$, TOC, biomarkers	[31]
NIOP 905	23˚20'N	66˚30'E	~820	Murray Ridge	Bulk $\delta^{15}N$, benthic foraminifera	[32]
NIOP 929	18˚58'N	57˚17'E	~650	Oman margin	Bulk $\delta^{15}N$	[15]
M5/2-15-GC	~24˚N	~59˚E	~1200	Gulf of Oman	Benthic foraminifera, $\delta^{15}N$, biomarkers	[29]
Site 722B	16˚37'N	59˚48'E	~930	Eastern Arabian Sea	Bulk $\delta^{15}N$ (800 kyr)	[33]

3.1. Nitrogen Isotopes

3.1.1. Bulk Sedimentary $\delta^{15}N$

Bulk sedimentary $\delta^{15}N$ was initially used as a proxy to reconstruct past denitrification in the Arabian Sea [6] [15] [16]. The core premise is that elevated $\delta^{15}N$ values signify intensified water-column denitrification and a more pronounced OMZ, whereas lower values suggest reduced denitrification and improved oxygenation. Records of bulk sediment $\delta^{15}N$ from the Oman margin and the eastern Arabian Sea have consistently exhibited a distinct pattern: low values during the LGM, a pronounced deglacial peak between 15 - 12 ka, and higher values throughout the Holocene [15] [31] [32].

The prevalent interpretation of this pattern suggests a notably reduced or diminished OMZ during the LGM, with a subsequent strengthening of the OMZ throughout the deglaciation and Holocene periods. The decrease in denitrification during the LGM is thought to result from diminished productivity of the southwest monsoon, enhanced ventilation due to the expansion of AAIW, and/or reduced sea levels that limited the entry of low-oxygen waters from marginal seas [23] [32].

However, bulk sediment $\delta^{15}N$ is susceptible to several confounding factors: 1) diagenetic alteration during early burial can shift $\delta^{15}N$ values; 2) changes in the relative contribution of terrestrial organic matter, which typically has lower $\delta^{15}N$ (~0 - 3‰), can affect the bulk signal; and 3) the proxy integrates both water-column and sedimentary denitrification signals, complicating attribution [34].

3.1.2. Foraminifera-Bound $\delta^{15}N$ (FB-$\delta^{15}N$)

To address the diagenetic and mixing challenges linked to bulk sediment $\delta^{15}N$, researchers have introduced foraminifera-bound nitrogen isotope analysis (FB-$\delta^{15}N$). This method assesses the $\delta^{15}N$ of organic material enclosed within the calcite shells of planktonic foraminifera, which remain shielded from post-depositional changes and capture the nitrogen isotopic signature of the ocean's surface or subsurface at the time the shells were formed [17] [18].

FB-$\delta^{15}N$ data from the eastern equatorial Pacific (EEP) have questioned the conventional interpretation of bulk $\delta^{15}N$ by revealing similar values during the Last Glacial Maximum (LGM) and the late Holocene. This suggests that the strength of water-column denitrification and the extent of suboxia remained largely consistent between glacial and interglacial periods [17]. Preliminary FB-$\delta^{15}N$ measurements from two locations in the Arabian Sea's oxygen-deficient zone (ODZ), specifically RC27-24 and RC27-61, dating back to 40,000 years ago, seem to mirror the EEP results. They indicate similar $\delta^{15}N$ values for the LGM and late Holocene, implying comparable denitrification rates and ODZ extents [30]. However, this interpretation requires qualification. FB-$\delta^{15}N$ records the isotopic composition of nitrate assimilated by planktonic foraminifera in the surface or subsurface ocean, which is controlled by several factors in addition to denitrification intensity. These include: **1) nitrate supply and source-water $\delta^{15}N$**, which depends on the mixing of water masses entering the Arabian Sea (e.g., AAIW, SAMW, RSW); **2) nitrate utilization**, since complete consumption of the upwelled nitrate pool dampens the expression of isotopic fractionation associated with denitrification [5]; **3) nitrogen fixation**, which introduces isotopically light nitrogen (~0‰) into the surface ocean and can lower the nitrate $\delta^{15}N$ signal independent of denitrification changes [17]; and **4) circulation changes** that alter the relative contributions of ^{15}N-enriched, denitrified waters versus ^{15}N-depleted waters from the Southern Ocean or marginal seas. Consequently, similar FB-$\delta^{15}N$ values during the LGM and late Holocene may reflect a balance among these processes rather than strictly invariant denitrification rates.

Should these FB-$\delta^{15}N$ findings be validated, they would suggest that the observed glacial-interglacial variations in bulk $\delta^{15}N$ might partly result from diagenesis, shifts in nitrogen fixation, or differences in preservation, rather than directly indicating a significant reduction in water-column denitrification during the LGM. This ongoing discussion highlights one of the most critical unresolved issues in the study of Arabian Sea paleoceanography.

3.2. Benthic Foraminiferal Assemblages

Benthic foraminifera are sensitive indicators of bottom-water oxygenation (BWO) and organic matter flux. The composition, diversity, and species-specific tolerances of their assemblages provide ecological evidence for past oxygenation states that is independent of geochemical proxies [35].

