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Millennial-Scale Denitrification Dynamics in the Arabian Sea: A Paleo-Bibliometric Review

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ABSTRACT

Arabian Sea (AS) is a region of significant oceanographic and climatic importance, characterized by a monsoon-driven productivity and extensive oxygen minimum zones (OMZs). This review synthesizes millennial-scale studies on denitrification in the AS, examining its links with past climate changes, oceanic oxygen levels, and biogeochemical cycles. Denitrification, a key microbial process transforming bioavailable nitrogen to inert nitrogen gas, plays a crucial role in the nitrogen budget of marine ecosystems, particularly in OMZs where low oxygen conditions favor such pathways. Reconstructions of past denitrification, based on isotopic and geochemical proxies preserved in sediments, reveal strong links with fluctuations in the South Asian Monsoon (SAM) and associated nutrient supply. This review highlights the sensitivity of OMZs to climatic and anthropogenic forcing, providing insights into how future climate change may alter nitrogen cycling and OMZ dynamics. The findings contribute to improving predictive models of biogeochemical feedbacks in the global climate system.

INTRODUCTION

The Arabian Sea (AS) is a dynamic region where climatic, oceanographic, and biogeochemical processes influence marine ecosystems and their biogeochemistry. This region is features a prominent oxygen minimum zone (OMZ), arising from intense biological productivity driven by the South Asian Monsoon (SAM) and subsequent oxygen depletion in subsurface waters. These OMZs are crucial in marine nitrogen cycling through denitrification, a microbial process that reduces nitrate to nitrogen gas, removing bioavailable nitrogen from the ocean and impacting global biogeochemical cycles (Altabet et al. 1995). Denitrification and OMZs are linked to regional climate fluctuations and broader climatic events (Lachkar et a7l. 2018). On millennial timescales, climate oscillations such as the Dansgaard–Oeschger cycles, Heinrich events, and changes in monsoon intensity have left discernible imprints on denitrification rates and oxygen minimum zone (OMZ) variability in the AS. The sediments provide valuable archives of past denitrification processes and OMZ dynamics, preserved through proxies like stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotopes and trace metal concentrations. Analyzing these records offers insights into the denitrification and OMZ intensity in response to climatic changes, helping to predict future responses to anthropogenic influences.
This review combines paleo-records with bibliometric analysis to investigate the key drivers of denitrification in the Arabian Sea and to outline future research directions. Drawing on insights from paleoclimatology, geochemistry, and oceanography, it seeks to provide a comprehensive understanding of how monsoon-driven productivity and oxygen dynamics have evolved over time, and how they may respond to future climate change.

1. Methodology for Review (Bibliometric Analysis)

For the bibliometric analysis, Scopus-indexed articles were retrieved using the keywords "Denitrification," "Oxygen Minimum Zone," and "AS," and exported in CSV format for visualization using VOSviewer v1.6.20. A total of 1,969 documents published between 1975 and 2025 were analyzed. Among 42 contributing countries, **(Figure 1)** the top five based on publication count and citation impact were the United States (774 documents, 64,314 citations), India (404 documents, 14,685 citations), Germany (375 documents, 29,228 citations), China (306 documents, 13,917 citations), and the United Kingdom (211 documents, 14,130 citations), forming six collaborative clusters. Keyword co-occurrence analysis yielded 9,115 unique terms, filtered to include only those occurring at least five times, resulting in a network of 1,273 keywords. The most frequently co-occurring keywords were "denitrification" (507 occurrences), "Indian Ocean" (417), "AS" (413), "oxygen" (400), and "nitrogen" (366), forming six distinct clusters visualized by color (red, yellow, sky blue, green, blue, and violet). The most cited article **(Table 1)** was published in *Science*, titled *"Declining oxygen in the global ocean and coastal waters"*, with 1,993 citations, followed by publications in *Ecological Applications*. In terms of publication volume, *Biogeosciences* led all journals, **(Table 2)** followed by *Global Biogeochemical Cycles*, *Deep-Sea Research Part II: Topical Studies in Oceanography*, *Frontiers in Marine Science*, and *Geochimica et Cosmochimica Acta*. Regarding total citations, *Biogeosciences* ranked highest (8,258 citations), followed by *Global Biogeochemical Cycles* (5,460), *Geochimica et Cosmochimica Acta* (4,846), *Deep-Sea Research Part II* (4,101), and *Annual Review of Marine Science* (4,049). The most prolific author was S.W.A. Naqvi, with 54 publications and 6,779 citations **(Figure 2).**

