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From effluent to algal bloom: linking wastewater infrastructure, nutrient enrichment, and ecosystem stress in the Arabian Gulf

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Municipal wastewater discharge has emerged as the dominant driver of coastal eutrophication in the Arabian/Persian Gulf, distinguishing the region from most marine basins where agricultural runoff prevails. This paper synthesizes data on nutrient loads, eutrophication symptoms and wastewater governance across the eight Gulf nations, drawing on a combination of national reporting, published literature, and long-term coastal monitoring records. The findings reveal that untreated or insufficiently treated municipal effluents contribute the majority of anthropogenic nitrogen and phosphorus input to Gulf waters, with agricultural sources playing only a minor role. Symptoms of eutrophication, such as harmful algal blooms, hypoxia and ecosystem degradation, have become increasingly frequent and spatially widespread. These impacts are particularly pronounced in semi-enclosed, poorly flushed lagoons and bays common to many parts of the Gulf, where anthropogenic nutrient enrichment coincides with elevated biological and physical vulnerability. Despite these trends, regulatory standards for wastewater treatment remain inconsistent across the region, and infrastructure upgrades have not kept pace with population growth and urban expansion. Addressing wastewater-driven eutrophication in the Gulf will require a coordinated regional response that includes harmonized effluent standards, strategic investment in tertiary treatment, and improved monitoring and data sharing. By identifying key knowledge gaps and management priorities, this paper provides a regional framework to support evidence-based policymaking and reduce the long-term ecological and socio-economic consequences of coastal nutrient enrichment.

KEYWORDS

wastewater discharge, eutrophication, harmful algal blooms, hypoxia, biodiversity loss, semi-enclosed seas, Arabian Gulf, Persian Gulf

Highlights

- Gulf cities generate 8.6 B m^3 $year^{-1}$ wastewater, over six times the Tigris–Euphrates inflow
- 69% of wastewater treatment plants are within 10 km of Gulf coasts
- Effluent nutrient limits vary among nations, increasing vulnerability
- Nutrient-enriched blooms are risks to food and water security
- Recommendations are proposed for research and monitoring on local biological responses

1 Introduction

Eutrophication is defined as excessive enrichment of nitrogen (N) and phosphorus (P) in the water column, enhancing primary production in aquatic ecosystems, primarily through phytoplankton growth (Figure 1B; Devlin and Brodie, 2023; Rabalais et al., 2015; Saleh A. et al., 2021). This enhanced productivity often leads to harmful algal blooms (HABs), which adversely affect water quality, marine biodiversity, and human health (Horta et al., 2021; Sellner et al., 2003; Viaroli et al., 2015). During algal blooms, increased algal cell density at the surface reduces the area available for air–water gas exchange, lowering dissolved oxygen (DO) and raising CO_2 levels, which can, in some cases, also cause local acidification (Ngatia et al., 2019). As eutrophication progresses, part of the algal cells involved in the bloom eventually dies, increasing the supply of organic matter to the bottom. This phenomenon increased microbial activity at the seabed, which, together with chemical imbalance in the water column and alterations in the carbon and nitrogen cycling, leads to hypoxic conditions (DO $\leq$ 2 mg L^{-1}, Figure 1C). Notably, in shallow aquatic ecosystems, oxygen consumption is significantly driven by the water column (Hopkinson Jr and Smith, 2004). A recent study, for example, has observed how, under hypoxic conditions in estuarine habitats, 70% of the oxygen depletion can be ascribed to water column consumption (Zhou et al., 2021). These dynamics are variable and may also be influenced by the presence of an external input of organic matter and the hydrodynamics of the area, as well as nutrient enrichment (Alosairi and Alsulaiman, 2020). Oxygen-depleted waters can ultimately develop into 'dead zones', persistent and often large areas of seabed where most marine life no longer survives (Figure 1D; Devlin and Brodie, 2023; Rabalais et al., 2015; Saleh A. et al., 2021). Since the 1950s, more than 500 coastal sites worldwide have been reported to be hypoxic, with dead zones covering over 250,000 km^2 of coastal seas globally (Breitburg et al., 2018).