3.2.1. Benthic Foraminiferal Oxygen Index (BFOI) and Enhanced BFOI (EBFOI)

The BFOI, initially created by [20] and later improved (EBFOI); [21] categorizes benthic foraminiferal species based on their oxygen tolerance levels (oxic, suboxic, dysoxic) and computes a numerical oxygen index. In the Arabian Sea's OMZ, assemblages with high diversity, primarily consisting of oxic indicators like *Cibicidoides wuellerstorfi* and *Oridorsalis umbonatus*, suggest well-oxygenated bottom waters. In contrast, assemblages with low diversity, dominated by dysoxic species such as *Bolivina* spp., *Bulimina* spp., *Chilostomella* spp., and *Fursenkoina* spp., indicate oxygen scarcity. Recent research has advanced the BFOI methodology by creating transfer functions that are aligned with current oxygen measurements in the Arabian Sea, facilitating quantitative reconstructions of BWO [21]. These calibrated methods provide dissolved oxygen estimates that can be directly compared with contemporary WOA data and geochemical proxy reconstructions.

3.2.2. Key Indicator Species

Many benthic foraminiferal species serve as particularly sensitive indicators of Arabian Sea oxygenation:

- ***Uvigerina peregrina***: An opportunistic species that does well in dysoxic environments with strong organic matter flux. Strong OMZ conditions and bottom-water deoxygenation are indicated by its dominance in Holocene sediments from the Gulf of Oman and the Oman margin [36].
- ***Bolivina* spp.:** As oxygen levels drop, these taxa become more prevalent because they can withstand low oxygen levels. Increased OMZ conditions are indicated by high Bolivina abundances in mid- to late-Holocene sediments from the northwestern Arabian Sea (ODP Hole 723A) (Academia.edu, 2024).
- ***Globobulimina* spp. *and Chilostomella* spp.:** These infaunal species are indicative of severe oxygen shortage and are typical of severely dysoxic to anoxic settings (**Figure 3**).

Benthic foraminiferal diversity, measured by the Shannon-Wiener index H(S), is a complementary metric. High diversity indicates well-oxygenated conditions, while low diversity indicates environmental stress due to oxygen depletion (e.g., Gulf of Oman LGM H(S) ~1.94 - 4.27 vs. Holocene decline [29]).