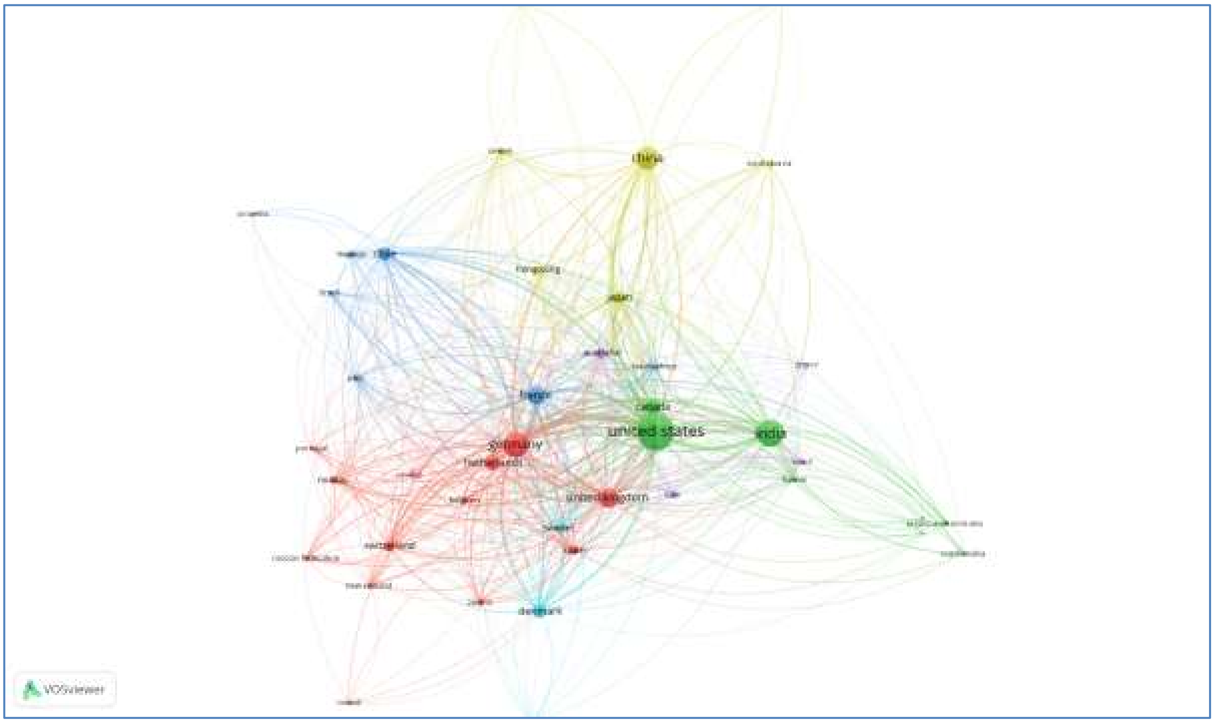

Figure 1. Country-based co-authorship network for a denitrification review: nodes represent countries; links show co-authorship strength. Node size reflects publication volume; colors indicate collaboration clusters.

Sr.no	Title	Cited by	Source title
1	Declining oxygen in the global ocean and coastal waters	1993	Science
2	Denitrification across landscapes and waterscapes: A synthesis	1393	Ecological Applications
3	Geochemistry of oceanic anoxic events	1391	Geochemistry, Geophysics, Geosystems
4	Ocean deoxygenation in a warming world	1273	Annual Review of MarineScience
5	Ocean Biogeochemical Dynamics	1140	Ocean Biogeochemical Dynamics

Table 1. The most cited articles and their sources.

Sr.no	Source title	Number of_Publications	Total_citations
1	Biogeosciences	132	8258
2	Global Biogeochemical Cycles	79	5460
3	Deep-Sea Research Part II: Topical Studies in Oceanography	70	4101
4	Frontiers in Marine Science	65	1038
5	Geochimica et Cosmochimica Acta	59	4846

Table 2. List of journals with highest publications and citations in the denitrification and OMZ