While natural factors, such as warm temperatures, limited flushing, or naturally low nutrient levels, may make a coastal system vulnerable to eutrophication (Vigouroux et al., 2021), it is typically human activities that drive most eutrophication in coastal environments. As human populations have continued to grow, mainly along coastal fringes, anthropogenically-driven eutrophication (ADE) has emerged as a leading threat to coastal ecosystems over the past

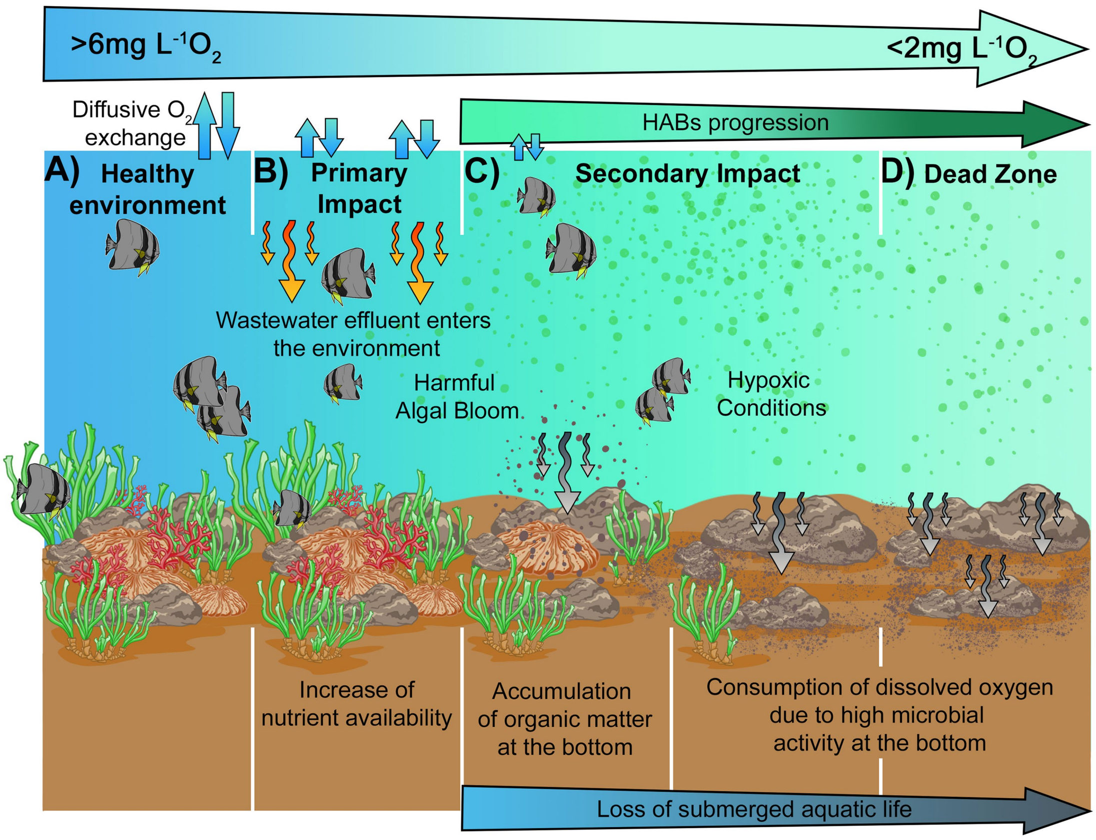

FIGURE 1
An illustration of the eutrophication phenomenon. **(A)** Stable situation with a healthy environment in which nutrient availability is within the standard range (i.e., dissolved oxygen levels above 6 mg L^{-1}). **(B)** Nutrient load is strongly linked with wastewater effluents discharged into the coastal environment. The eutrophication of the environment begins, and the first symptoms become detectable. We can observe an algal bloom that can be classified as harmful (Primary Impact). **(C)** The propagation of the HAB induces a strong consumption of dissolved oxygen in the water column due to the high microbial activity at the bottom of the area alongside the alteration of gas exchanges at the surface layer (Secondary Impact). The hypoxic condition is established (DO < 2 mg L^{-1}). Marine organisms start to encounter difficulties. At this point, complex organisms experience physiological stress that can result in death (i.e., mass mortality events) or they can migrate to a healthier environment, if possible. **(D)** Dead zone formation unfolds. Orange arrows: nutrient load input; Grey arrows: accumulation of organic matter and dead organisms at the bottom; Blue arrows: oxygen dynamics at the surface level.

50 years (Devlin and Brodie, 2023; Horta et al., 2021; Jessen et al., 2015). Major anthropogenic drivers include agricultural runoff and wastewater discharge from municipal and industrial sources, characterized by elevated concentrations of nitrogen, phosphorus, and other pollutants (Devlin and Brodie, 2023; Horta et al., 2021). Semi-enclosed, densely populated basins are especially susceptible to ADE due to the co-occurrence of both limited water exchange and concentrated anthropogenic input, leading to high nutrient loads that can trigger or exacerbate eutrophication. As such, ADE events have been recorded in semi-enclosed basins across the world (Annabi-Trabelsi et al., 2024; Devlin et al., 2015; European Environment Agency et al., 2019; Kotta et al., 2019; Mohamed, 2018; Snickars et al., 2015).