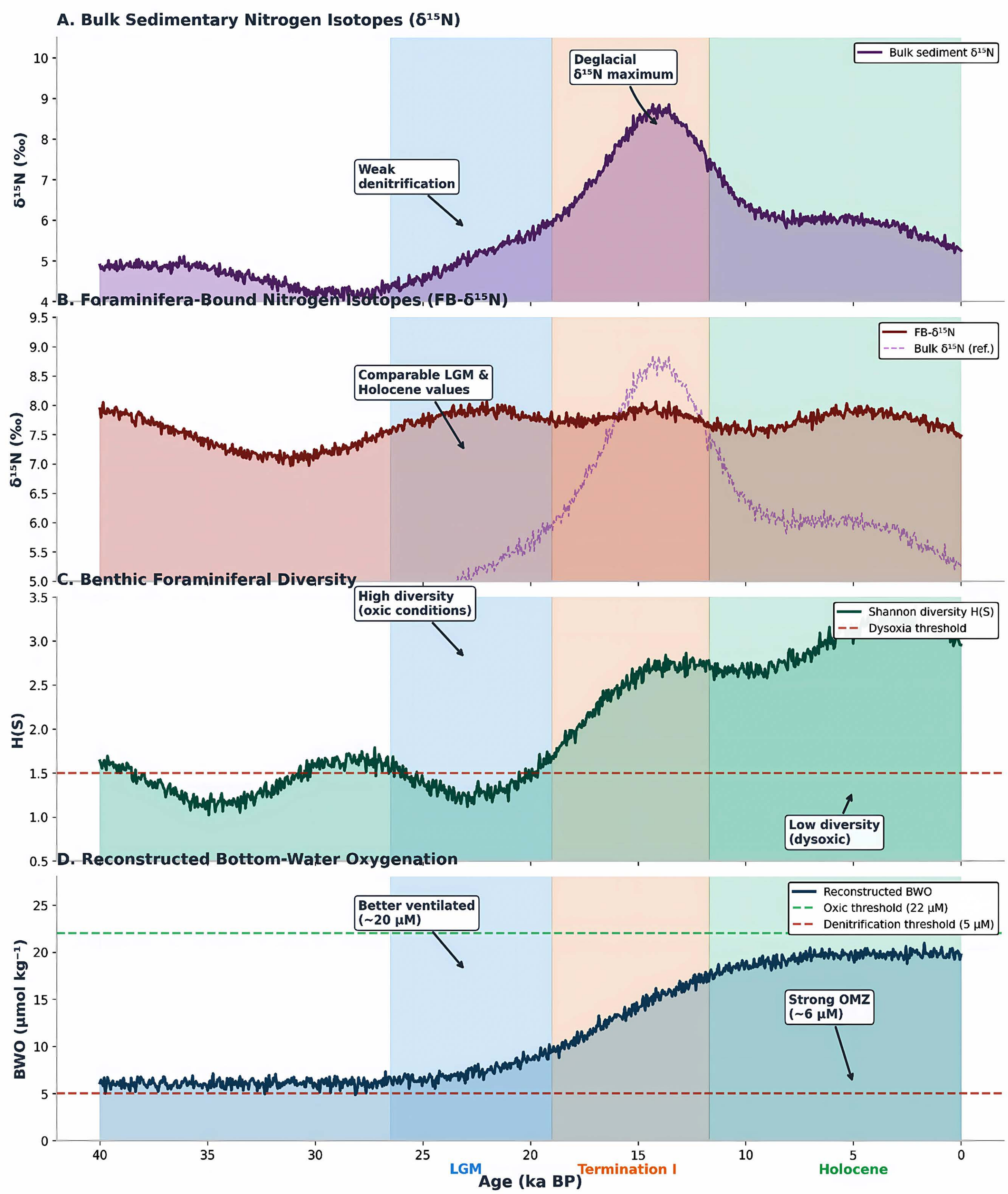

Figure 3. Multi-proxy synthesis of Arabian Sea denitrification and oxygenation over the past 40 kyr. (A) Bulk sedimentary $\delta^{15}N$ showing the characteristic deglacial maximum and elevated Holocene values. (B) Foraminifera-bound $\delta^{15}N$ showing comparatively smaller glacial-interglacial amplitude. (C) Benthic foraminiferal Shannon diversity H(S), declining from LGM high-diversity (oxic) to Holocene low-diversity (dysoxic) assemblages. (D) Reconstructed bottom-water oxygenation (BWO) from multiple proxies, showing the transition from better-ventilated LGM to strongly deoxygenated Holocene conditions. Shaded bars denote climatic periods: LGM (blue), Termination I (orange), Holocene (green).

3.3. Geochemical Proxies

3.3.1. Iodine-to-Calcium Ratios (I/Ca) in Planktonic Foraminifera

The predominant form of iodine in foraminiferal calcite in oxic conditions is iodate (IO_3^-). Iodate is converted to iodide (I^-), which is incompatible with the calcite lattice, when oxygen levels drop. Thus, I/Ca ratios in planktonic foraminifera are a semi-quantitative indicator of upper-ocean oxygenation; dissolved oxygen contents < 90 μmol/kg are associated with values < 2 μmol/mol [37]. Although its use in deglacial-Holocene sequences is still limited, I/Ca has been applied to Miocene Arabian Sea records [38] and shows promise for Quaternary applications.

3.3.2. Manganese-to-Calcium Ratios (Mn/Ca)

Mn/Ca ratios in bulk sediment or foraminiferal calcite reflect redox shifts because manganese oxides precipitate in oxic conditions and dissolve in suboxic situations. Mn/Ca declines have been used to monitor the Arabian Sea's gradual deoxygenation during the Miocene [38], and they may give additional limits on glacial-interglacial oxygenation variations.

3.3.3. Uranium and Barium Enrichment Factors (UEF, U/Ba)

Under reducing conditions, soluble U(VI) is reduced to U(IV), which is relatively insoluble and can precipitate or become retained in sediments, resulting in uranium enrichment. In contrast, oxidizing conditions favour the more soluble and mobile U(VI) species. Barium, primarily associated with biogenic barite, is commonly linked to organic-matter export and productivity. Therefore, U enrichment factors (UEF) and U/Ba ratios can provide information on bottom-water redox conditions and oxygenation, particularly where oxygen concentrations and redox conditions fluctuate [23]. In the western Arabian Sea, data from core TN041-8JPC indicate increased bottom-water oxygenation during MIS 6 and decreased oxygenation during MIS 5e based on UEF and U/Ba records.

3.3.4. Benthic Foraminiferal Surface Porosity

The porosity of the surface of benthic foraminifera, especially Cibicidoides and Uvigerina, is linked to the levels of dissolved oxygen in their environment. In conditions where oxygen is scarce, these foraminifera form tests with increased porosity to enhance respiration through the shell wall. This method has been calibrated and utilized to reconstruct bottom water oxygen (BWO) levels in the Arabian Sea, providing estimates of approximately 20 μmol/kg during the Last Glacial Maximum (LGM), which decreased to around 6 μmol/kg during the Holocene in the western Arabian Sea's oxygen minimum zone (OMZ) [27].

3.3.5. Benthic Carbon Isotope Gradients ($\Delta\delta^{13}C$)

The carbon isotopic difference ($\Delta\delta^{13}C$) between epifaunal (*Cibicidoides wuellerstorfi*) and deep infaunal (*Globobulimina affinis*) benthic foraminifera reflects the intensity of porewater organic matter remineralization and, by extension, bottom-water oxygenation. Smaller gradients indicate more oxygenated conditions. $\Delta\delta^{13}C$-based BWO reconstructions from a depth transect (600 - 3650 m) in the Arabian

Sea suggest that the glacial OMZ was slightly better oxygenated in the upper 1000 m but that deeper waters (>1500 m) were actually less oxygenated than today [39].

4. Deglacial to Holocene Evolution of Arabian Sea Denitrification and Oxygenation

To accurately interpret changes in the OMZ from the deglacial to the Holocene period, it is crucial to differentiate the processes each proxy represents (see **Table 1**). Bulk δ^{15}N, which reflects sedimentary organic nitrogen, combines signals from both water-column and sedimentary denitrification but is prone to alteration through diagenesis. In contrast, foraminifera-bound δ^{15}N (FB-δ^{15}N) provides a more reliable record of surface-ocean nitrate and water-column denitrification. Benthic foraminiferal indices (BFOI/EBFOI) offer direct evidence of bottom-water oxygen levels, while I/Ca, U/Ba, and porosity are indicative of upper-ocean oxygenation, redox conditions at the seafloor, and oxygen availability on the seafloor, respectively. Lycopane ratios serve as indicators of anaerobic bacterial activity, and TOC gives a general measure of organic-matter flux and oxygen demand. These proxies collectively capture related yet distinct processes such as denitrification, ventilation, oxygenation, and productivity. Consistency among independent proxies enhances the interpretation of OMZ changes, whereas differences, especially between bulk and FB-δ^{15}N, might suggest specific process responses or effects of diagenesis.