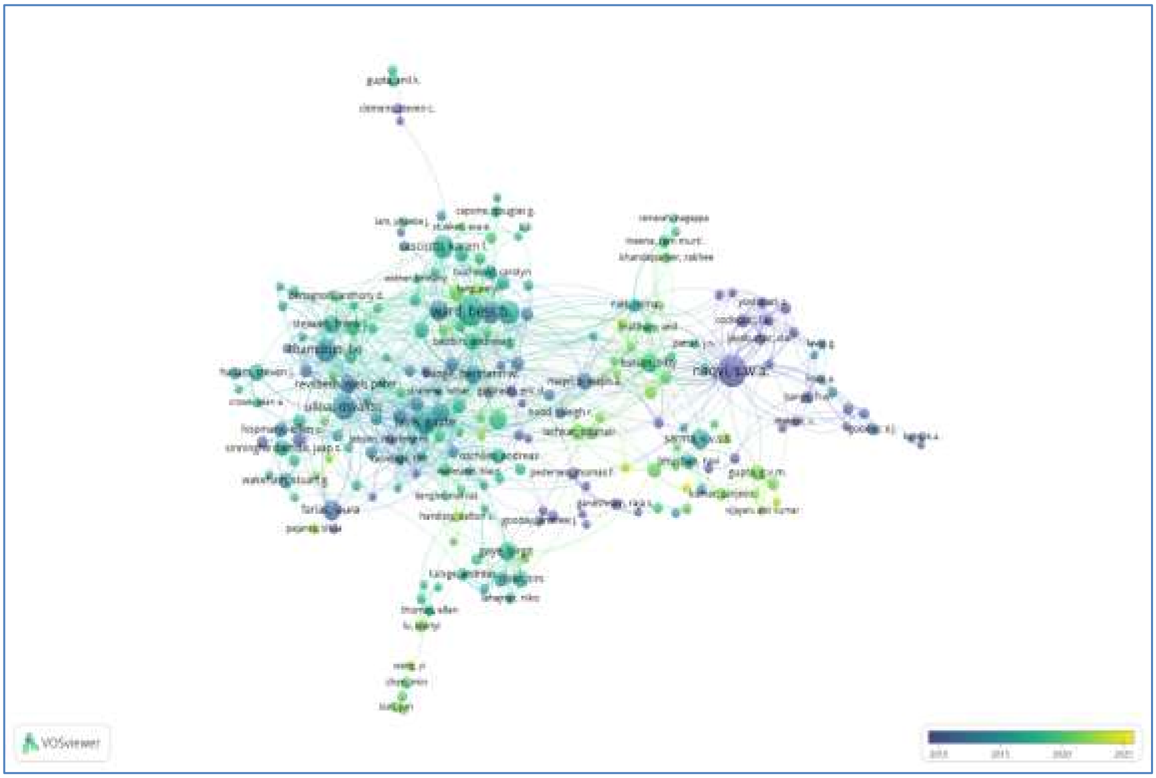

Figure 2. The VOSviewer overlay map shows the temporal dynamics of co-authorship in denitrification and marine biogeochemistry. Nodes represent authors; edges indicate co-authorships. Colors range from blue (older) to yellow (recent) based on average publication year.

2. Oceanic nitrogen cycle in oxygen minimum zone

Nitrogen is essential for biogeochemical cycles as a key part of nucleic acids, amino acids, porphyrins, and amino sugars (Falkowski et al. 1998). In marine and aquatic environments, nitrogen is shared with other elements and plays a role in reduction and oxidation reactions (Murray et al. 1995; Hulth et al. 1999). In marine environments, nitrogen exists in several forms: Dinitrogen (N_2)- a stable diatomic molecule requiring specialized enzymatic systems to break and use; Nitrate (NO_3-), the most oxidized and dominant biologically utilizable form in oxic environments; ammonium (NH_4), the most reduced natural form found in anoxic environments; particulate nitrogen, predominant in sediments primarily as organic N; and dissolved organic N (DON), a complex mixture of compounds. Nitrate, nitrite, ammonium, and organic nitrogen comprise "fixed N" in discussions of nitrogen availability (Devol et al. 2006; Brandes et al. 2007). In the nitrogen cycle, nitrification and denitrification are key processes. Nitrification is the microbial oxidation process transforming ammonium (NH_4+) into nitrate (NO_3-), facilitated by specific bacteria in oxygen-rich waters, particularly the water column and surface sediments. Denitrification occurs in low oxygen or anaerobic conditions, reducing nitrate (NO_3-) to gaseous form through a series of reductions to nitrite (NO_2-), nitric oxide (NO), nitrous oxide (N_2O) and finally dinitrogen N_2 gas **(Figure 3)**. OMZ waters account for 30-50% of nitrogen loss from world's seas, or 16-27% from land and oceans combined (Codispoti et al. 2001; Gruber and Galloway 2008). These nitrogen losses from the OMZs have left imprints in seawater nutrient, ratios of nitrogen to phosphorus, with negative deviations from the constant value of 16 (Redfield et al. 1963). These nitrogen deficits are commonly expressed as N∗. (N∗ = [Total inorganic nitrogen] − 16[$PO4^{3-}$] + 2.9 μmol kg^{-1}) (Gruber and Sarmiento 1997; Deutsch et al. 2001). Three major OMZs, show strongly negative N∗, implying nitrogen loss (Gruber and Sarmiento 1997).

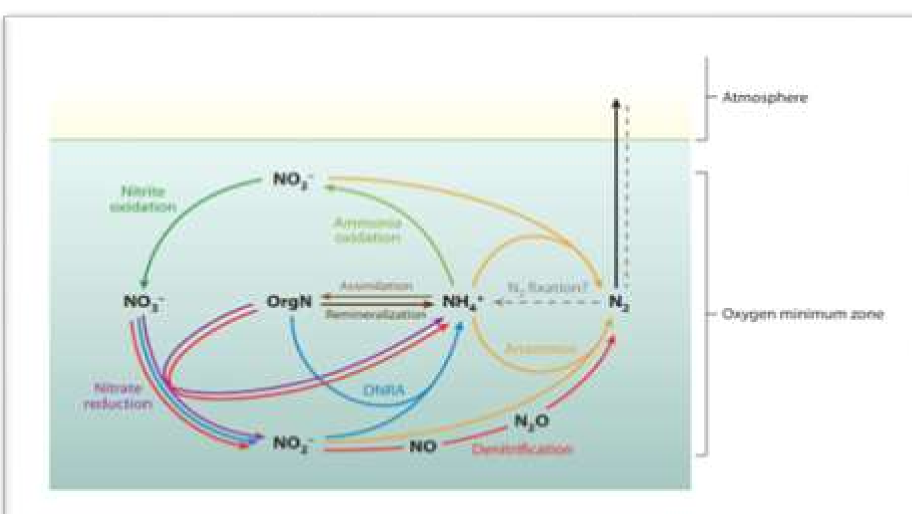

Figure 3. Nitrogen cycling in oceanic OMZs: N_2 is produced via anammox (orange) and denitrification (red). Nitrification occurs in two steps—ammonia oxidation (light green) and nitrite oxidation (dark green) (Lam et al., 2009).