Global fertilizer use has risen substantially in recent decades, with the agricultural application of inorganic fertilizers increasing from 82 kg per hectare in 2000 to 112 kg per hectare in 2021, a 37% increase, reflecting intensified farming practices aimed at meeting growing food demands (FAO, 2023). Of the total fertilizers produced annually, nitrogen-based fertilizers accounted for about 56%, increasing from 85 million tons in 2000 to 119 million tons in 2021, while phosphorus fertilizers represented approximately 22–23% of total production in 2021 (FAO, 2023).

At the same time, wastewater discharge remains a significant environmental concern. In 2022, approximately 113 billion cubic meters of household wastewater were released worldwide into the environment without adequate treatment, highlighting the urgent need for improved wastewater management infrastructure worldwide (World Health Organization, 2024). With ongoing population growth, global wastewater production is projected to increase by over 50%, reaching 470 billion m^3 in 2030 and 574 billion m^3 in 2050 (Qadir et al., 2020). Currently, based on an average nitrogen concentration of 43.7 mg L^{-1} in wastewater, it is estimated that approximately 16.6 million metric tons of nitrogen are released annually through effluents (Qadir et al., 2020). Similarly, assuming an average phosphorus concentration of 7.8 mg L^{-1}, wastewater is estimated to contribute around 3 million metric tons of phosphorus per year on a global scale (Qadir et al., 2020). Obtaining regional data on nutrient concentrations downstream of wastewater discharges is currently highly desirable, as it would significantly enhance monitoring and management programs. However, such data are largely unavailable for this region, since most records report only discharge volumes rather than nutrient loads.

The Arabian/Persian Gulf (hereafter referred to as 'the Gulf') is particularly susceptible to anthropogenically driven eutrophication due to a combination of unique natural conditions and intensive human activities. Unlike many other semi-enclosed basins, where agricultural runoff typically contributes significantly to nutrient inputs, the Gulf's arid climate greatly restricts this nutrient pathway. Consequently, municipal wastewater discharge emerges as the predominant nutrient source fueling eutrophication and associated hypoxic conditions in this region (de Verneil et al., 2021). Over the past five decades, rapid population growth and urbanization have dramatically increased wastewater production, which, coupled with inadequate wastewater treatment infrastructure, exacerbates nutrient loads (Qadir et al., 2020). These anthropogenic influences interact with the Gulf's natural conditions, such as extreme temperatures, limited water exchange, and oligotrophic coastal waters, to render the basin exceptionally vulnerable to eutrophication and its associated ecological consequences (Nazari-Sharabian et al., 2018; Rodgers, 2021).