4.1. Last Glacial Maximum (LGM; ~26.5 - 19 ka)

Multi-proxy data suggest that the LGM Arabian Sea was considerably more oxygenated than the Holocene; however, the degree of this difference is still contested.

Isotopic evidence: Sediment δ^{15}N data from the Oman margin, Murray Ridge, and eastern Arabian Sea generally reveal LGM levels 2‰ - 4‰ lower than Holocene values [15] [31] [32] [40]. Lower δ^{15}N levels have historically been viewed as indicating decreased denitrification in the water column and a weaker or constricted OMZ. However, new FB-δ^{15}N data reveal comparable LGM and late Holocene values, raising concerns about the integrity of the bulk sediment signal, although alternative explanations involving changes in nitrate utilization, nitrogen fixation, or source-water mixing cannot be excluded ([30]; see Section 3.1.2).

Ecological evidence: Benthic foraminiferal assemblages from the Gulf of Oman and western Arabian Sea reveal well-oxygenated bottom waters during the LGM. The Gulf of Oman record reveals substantial benthic diversity (H(S) up to 4.27) and reconstructed BWO values that are significantly greater than those from the Holocene. Similarly, ODP Hole 723A (**Figure 1**) in the northwestern Arabian Sea has an abundance of oxic indicator species during the late Pleistocene, indicating a relatively weak OMZ.

Geochemical evidence: Surface porosity and $\Delta\delta^{13}$ of benthic foraminifera. According to C-based BWO reconstructions, LGM oxygen concentrations were around 10 - 15 μmol/kg greater than present levels in the shallow OMZ (<1000 m), although deeper waters may have been less oxygenated [28]. UEF and U/Ba proxies also show increased BWO throughout glacial eras.

Mechanisms: The better-oxygenated LGM conditions may reflect several competing mechanisms, each supported by proxy evidence: 1) stronger wind-induced mixing due to intensified northeast winter monsoon winds; supported by low bulk $\delta^{15}N$ and reduced TOC [15] [32]. 2) expanded northward penetration of oxygen-rich AAIW; consistent with high benthic diversity and expanded AAIW inferred from $\Delta\delta^{13}C$ [29]. 3) lower sea levels that disconnected the Persian Gulf and restricted Red Sea Water inflow; suggested by UEF/U/Ba proxies indicating higher BWO when marginal-sea outflow was restricted [27]. 4) weaker southwest summer monsoon upwelling, reducing surface productivity and subsurface oxygen demand, indicated by benthic porosity estimates of ~20 μmol/kg BWO [27] [32] [41].

4.2. Deglacial Transition (Termination I; ~19 - 11.7 ka)

The deglaciation is the most dramatic period in Arabian Sea OMZ history, characterized by a strong $\delta^{15}N$ maximum and significant faunal changes.

Isotopic evidence: Sediment $\delta^{15}N$ records from the Arabian Sea show a sharp increase beginning ~18 - 17 ka, reaching maximum values of 8‰ - 10‰ during the Bølling-Allerød (~14.7 - 12.9 ka), before slightly declining through the Younger Dryas and early Holocene [15] [16]. This deglacial $\delta^{15}N$ maximum is one of the most durable aspects of the Arabian Sea paleoceanographic records. It is usually understood as reflecting peak denitrification intensity during a period of maximum OMZ expansion.

Ecological evidence: Benthic foraminiferal assemblages exhibit a shift from LGM oxic communities to deglacial dysoxic-dominated assemblages. In the Gulf of Oman, diversity indices deteriorate with deglaciation, and reconstructed BWO levels drop to suboxic levels (<1 $mL \cdot L^{-1}$) by the early Holocene.

Geochemical evidence: Benthic porosity data show that BWO levels decreased from ~20 μmol/kg during the LGM to ~10 μmol/kg during the deglaciation and stabilized at ~6 μmol/kg during the Holocene [27].

Mechanisms: The deglacial intensification of denitrification and deoxygenation was driven by: 1) strengthening of the southwest summer monsoon in response to rising boreal summer insolation, increasing upwelling and productivity; supported by the bulk $\delta^{15}N$ peak and enhanced TOC burial [15] [42]. 2) sea-level rise reconnecting the Persian Gulf (~13 ka) and enhancing Red Sea Water inflow, contributing low-oxygen water masses; indicated by the shift to dysoxic benthic assemblages and declining BWO in porosity records [27]. 3) weakening of AAIW ventilation as Southern Ocean stratification changed; consistent with the timing of Persian Gulf flooding (~13 ka; [43] and increased RSW influence. And 4) rising temperatures reducing oxygen solubility, inferred from rising temperatures and reduced oxygen solubility.

4.3. Holocene (~11.7 ka to Present)

The Holocene is distinguished by chronically high OMZ conditions and enhanced denitrification, but with significant geographical and temporal fluctuations.

Early to Mid-Holocene (11.7 - 4.2 ka): Bulk $\delta^{15}N$ levels remain elevated with slight changes, indicating continued denitrification. Benthic foraminiferal records from ODP Hole 723A indicate that intense southwest monsoon-driven productivity facilitated OMZ development, but periodic incursions of oxygen-rich intermediate waters from the south (SAMW/AAIW) limited full OMZ intensification during the early Holocene. The Gulf of Oman has consistently low reconstructed O_2 and high $\delta^{15}N$, with little oscillation, indicating significant OMZ and suboxic bottom water.