3. Denitrification in the Arabian Sea

The Arabian Sea has a prominent oxygen minimum zone (OMZ) and nitrogen losses through denitrification, driven by suboxic conditions from high primary productivity and organic matter remineralization. These traits result from high oxygen demand below the euphotic zone and low-oxygen water influx from the South Indian Ocean (Swallow 1984; Olson et al. 1993). The Arabian Sea significantly contributes to N biogeochemical cycling as one of three major sites where fixed-N transforms to dissolved N_2. The breakdown of organic material depletes oxygen in the upper sub-thermocline water column. Particle flux is seasonal, with over half occurring in summer (Nair et al. 1989; Haake et al. 1993; Rixen et al. 1996). Denitrification estimates range between 21-33 Tg N yr-1 based on nitrate deficit calculations (Naqvi and Shailaja 1993; Howell et al. 1997; Bange et al. 2000), while a water column N transformation model suggests 11-24 Tg N yr-1 (Yakushev and Neretin, 1997). Surface circulation reverses from clockwise during SW monsoon to anticlockwise during NE monsoon (Schott et al. 2002) , with temperature lowest and productivity maximum occurring in northeastern Arabian Sea during winter cooling (Rixen et al. 2005; Wiggert et al. 2005).

5. Factors Influencing Denitrification in the Arabian Sea

5.1. *Oxygen Minimum Zone (OMZ)*

The AS features a strong OMZ, where oxygen concentrations drop to near-anoxic levels (<20 μM) (Paulmier et al. 2006). Denitrification occurs in this zone when the oxygen concentration falls below 2 μM, that favouring nitrate as the terminal electron acceptor (Naqvi et al. 1998; Paulmier et al. 2006). The OMZ's vertical extent and intensity directly regulate denitrification rates. Suboxia at the Arabian Sea OMZ core promotes significant denitrification fluxes, accounting for 20-30% of global pelagic nitrogen loss, despite covering less than 2% of the World Ocean area (Dueser et al. 1978; Naqvi et al. 1982; Gupta and Naqvi 1984; Naqvi 1987; Bange et al. 2005; Hood 2023).

5.2. *South Asian monsoon induced primary productivity*

Monsoonal circulation influences denitrification through seasonal winds. Summer southwesterly winds cause upwelling off Oman and Somalia, while winter northeasterly winds drive convective mixing in the northern Arabian Sea, moving nutrients to the upper ocean and creating phytoplankton blooms (Banse and McClain 1986; Madhupratap et al. 1996; Wiggert et al. 2005; Lévy et al. 2007; Resplandy et al. 2012; Lachkar et al. 2018). During Southwest Monsoon, coastal upwelling along India increases productivity, accelerates OMZ and denitrification (Jayakumar et al. 2009). while northeast monsoon convective mixing brings nutrient-rich deep waters to the surface, indirectly affects the nitrogen cycle and denitrification (Banse 1987; Sarma 2002).

5.3. *Hydrography and Stratification*

Water column stratification reduces oxygen replenishment in the OMZ, creating conditions for denitrification. Water mass circulation, influenced by mesoscale eddies and gyres, affects OMZ spatial variability and denitrification hotspots (Naqvi et al. 2006). Eddies primarily transport organic debris and trace metals. Mesoscale eddies and sub mesoscale filaments transport nutrients from coastal upwelling to the oligotrophic central Arabian Sea (Koné et al. 2009; Resplandy et al. 2011).

5.4 *Trace metal*

Trace metal availability in the Arabian Sea affects microbial denitrification effectiveness and extent. Limited metals can restrict enzyme action, while their abundance improves the process. For example, (Glass et al. 2015) suggested that trace metal scarcity could limit denitrification in suboxic conditions, (Naqvi et al. 2010) proposed that human inputs, such as industrial discharge and air deposition, could affect trace metal concentrations, thereby impacting denitrification rates in coastal zones. Previous studies have shown that the region along the shores of Somalia and Oman is vulnerable to iron deficiency during both the summer and winter monsoon seasons (Wiggert et al. 2006; Wiggert and Murtugudde 2007; Moffett and Landry 2020). According to a new modeling study by (Guieu et al. 2019), iron supply through aeolian dust deposition accounts for over half of summer primary output in the AS, demonstrating the significant role that iron may play in limiting biological production in the AS.

5.5 *Nitrate Availability*

Denitrification requires nitrate, is supplied by nitrification in oxygenated layers and oceanic/terrestrial inputs. The availability of nitrate influences denitrification intensity (Ward et al., 2009). The Arabian Sea's OMZ absorbs nitrate from upwelled waters and riverine inputs, boosting microbial denitrification. Anthropogenic nitrate from agricultural runoff and atmospheric deposition increases nitrate availability, potentially accelerating denitrification in coastal zones (Naqvi et al. 2010).

5.6 *Organic Matter Quality and Microbial Community Structure*

The type and lability of organic matter in the OMZ impact microbial activity and denitrification rates. Labile organic carbon promotes faster microbial respiration, increasing oxygen depletion and denitrification (Codispoti et al. 2001). Denitrifying bacteria and archaea control denitrification rates, with their communities affected by oxygen levels, organic matter, and nitrate concentrations (Devol 2003). The lateral advection of organic matter and unutilized nutrients from the upwelling zone into the Arabian Sea's central sectors influences OMZ intensity (McCreary et al. 2013; Moffett and Landry 2020). Modelling shows that lateral organic matter flow from the western Arabian Sea into central and eastern sectors enhances remineralization, lowering O_2 and intensifying denitrification below suboxic thresholds.

5.7. *Depth of Remineralization*

The depth of remineralization, defined as the depth at which sinking organic matter converted back into inorganic carbon and nutrients (Kwon et al. 2009; Cavan et al. 2017), influences the Arabian Sea OMZ intensity. For example, early observational studies showed that organic matter aggregation with river-derived lithogenic particles improves export fluxes in the Bay of Bengal compared to the AS (Nair et al. 1989; Ittekkot 1991; Rao et al. 1994). In a modelling investigation, (Al Azhar et al. 2016) demonstrated that the AS's thinner remineralization depth versus the Bay of Bengal (due to slower particle sinking speeds in the former) contributes to OMZ enhancement. The absence of ballast minerals from riverine input reduces particle sinking speed, increasing organic matter residence time in the OMZ layer and enhancing denitrification.