The Gulf has experienced a number of anthropogenically driven eutrophication events, resulting in HABs and coastal hypoxic conditions severely impacting marine biodiversity, fisheries and ecosystem health (Santos et al., 2023; Vaughan et al., 2019). While several localized studies have explored aspects of wastewater-related eutrophication, research efforts at the Gulf-wide regional scale have not kept pace with the increasing frequency and intensity of these events and their ecological ramifications. Consequently, no comprehensive synthesis exists on the state and environmental consequences of municipal wastewater discharge across the entire Gulf, leaving the full extent of wastewater-driven environmental risks uncertain. The Gulf hosts broad areas of ecologically significant ecosystems, including coral reefs, seagrass beds, and mangrove forests, making it an ideal region to assess the compounded biological effects of climate-driven temperature increases and direct anthropogenic nutrient loading. To address this critical knowledge gap, we specifically assess wastewater-driven eutrophication in the Gulf through a review of existing scientific literature. We aim to: (1) identify the regional drivers of municipal wastewater eutrophication in the Gulf, (2) assess ecological consequences of wastewater-induced eutrophication, focusing specifically on hypoxia and HABs, and (3) evaluate the management approaches used to regulate wastewater discharge and reduce nutrient loads. This review highlights both the environmental threats posed by wastewater discharge and opportunities to implement effective wastewater management policies in the Gulf.

2 The Arabian/Persian Gulf

The Gulf is a shallow, semi-enclosed subtropical sea bordered by Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (Van Lavieren et al., 2012; Vaughan et al., 2019). Characterized by extreme aridity, high sea temperatures (summer max. >36 °C), and hypersaline conditions (>60 PSU in lagoons), the Gulf represents a uniquely stressful environment for marine life (Burt et al., 2013; Sheppard et al., 2010; Vaughan et al., 2019). The basin averages just 30 meters in depth, reaching a maximum of 100 meters near the Strait of Hormuz, the primary channel facilitating seawater exchange with the Indian Ocean (Vaughan et al., 2019). Freshwater input is minimal, primarily sourced from the Shatt Al-Arab River in Iraq (Abaychi et al., 1988; Ismail and Shehhi, 2022; Vaughan et al., 2019). Instead, the Gulf experiences a net influx of water from the Gulf of Oman due to high evaporation rates (3 m y^{-1}) driven by high solar insolation and extreme aridity (Aleisa and Al-Zubari, 2017; Burt and Paparella, 2024). The net seawater inflow brings nutrients, such as N and P, into the basin, driving a dominant anti-clockwise halocline circulation around the Gulf (Figure 2). Compared to the Arabian Gulf, waters of the Gulf of Oman exhibit higher nitrogen and phosphate concentrations, contributing to a low N: P ratio (≤ 4.6:1) that falls significantly below the standard Redfield Ratio (16:1; Al-Thani et al., 2023; Devlin and Brodie, 2023; Ismail and Shehhi, 2022), making the Gulf an oligotrophic system that is highly vulnerable to nutrient imbalances. Seasonal shifts further complicate nutrient dynamics, with nitrogen typically limiting primary productivity in autumn, and phosphorus becoming the limiting nutrient during spring and summer months (Ghaemi et al., 2024; Ismail and Shehhi, 2022). These