Mid-Holocene Transition (~6.5 - 4.2 ka): The middle Holocene marks a change to more intense OMZ conditions in the northwestern Arabian Sea. This intensification could be attributed to the substitution of oxygen-rich southern-source SAMW/AAIW with oxygen-poor northern Red Sea Water.

Late Holocene (~4.2 ka to present): The Arabian Sea OMZ expanded as the southwest monsoon weakened in the late Holocene. This apparent disconnect between production and oxygenation has been related to the complete halt of oxygenated SAMW/AAIW intrusions, allowing the OMZ to strengthen despite reduced surface forcing. The Gulf of Oman record shows the highest lycopane ratios and Uvigerina peregrina dominance in the late Holocene, indicating maximum deoxygenation [44].

Spatial heterogeneity: The eastern Arabian Sea (Site 722B) reveals orbital-scale denitrification fluctuations closely linked to monsoon severity during the last 800 kyr, with higher $\delta^{15}N$ during interglacials, according to [33]. The southeastern Arabian Sea has centennial-scale denitrification variability overlaid on the glacial-interglacial pattern, indicating high-frequency climate forcing.

4.4. Centennial to Millennial Variability

High-resolution records show that Arabian Sea oxygenation did not remain constant during the LGM or Holocene, but instead responded to centennial- to millennial-scale temperature oscillations.

MIS 3 (~57 - 29 ka): This interval has an "unstable" oxygenation mode, alternating between moderately oxygenated circumstances during stadials and deoxygenated/denitrification conditions during interstadials and Dansgaard-Oeschger (D/O) events. In the Gulf of Oman, $\delta^{15}N$ peaks and benthic diversity minima coincide with D/O events, while Heinrich events (H1, H2) and stadials have better oxygenation [44]. Spectral analysis revealed substantial high-frequency periodicities ranging from 570 to 710 years during MIS 3, which may be linked to AMOC variability (**Figure 4**).

Holocene rapid events: Brief FB-$\delta^{15}N$ maxima at ~8.3, 5.8, and 4.4 ka in regional records may reflect short-lived intensifications of denitrification or changes in thermocline ventilation, although these events require further confirmation in

Arabian Sea records [17].

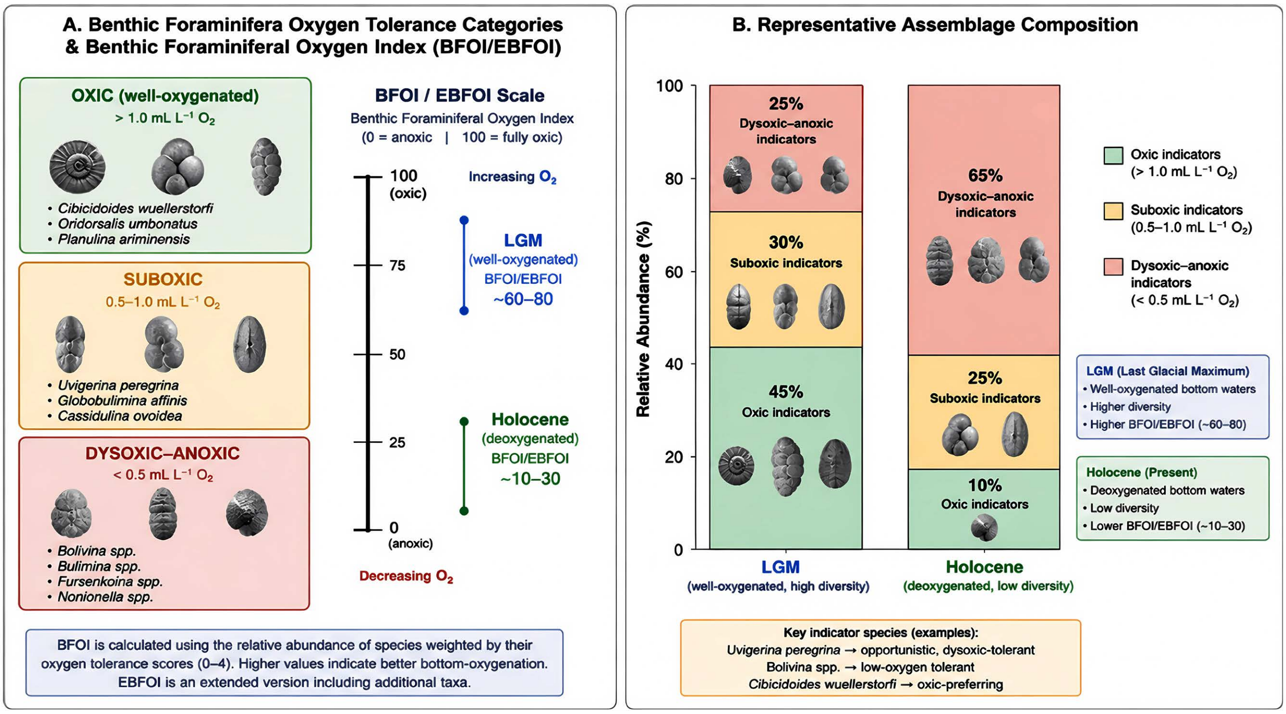

Figure 4. (A) Benthic foraminifera oxygen tolerance categories (oxic, suboxic, dysoxic-anoxic) with representative indicator species for each category, and the Benthic Foraminiferal Oxygen Index (BFOI/EBFOI) scale showing typical LGM and Holocene values. (B) Representative assemblage composition comparing LGM (well-oxygenated, high diversity) and Holocene (deoxygenated, low diversity) states.