6. Stable Isotopic Method for Studying Denitrification

The oceanic fixed N inventory and surface availability control primary production. Changes in these parameters over geologic time impact global biogeochemical cycling of nitrogen, carbon, and oxygen throughout Earth's history. Sedimentary N isotope measurements developed as a powerful tool for reconstructing past marine N cycle and testing ice core CO_2 hypotheses (Galbraith et al. 2008). However, initial tests of the proxy demonstrated alteration of the primary isotopic signal during sinking, sedimentation and burial in some settings (Altabet and Francois 1994; Galbraith et al. 2008). Paleoceanographic research proceeded in spite of alteration evidence because sediments still showed local-to-regional spatial patterns of the surface and subsurface in water column N isotope composition (Altabet and Francois 1994) Biological processes transform N between forms, involving fractionation of N isotopes (15N/14N) (Wellman et al. 1968; Codispoti et al. 1989; Altabet and Francois 1994). The heavy and light isotopes react at different rates, which causes kinetic isotope effects. N2 fixation by diazotrophs influences DIN isotopic composition in modern oceans **(Karl et al., 1997),** along with surface NO_3 utilization, nitrification (Karl et al. 1997), along with surface NO_3 utilization, nitrification (Altabet and Francois 1994), denitrification (Liu and Kaplan 1989), and the anammox reaction. Internal cycling occurs through nitrification and absorption, while N_2 fixation and denitrification/anammox regulate the ocean's nutrient N inventory.

In the modern ocean, the N isotopic compositions **(as $\delta^{15}N$, where $\delta\,^{15}N = {}^{15}N/{}^{14}N_{(sample)} / {}^{15}N/{}^{14}N_{(standard)} - 1*1000‰$,** where the standard is atmospheric N_2) of different N pools are used to evaluate the relative roles of these various processes within the N cycle (Brandes and Devol 2002; Lehmann et al. 2004; Deutsch et al. 2004; Sigman et al. 2009). During denitrification process, microbes preferentially use NO_3^- with a lighter isotope ^{14}N, thus enriching residual nitrate in heavier isotope ^{15}N, which gets upwelled to the sea surface and it taken by organisms. The enriched ^{15}N signature is preserved when the organic matter settles and gets preserved in the sea sediments (Saino and Hattori 1980).

7. Past studies, Current Gaps and Future Directions

Past studies on Arabian Sea denitrification

Past variability in denitrification in the AS is closely linked to climatic changes, ocean circulation, and the strength of the Indian Summer Monsoon (ISM). Key insights come from sedimentary records, particularly nitrogen isotope ($\delta^{15}N$) analyses, which track changes in the intensity of water-column denitrification over geological timescales. In AS studies which are carried out on different geological time scales. On a longer timescale (100kyrs<) only a few studies are available, (Altabet et al. 1999) investigated sedimentary core from the Oman margin and Owen ridge and identified that denitrification was most active during interglacial periods and essentially inactive during glacial intervals, implying a strong link between climatic circumstances and denitrification processes. The site U1456 from the IODP-355 expedition in the Eastern Arabian Sea, within the Laxmi basin recorded by (Tripathi et al. 2017). gives origins, development, and intensification of the South Asian Monsoon (SAM). The study provides the first long-term record of denitrification in the AS since the Late Miocene. Denitrification occurred around 3.2 to 2.8 million years ago, during the Mid-Pliocene Warm Period (MPWP), when surface water productivity increased. Surface productivity is the primary factor controlling denitrification in the Eastern AS. The analysis implies that both the SAM and the East Asian Monsoon (EAM) changed concurrently during a tectonic period.