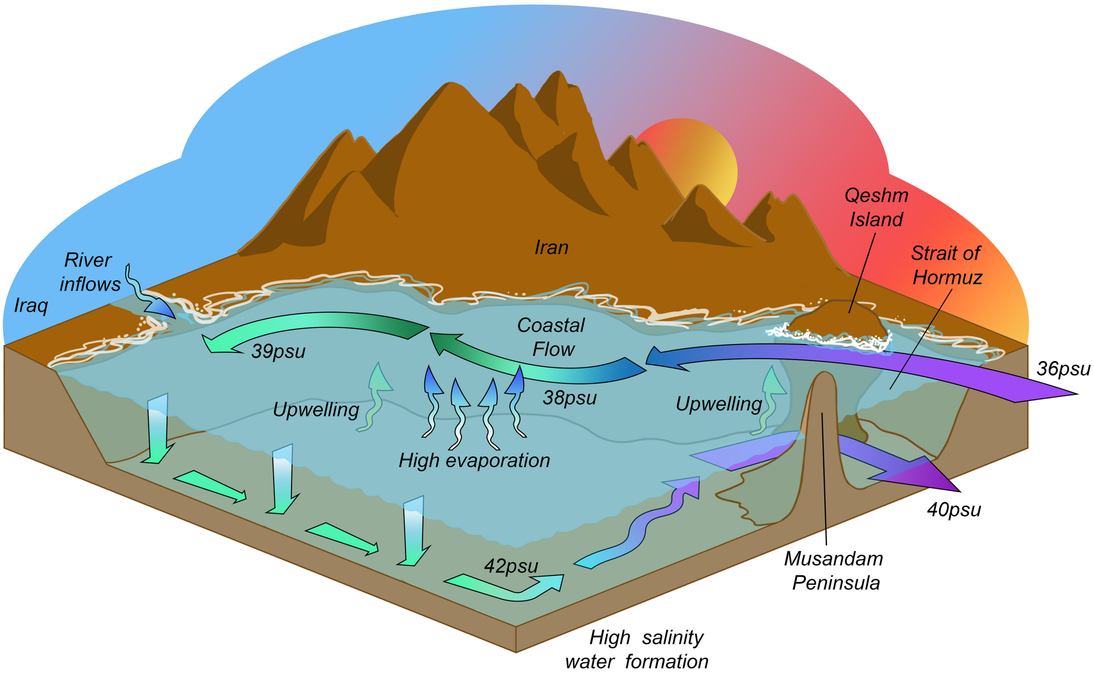

FIGURE 2
The tidal Current of the Gulf, modified from Burt and Paparella (Burt and Paparella, 2024).

natural physical and chemical characteristics collectively predispose the Gulf to heightened vulnerability toward eutrophication, particularly when exacerbated by anthropogenic nutrient loading.

The Gulf's extreme conditions make it a marginal marine system from an environmental perspective, but rapidly increasing human pressures, due to urbanization and industrial expansion, significantly compound these vulnerabilities. Since the discovery of oil and gas reserves in the 1930s, the eight Gulf-bordering nations have experienced rapid population growth, driven initially by fossil fuels and subsequently by diversified economic activities such as tourism, real estate development, manufacturing, construction and transportation (Van Lavieren et al., 2012). In 2012, the regional population growth rate for the countries surrounding the Gulf stood at 2.1%, nearly double the global average (1.1%; Van Lavieren et al., 2012). Current projections anticipate a further population increase of 19% between 2023 and 2050 (Figure 3), bringing the total regional population to 250 million (World Bank Group, 2024a). Notably, this growth is highly concentrated in coastal areas; in most countries surrounding the Gulf, at least 85% of the population resides within 100 km of the shoreline (Van Lavieren et al., 2012), and approximately 15 million people occupy 26 major urban centers along the Gulf coast (Burt et al., 2024). Such high-density coastal urbanization directly amplifies municipal wastewater discharge, intensifying nutrient loading and exacerbating eutrophic conditions in coastal marine environments (Ismail and Shehhi, 2022).