5. Controls and Mechanisms

The mechanisms below are presented as competing hypotheses, each supported by distinct proxy evidence, and may have dominated in different regions or time intervals.

5.1. Monsoon-Driven Productivity

The Indian monsoon system is the fundamental driving force behind Arabian Sea surface production and, by extension, subsurface oxygen demand. Southwest (summer) monsoon winds produce coastal upwelling off Somalia and Oman, introducing nutrient-rich waters into the euphotic zone. This interpretation is supported by bulk $\delta^{15}N$ records and benthic faunal assemblages tracking monsoon strength [42] [45]. Summer monsoon strength was much weaker during the LGM, strengthened during deglaciation, peaked during the early Holocene "Holocene Climate Optimum," and weakened again during the late Holocene [42] [45]. This monsoon history is closely related to Arabian Sea denitrification intensity: weaker monsoon = lower productivity = less oxygen demand = weaker OMZ (LGM); stronger monsoon = higher productivity = more oxygen demand = stronger OMZ (Holocene). However, the late Holocene paradox shows that diminishing monsoons coincide with intensifying OMZ, which shows that productivity is not the only regulator (Figure 5).

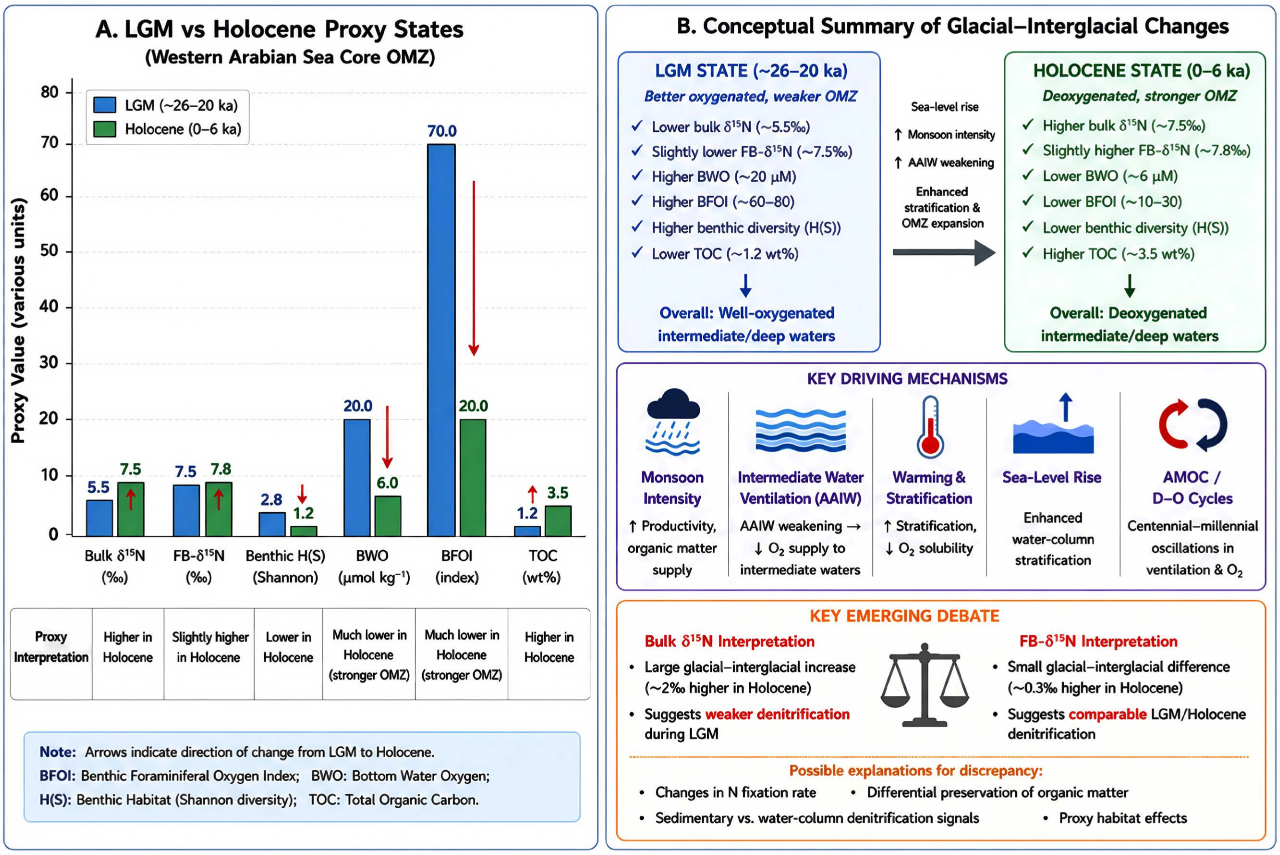

Figure 5. (A) Grouped bar chart comparing representative LGM and Holocene proxy values from the western Arabian Sea core OMZ, illustrating the magnitude and direction of glacial-interglacial changes. (B) Conceptual summary of the LGM state (better oxygenated, weaker OMZ) versus the Holocene state (deoxygenated, stronger OMZ), with key driving mechanisms and the emerging debate between bulk $\delta^{15}N$ and FB-$\delta^{15}N$ interpretations.

5.2. Intermediate Water Ventilation

The oxygen level of intermediate seas that ventilate the Arabian Sea has a significant impact on OMZ strength, regardless of local production. Glacial expansion of oxygen-rich AAIW is supported by high benthic diversity and oxic indicator species [44], whereas deglacial-Holocene weakening is indicated by declining BWO in porosity [27].