On the millennial time scale (glacial-interglacial) past changes in the OMZ intensity and water column denitrification have been inferred from sedimentary $\delta^{15}N$ with higher/lower values qualitatively indicating increases/decreases in denitrification intensity in the intermediate waters. The inferred changes have been related to variations in water mass composition, monsoon intensity, deep convective mixing, upwelling strength, and N_2 fixation (Reichart et al. 1998; Ganeshram et al. 2000; Suthhof et al. 2001; Agnihotri et al. 2003; Banakar et al. 2005; Pichevin et al. 2007; Kessarkar et al. 2010; Kao et al. 2015; Gaye et al. 2018). Core from the Murray Ridge, Pakistani, and Oman margins were examined by (Reichart et al. 1998). To gain a better understanding of OMZ and denitrification over 2,25,000 years, they contrasted the data with a number of tracers for sea surface productivity, aragonite compensation depth, and water column denitrification. The study's key finding is that variations in surface water productivity and the depth of winter mixing are the main causes of the OMZ's intensity fluctuations over orbital periods. A study of six piston cores collected from the eastern Pacific margin and the western AS concluded that denitrification in this region dropped significantly throughout glacial times. The sedimentary $\delta^{15}N$ was heavier (9-10.5 ‰) during interglacial and lighter (2-3 ‰) during glacial periods. The glacial decline is caused by reduced upwelling and organic material flux across the OMZ (Ganeshram et al. 2000). According to a study conducted by (Suthhof et al. 2001), the results show a close relationship to the Greenland ice core record, with low or nonexistent water column denitrification throughout the last glacial maximum, stadial, and Heinrich occurrences, including Younger Dryas. Denitrification was high during the Holocene and interstadial periods, and its amplification is linked to SW monsoonal upwelling, which increases organic matter flux and degradation. This study reported the results from three sediment cores from the north-eastern, northern central, and western AS. Denitrification rates in the AS fluctuate dramatically, indicating that the AS ecosystem is extremely susceptible to climate change and has a significant impact on atmospheric CO_2 concentrations. The $\delta^{15}N$ record from the WAS shows frequent fluctuations in marine denitrification strength due to upwelling oscillations, which imitate surface productivity on short timeframes (Altabet et al. 2002). A multiproxy analysis of the eastern AS revealed regional and temporal changes in the strength of subsurface denitrification in the water column. The findings suggest that denitrification intensity increased steadily from 2 ka to 10ka BP, most likely due to changes in surface productivity driven by stronger monsoonal upwelling (Agnihotri et al. 2003). Due to weakened summer monsoons and strengthened winter winds, the multiproxy study from the EAS single sediment core found that productivity was higher during the cold and dry glacial climate than during the warm and wet Holocene climate. Additionally, the water column denitrification was separated from local productivity during the extremely cold LGM climate (Banakar et al. 2005). The high resolution 50 kyr record of nitrogen isotope from Pakistan margin compared with five other denitrification records across the AS reveals, east-west heterogeneities in denitrification intensity across millennial-scale climate shifts and throughout the Holocene. Denitrification in the world's OMZs, including the western AS, gradually fell after the deglacial maximum (10-9 ka BP), however, the north-eastern AS record clearly shows rising denitrification beginning at 8 ka BP. This would have had an impact on the global Holocene climate through increased N_2O production and marine nitrogen loss (Pichevin et al. 2007). According to (Kessarkar et al. 2010) Higher primary production and lower denitrification intensity during LGM and MIS 4 could be attributed to convective winter mixing and more oxygenated subsurface waters. Reduced primary productivity during MIS 1/2 and MIS 3 could be attributed to increased precipitation from the amplified southwest monsoon, which fortifies near surface stratification. This study is based on sedimentological and isotopic characteristics of a sediment core from the southeastern AS containing records of 70 ka. Postglacial intensification of ISM with intensification of subsurface denitrification appears to have begun at about 15.2 ka BP coinciding with the onset of the Bolling-Allerod event. The ISM intensification was coupled with the strengthening of the Asian summer monsoon and warming in the North Atlantic. This trend probably forced an increase in northern hemisphere summer insolation (Kessarkar et al. 2013) The brief study on Spatiotemporal variations of nitrogen isotopic records in the AS by (Kao et al. 2015) studied available reports of dissolved oxygen, $\delta^{15}N$ of nitrate ($\delta^{15}N_{NO3}$) and $\delta^{15}N$ of total nitrogen ($\delta 15N_{bulk}$) for trap material and surface/downcore sediments from the AS (AS) were synthesized to explore the AS' past nitrogen dynamics and classified all reported data into northern and southern groups. Additionally, to the data set, nitrogen and carbon contents vs. their isotopic compositions of a sediment core (SK177/11) collected from the most southeastern part of the AS were measured for comparison. The study revealed that $\delta^{15}N_{NO3}$ at the base of the euphotic zone (~150 m) matched $\delta^{15}N$ SP, indicating that nutrients for sinking organic matter primarily originate from this depth. Sedimentary $\delta^{15}N$ bulk values were higher than $\delta^{15}N$ SP locally, suggesting post-depositional enrichment. Variations in nitrogen isotopic records linked to bottom depth were less pronounced in the northern AS compared to the southern region across climate stages. Prior to 6 ka, the $\delta^{15}N$ bulk offset between the southern and northern AS remained relatively constant (1.0 ‰ for the early Holocene and 0.9 ‰ for glacial periods). This suggests a synchronous shift in the relative intensity of denitrification and N_2 fixation across the basin. (Gaye et al. 2018) analyzed sea surface temperature (SST) and $\delta^{15}N$ ratios over 1000-year intervals during the last 25 kyr to explore the development of the AS OMZ and its link to Asian monsoon changes. Low $\delta^{15}N$ values (4–7‰) during the last glacial maximum (LGM) and stadials (e.g., Younger Dryas, Heinrich events) indicate weak or inactive denitrification during cold Pleistocene phases, while warm interstadials showed elevated $\delta^{15}N$, driven by Antarctic ventilation, causing strong millennial-scale variations. This paper presents a summary of $\delta^{15}N$ records from the AS including two new records from the Oman upwelling area. The records are from different areas and trace the regional history of mid-water oxygenation over the last 25 Kyr. Based on these integrated $\delta^{15}N$ and SST records for different regions of the AS they examine contrasts between glacial and Holocene conditions over the entire basin and contrasting regional evolution within the basin during the Holocene. the study carried out by (Kessarkar et al. 2018) worked on gravity core SK148/55 collected by (Thamban et al. 2007) concludes During the Holocene, denitrification in the AS was influenced by factors beyond upwelling and productivity. Strong pelagic denitrification occurred in the early Holocene (9.5–8 ka BP) within a thinner upper water layer, as suggested by light molybdenum isotope signatures and better-oxygenated bottom waters. A marked decline in denitrification during the mid-Holocene (7.6–5.4 ka BP) corresponded to enhanced OMZ ventilation, driven by a stronger summer monsoon and reduced atmospheric N_2O levels. These findings emphasize the complex interplay of environmental factors influencing denitrification and ventilation in the AS's OMZ over the Holocene. The latest study by (Singh et al. 2023) emphasizes Proxy records like $\delta^{15}N$ and aragonite preservation highlighting regional variability in OMZ dynamics across the AS, and reflecting unique responses to climatic and oceanographic changes. The study emphasizes the role of intermediate water circulation and thermocline ventilation in shaping OMZ evolution. Periodic inflow of oxygen-rich southern waters has been associated with reduced OMZ intensity, underscoring the importance of these water mass pathways for predicting future OMZ behavior. All Core locations of denitrification studies from AS are mentioned in **(Figure 4)** and details in **(Table 3).**