Effective wastewater management is critical in the Gulf context, where extreme evaporation, limited riverine input, and rapid population growth enhance the vulnerability of coastal waters. In 2020, the eight Gulf nations collectively produced an estimated 8.6 billion $m^3\ y^{-1}$ of municipal wastewater (Supplementary Table 1; World Bank Group, 2024b), a volume more than six times larger than the annual discharge of the Tigris-Euphrates River (1.39 billion $m^3\ y^{-1}$) into the Arabian Gulf (Al-Asadi, 2017). This production varies significantly, with just three countries contributing 84% of the total wastewater (Iran: 4.6 B $m^3\ y^{-1}$, Saudi Arabia: 1.55 B $m^3\ y^{-1}$, and Iraq: 1.11 B $m^3\ y^{-1}$), whereas less populous nations such as Bahrain generated only 0.15 B $m^3\ y^{-1}$ (Supplementary Table 1). A large fraction of this wastewater effluent has been released directly into the marine environment either untreated or only partially treated (Qureshi, 2020). Insufficient nutrient removal elevates coastal nitrogen and phosphorus loads, driving harmful algal blooms and hypoxic events (Devlin et al., 2019a; Devlin et al., 2015). The underutilization of reclaimed water further exacerbates freshwater scarcity, imposing heavy and largely avoidable economic and ecological costs on Gulf nations.

The rising volume of wastewater highlights the region's limited treatment and wastewater reuse. In 2020, the six Gulf Cooperation Council (GCC) states[1] treated only 73% of the collected municipal wastewater, equivalent to 39% of total production (Qureshi, 2020). Treatment infrastructure is unevenly distributed and relies on a mix of private and public funding. Across the GCC more than 300 public plants operate (Qureshi, 2020), ranging from Bahrain's 17 extensive

1 The Gulf Cooperation Council, or GCC, is a regional, intergovernmental, political, and economic union comprising Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. The council's main headquarters is in Riyadh, Saudi Arabia's capital. The Charter of the GCC was signed on 25 May 1981, formally establishing the institution - General Secretariat of the Gulf Cooperation Council (1981). *Gulf Cooperation Council*. https://gcc-sg.org/en/Pages/default.aspx

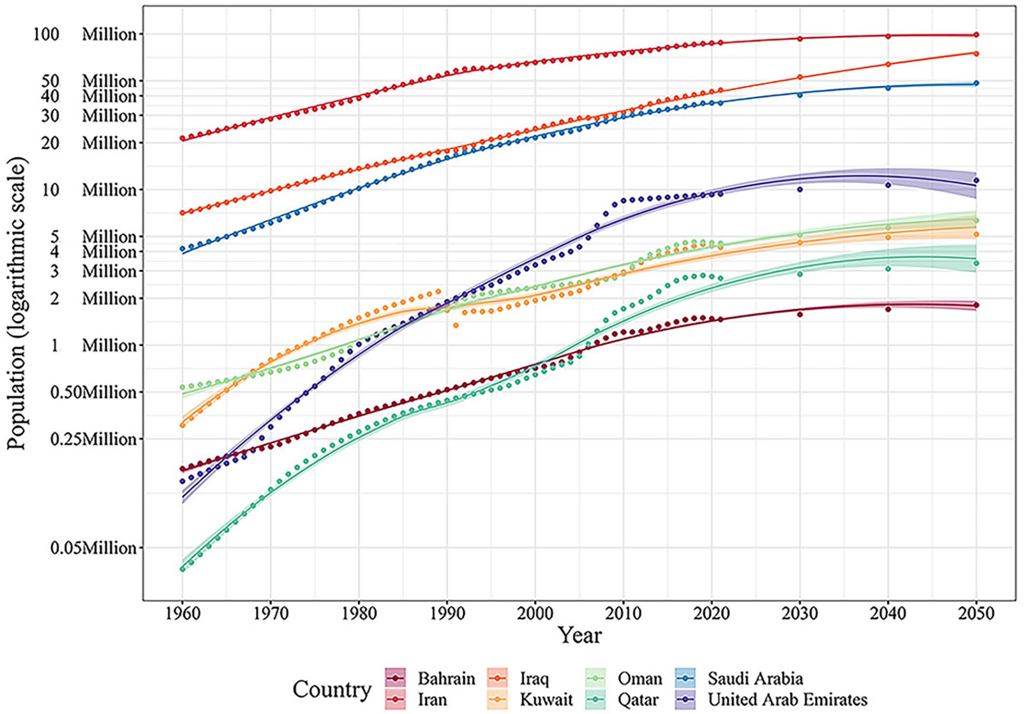

FIGURE 3
Population growth rate from 1960 to 2023, with the projection for 2030, 2040 and 2050. The data source is the World Bank dataset (World Bank Group, 2024a).