Antarctic Intermediate Water (AAIW) and SAMW: During glacial eras, increased AAIW/SAMW penetration into the northern Indian Ocean resulted in better-ventilated, oxygen-rich intermediate waters [32] [41]. During the interglacial period, decreased AAIW production and/or altered routes weakened this ventilation source. The northward spread of AAIW during stadials has been related to higher oxygen levels in the Gulf of Oman during the LGM [44].

Red Sea Water (RSW): Changes in sea level control the outflow of RSW into the Arabian Sea. During the LGM, lower sea levels (~120 m below current) limited RSW outflow across the Bab el Mandeb Strait. During the Holocene, rising sea levels increased RSW influx, bringing warmer, saltier, and lower-oxygen water to the northern Arabian Sea.

Persian Gulf Water (PGW): During the LGM, the Persian Gulf was almost dry and only connected to the Gulf of Oman via the Strait of Hormuz at ~13 ka. Full flooding occurred by ~11.5 ka [43]. Since the mid-Holocene, PGW has helped to ventilate the upper OMZ (150 - 300 m) in the northern Arabian Sea, but its oxygen contribution is minimal (~0.5 $mL \cdot L^{-1}$ increase; [11] [46]).

5.3. Sea-Level and Marginal Sea Connections

Post-LGM sea-level rise fundamentally altered Arabian Sea hydrography by: 1) reconnecting marginal seas (Persian Gulf, Red Sea) that contribute distinct water masses; 2) flooding continental shelves, potentially increasing nutrient input from land; and 3) changing coastline configurations that influence upwelling dynamics. The date of Persian Gulf flooding (~13 - 11.5 ka) correlates with the early deglacial $\delta^{15}N$ rise, indicating a potential role for marginal sea connections in OMZ intensification [44].

5.4. Temperature and Oxygen Solubility

Warmer temperatures during interglacials decrease oxygen solubility (by ~2 - 3 $\mu mol \cdot kg^{-1}$ per ˚C), resulting in thermodynamic feedback that accelerates OMZ expansion. Glacial freezing would have enhanced oxygen solubility, somewhat offsetting any productivity-related oxygen demand [27]. Hypothesized that the minor increase in glacial Arabian Sea OMZ oxygenation was caused by weaker upper-ocean stratification (due to stronger winter monsoon winds) and increased oxygen solubility from lower temperatures, which offset enhanced productivity.

6. Synthesis and Emerging Perspectives

6.1. Oxygenation Variability and Proposed Modes

High-resolution records, particularly from the Gulf of Oman, indicate contrasting modes of oxygenation variability over the last ~43 kyr. The relatively stable mode describes intervals in which a dominant long-term oxygenation state persisted despite superimposed centennial- to millennial-scale fluctuations, whereas the unstable mode, most clearly documented during MIS 3, is characterized by pronounced alternations between better-oxygenated and deoxygenated conditions associated with D/O events and AMOC variability [44]. The LGM and Holocene can therefore be considered broadly persistent long-term oxygenation states in the available records, but not strictly constant conditions. Importantly, this framework is currently record-specific and should not be regarded as a basin-wide classification. Its applicability to the Arabian Sea as a whole requires spatially replicated, high-resolution, multi-proxy records that demonstrate consistent temporal patterns across different regions and depths.

6.2. The Bulk $\delta^{15}N$ vs. FB-$\delta^{15}N$ Debate

The most important methodological challenge in the research is the apparent contradiction between bulk sediment $\delta^{15}N$ (showing significant glacial-interglacial changes) and FB-$\delta^{15}N$ (showing negligible differences). This ongoing discussion highlights one of the most critical unresolved issues in the study of Arabian Sea paleoceanography, and underscores the need to consider non-denitrification controls on FB-$\delta^{15}N$ (Section 3.1.2). Possible theories include:

- **Diagenetic alteration:** During early diagenesis, bulk sediment N may undergo microbial modification, with preferential loss of ^{14}N-rich compounds. This can artificially elevate or lower glacial bulk $\delta^{15}N$ through multiple mechanisms.
- **N fixation changes:** Higher glacial N fixation may have decreased the regional nitrate pool's $\delta^{15}N$, decreasing the bulk signal without affecting denitrification.
- **Sedimentary vs. water-column denitrification:** Bulk $\delta^{15}N$ may integrate both signals, whereas FB-$\delta^{15}N$ focuses on the water-column signal.
- Preservation **bias:** Glacial sediments' retention of organic materials can impact bulk $\delta^{15}N$ levels.

To resolve this debate, we need more FB-$\delta^{15}N$ records from multiple Arabian Sea sites, paired bulk and FB-$\delta^{15}N$ measurements on the same cores, improved understanding of N cycling and diagenesis in Arabian Sea sediments, and modeling studies that can predict the relative contributions of different N cycle processes.

6.3. Spatial Heterogeneity

The Arabian Sea is not a single, homogeneous system. The western Arabian Sea (Oman margin, core OMZ) has the strongest upwelling and denitrification. The Gulf of Oman exhibits unusual behavior, with LGM ventilation patterns that differ from the open Arabian Sea. The eastern Arabian Sea responds to various wind forces and water mass impacts. Future reviews and syntheses must consider this geographical complexity rather than treating the basin as a single entity.