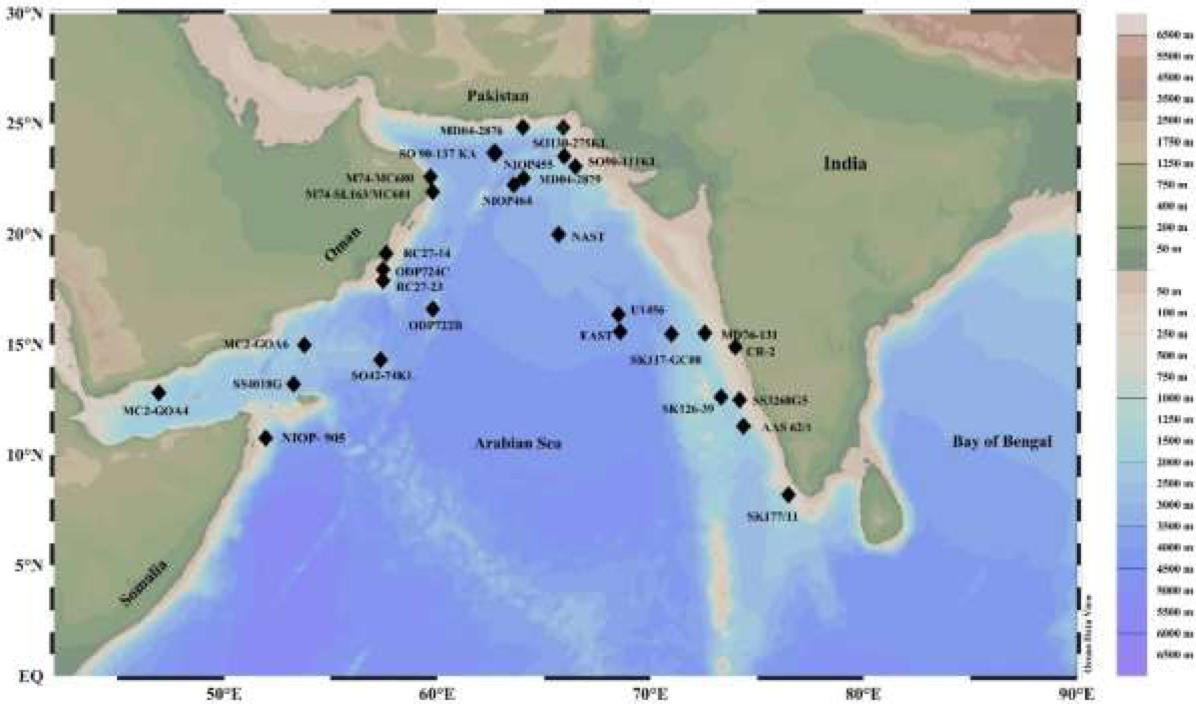

Figure 4 All Core locations of denitrification studies from Arabian sea. (refer Table 1 for details)

Core	Latitude	Longitude	Depth (m)	Reference	Variables
SO130-275KL	24.8218° N	65.9100° E	782	(Böll et al., 2014)	$\delta^{15}N$
M74-SL163/MC681	21.9328° N	59.8025° E	650	(Gaye et al., 2018)	$\delta^{15}N$
SO42-74KL	14.3210° N	57.3470° E	3212	(Huguet et al., 2006)	$\delta^{15}N$
MC2-GOA4	12.8215° N	46.921666° E	1474	(Isaji et al., 2015)	$\delta^{15}N$
MD04-2876	24.842833° N	64.008167° E	828	(Pichevin et al., 2007)	$\delta^{15}N$
NIOP455	23.5506° N	65.95° E	1002	(Reichart et al., 1998)	$\delta^{15}N$
SO90-111KL	23.0766° N	66.4836° E	775	(Suthhof et al., 2001)	$\delta^{15}N$
M74-MC680	22.6193° N	59.6916° E	789	(Gaye et al., 2018)	$\delta^{15}N$
MD04-2879	22.5483° N	64.0467° E	920	Jaeschke et al. (2009)	$\delta^{15}N$
NIOP464	22.2506° N	63.5836° E	1470	(Reichart et al., 1998)	$\delta^{15}N$
NAST	19.999° N	65.6843° E	3170	(Möbius et al., 2011)	$\delta^{15}N$
ODP724C	18.2833° N	57.4667° E	600	(Möbius et al., 2011)	$\delta^{15}N$
RC27-14	18.25333° N	57.6550° E	596	(Altabet et al., 2002)	$\delta^{15}N$
RC27-23	17.993333° N	57.5900° E	820	(Altabet et al., 2002)	$\delta^{15}N$
ODP722B	16.6167° N	59.8° E	2028	(Möbius et al., 2011)	$\delta^{15}N$
EAST	15.5917° N	68.5817° E	3820	(Möbius et al., 2011)	$\delta^{15}N$
MD76-131	15.53° N	72.5683° E	1230	(Ganeshram et al., 2000)	$\delta^{15}N$
SK117-GC08	15.4833° N	71.0° E	2500	(Banakar et al., 2005)	$\delta^{15}N$
MC2-GOA6	14.9800° N	53.767333° E	2416	(Isaji et al., 2015)	$\delta^{15}N$
CR-2	14.9° N	74° E	45	(Agnihotri et al., 2008)	$\delta^{15}N$