6.4. Implications for Future Climate Change

The palaeoceanographic record indicates that Arabian Sea OMZ intensity is affected by: 1) monsoon strength and productivity; 2) intermediate water ventilation from the Southern Ocean; 3) marginal sea connections and sea level; and 4) temperature-driven oxygen solubility. All of these factors are likely to change under future high-emission scenarios (SSP5-8.5): monsoons will intensify with more intense rainfall; ocean warming will diminish oxygen solubility and enhance stratification; and Southern Ocean ventilation will weaken. The paleo-record implies that the Arabian Sea could adopt a stable, substantially deoxygenated phase with extended denitrification, thereby boosting N_2O emissions and affecting global marine productivity. However, the exact trajectory will be determined by the balance of these competing forces.

7. Conclusions

This review combines ecological and isotopic data for deglacial to Holocene changes in Arabian Sea denitrification and oxygenation, reaching the following important conclusions (Table 3).

Table 3. Summary of LGM vs Holocene proxy states in the Arabian Sea core OMZ.

Proxy/Parameter	LGM (~26.5 - 19 ka)	Holocene (~11.7 - 0 ka)	Interpretation
Bulk $\delta^{15}N$	~5 - 6‰	~7 - 8‰	Lower = weaker denitrification; Higher = stronger denitrification
FB-$\delta^{15}N$	~7 - 8‰	~7.5 - 8.5‰	Comparable values → debate over true glacial-interglacial change
Benthic diversity H(S)	~2.5 - 4.3	~1.0 - 2.0	Higher = better oxygenated; Lower = dysoxic stress
BWO (reconstructed)	~15 - 25 $\mu mol \cdot kg^{-1}$	~5 - 10 $\mu mol \cdot kg^{-1}$	Better ventilated LGM; strongly deoxygenated Holocene
BFOI/EBFOI	~60 - 80	~10 - 30	Higher = oxic; Lower = dysoxic
Dominant benthic taxa	C. wuellerstorfi, O. umbonatus*	U. peregrina, Bolivina spp.	Oxic indicators vs. dysoxic opportunists
TOC accumulation	~0.8 - 1.5 wt%	~2.5 - 4.5 wt%	Lower productivity LGM; higher productivity Holocene
Lycopane ratio	<1.0	>1.0 (late Holocene)	Lower = oxic; Higher = suboxic-anoxic
Monsoon strength	Weak SWM/Strong NWM	Strong SWM (early); weakening (late)	Productivity forcing
AAIW ventilation	Stronger, expanded	Weaker, contracted	Ventilation forcing
Sea level	~−120 m	Near modern	Marginal sea connection forcing

1) The LGM Arabian Sea had moderately better oxygenation than the Holocene, with weaker OMZ conditions indicated by bulk $\delta^{15}N$ minima, high benthic foraminiferal diversity, and geochemical proxies suggesting stronger BWO. However, recent FB-$\delta^{15}N$ data contradict the extent of this discrepancy, suggesting that glacial-interglacial variations in water-column denitrification were smaller than previously supposed or that compensating changes in nitrate utilization, nitrogen fixation, and circulation masked larger denitrification differences.

2) The deglacial transition (Termination I) was defined by a significant $\delta^{15}N$ maximum, representing peak denitrification intensity. This was driven by increased summer monsoon productivity, reduced intermediate water ventilation, and increasing sea levels reconnecting low-oxygen peripheral seas.

3) The Holocene was characterized by persistently strong OMZ conditions and elevated denitrification, with early Holocene monsoon maxima sustaining high productivity and late Holocene weakening of AAIW ventilation allowing further OMZ intensification despite reduced surface forcing.

4) Benthic foraminiferal assemblages confirm oxygenation changes, with high-diversity oxic communities during the LGM and low-diversity dysoxic assemblages during the Holocene. Key indicator species (Uvigerina peregrina, Bolivina spp.) track OMZ strength.

5) High-resolution records, particularly from the Gulf of Oman, indicate contrasting oxygenation variability, including relatively persistent long-term states dur-

ing the LGM and Holocene and pronounced centennial- to millennial-scale oscillations during MIS-3. However, these "stable" and "unstable" modes should currently be regarded as a record-specific framework rather than a basin-wide classification, pending confirmation from spatially replicated, high-resolution multi-proxy records across the Arabian Sea.

6) Spatial heterogeneity is significant: The Gulf of Oman, western Arabian Sea core OMZ, and eastern Arabian Sea have diverse deglacial-Holocene trends that reflect differing balances of local productivity, intermediate water ventilation, and marginal sea impacts.

7) Multi-proxy convergence is essential: Isotopic (bulk $\delta^{15}N$, FB-$\delta^{15}N$), ecological (benthic foraminifera), and geochemical (I/Ca, U/Ba, porosity, biomarkers) proxies must be integrated for robust reconstructions, as no single proxy is without uncertainty.

Future research priorities include expanding FB-$\delta^{15}N$ records across the Arabian Sea, developing high-resolution, absolutely dated records to capture centennial-scale variability, improving proxy calibrations under previous boundary conditions, and integrating paleodata with Earth system models to better constrain the climate-OMZ-denitrification feedbacks that will shape the future of the Arabian Sea N cycle.

Author Statement

We declare that this manuscript is original; it has not been published before.

Author Contributions

Conceptualization: Dhiraj Shinde, Yoganandan Veeran. Data curation: Dhiraj Shinde. Formal analysis and investigation: Dhiraj Shinde. Methodology: Dhiraj Shinde. Supervision: Yoganandan Veeran. Validation: Visualization: Dhiraj Shinde. Writing—original draft preparation: Dhiraj Shinde. Writing review and editing: Dhiraj Shinde. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare there is no competing interest.

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