SS4018G	13.2133° N	53.2567° E	2830	(Tiwari et al., 2010)	$\delta^{15}N$
SK126-39	12.63° N	73.33° E	1940	(Kessarkar et al., 2010)	$\delta^{15}N$
SS3268G5	12.5° N	74.2° E	600	(Agnihotri et al., 2003)	$\delta^{15}N$
NIOP-905P	10.76666° N	51.9500° E	1586	(Ivanochko et al., 2005)	$\delta^{15}N$
SK-177/11	8.2^0 N	76.47^0E	776	(Kao et al., 2015)	$\delta^{15}N$
U1456	16.3728^0N	68.5033°E	3640	(Tripathi et al., 2017)	$\delta^{15}N$
AAS62/1	11.30456N	74.37388E	800	(Kessarkar et al., 2013)	$\delta^{15}N$

Table 3. Station number, locations, water depth (m), data sources (references), and variable used $\delta^{15}N$ ratios of total N. The given table modified from (Gaye et al., 2018.)

Current gaps

Research on denitrification in the Arabian Sea shows key gaps. Studies lack high-resolution temporal data to capture fine-scale variations, restricting understanding of short-term climatic or anthropogenic impacts. Research concentrates on central and northern regions, leaving the southern area underexplored, limiting understanding of spatial variability in denitrification. The relationship between South Asian Monsoon (SAM) variability and denitrification intensity remains poorly quantified, particularly regarding seasonal and interannual variations. The impact of increasing nutrient inputs from riverine and coastal runoff due to agricultural and urban runoff on oxygen minimum zone (OMZ) dynamics and denitrification rates needs further investigation. The role of microbial communities and functional genes in OMZ denitrification requires study, especially regarding adaptation to oxygen changes. The Arabian Sea OMZ's response to global ocean deoxygenation, with limited projections for future denitrification rates and their implications for the nitrogen cycle, remains poorly understood.

Interactions between denitrification and biogeochemical processes, particularly organic matter's role in driving denitrification, remain understudied. Research predominantly focuses on water column processes, while the significant role of sedimentary denitrification in nitrogen removal is overlooked. While nitrogen stable isotopes ($\delta^{15}N$) are used in denitrification studies, confounding factors like sediment diagenesis, lateral transport, and isotopic fractionation remain poorly understood, hindering a comprehensive understanding of Arabian Sea denitrification dynamics.

Future changes in Arabian Sea denitrification

Climate-induced Ocean deoxygenation from warming and reduced oxygen solubility will expand the Arabian Sea's oxygen minimum zone (OMZ), intensifying nitrogen loss through water-column and sedimentary denitrification. Enhanced stratification will limit oxygen replenishment, creating larger hypoxic zones, though the magnitude and variability of these changes remain uncertain, requiring advanced modelling and observation.

Rising anthropogenic nutrient inputs from agricultural and urban runoff inputs will increase primary productivity and organic matter flux to deeper waters. This organic matter decomposition will exacerbate oxygen depletion, further intensify denitrification. SAM changes may disrupt nutrient cycling through altered upwelling and monsoon patterns, affecting productivity.

Shifts in productivity and phytoplankton composition affect organic matter quality and quantity and denitrification efficiency. OMZ expansion will increase N_2O emissions, exacerbating global warming and stratospheric ozone depletion. Benthic processes at the sediment-water interface may significantly influence nitrogen cycling under future deoxygenation, requiring integrated studies on benthic-pelagic interactions to understand the Arabian Sea's nitrogen budget.

CONCLUSION

The Arabian Sea's oxygen minimum zone (OMZ) influences marine nitrogen cycling through denitrification. This review examines denitrification's millennial-scale evolution, shaped by monsoon variability, organic matter flux, and microbial activity. Knowledge gaps remain in understanding spatial and temporal variability, particularly in the southern Arabian Sea. High-resolution paleoclimate studies are needed to link monsoonal changes with OMZ dynamics and denitrification intensity. Anthropogenic impacts like eutrophication and deoxygenation require further exploration. Addressing emerging challenges like ocean deoxygenation and nutrient loading demands requires combining molecular biology, stable isotope geochemistry, and advanced modelling to understand microbial and biogeochemical mechanisms. Investigating the interactions between denitrification and other cycles, especially carbon and phosphorus, is crucial for predicting climate feedback. The Arabian Sea OMZ serves as a platform for studying denitrification over millennial timescales, essential for understanding global nitrogen cycling and environmental responses.

Author's Contribution

Author 1 conceived the review and wrote the manuscript with contributions from all authors. Author 3 and Author 4 performed the bibliometric analysis. All authors contributed to the article and approved the submitted version.

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