facilities serving 90% of its population and Kuwait's five high-capacity plants, to Oman's 402 smaller units that cover 86% of residents (Aleisa, 2019; General Directorate of Environment Bahrain, 2009; Jaffar Abdul Khaliq et al., 2017). Qatar relies on 27 plants to serve 94.7% of urban buildings (Planning and Statistics Authority Qatar, 2021), while Saudi Arabia and the UAE manage 81 and 140 plants, respectively (Aleisa and Al-Zubari, 2017; Federal Competitiveness and Statistics Centre, 2021). Outside the GCC, Iraq operated just 50 plants in 2013 (Dunia Frontier Consultants, 2013), and Iran reported 237 plants in 2023, which reach only 40% of its population, leaving 60% dependent on inadequate or informal sewage disposal (Akbarzadeh et al., 2023). These figures highlight the substantial gap between wastewater generation and effective treatment, thereby reinforcing the region's vulnerability to nutrient-driven coastal eutrophication.

Although every wastewater treatment plant is nominally connected and fed by a municipal sewage network, system inefficiencies permit untreated effluent to bypass treatment at multiple points. Structured sewage is primarily confined to major urban centers, while, in contrast, many rural and near-rural coastal communities rely on rudimentary collection systems or, in some cases, discharge raw sewage directly to the environment (Aleisa and Al-Zubari, 2017). These gaps substantially undermine regional treatment capacity and accentuate nutrient delivery to coastal waters.

The geographic distribution of wastewater treatment plants mirrors these disparities. Figure 4 shows that facilities are heavily clustered near large coastal cities: over two-thirds (69%) lie within 10 km of the shoreline (orange dots in Figure 4) and over a quarter (28%) are built less than 1 km from the coast (red dots in Figure 4). Interior settlements, by contrast, are sparsely served, reinforcing the urban–rural divide in wastewater management.

Technology choice further determines the efficacy of nutrient removal. Conventional primary treatment removes settleable solids, whereas secondary (biological) processes oxidize organic matter and achieve partial nitrogen and phosphorus reduction (Gerba and Pepper, 2019; Saleem et al., 2023). Tertiary treatment, utilizing filtration, activated carbon, chlorination, or advanced membrane systems, can reduce residual nutrients and pathogens to potable water standards, a capability of particular value in the Gulf region (Gerba and Pepper, 2019; Saleem et al., 2023). Most wastewater treatment plants in the eight Gulf states employ secondary or tertiary processes, yet up-to-date data for Iran and Iraq remain scarce (Saleem et al., 2023).

Tertiary treatment enables the safe reuse of reclaimed water for non-potable purposes, such as gardening and landscaping, as is currently practiced in Bahrain, Kuwait, Oman, Qatar, and the UAE (Aleisa, 2019; Aleisa and Al-Zubari, 2017; Saleem et al., 2023). Across the GCC, however, less than a third (28.6%) of collected municipal wastewater is treated and reused; socio-cultural concerns about irrigating food crops with reclaimed water partly explain this low uptake (Qureshi, 2020). The remainder of the treated effluent is typically discharged to rivers (i.e., in Iraq and Iran) or released directly into coastal waters (Akbarzadeh et al., 2023; Aleisa and Al-Zubari, 2017; Dunia Frontier Consultants, 2013), thereby forfeiting potential freshwater savings and perpetuating nutrient loading. Where tertiary treatment is absent, effluents retain elevated nitrogen and phosphorus concentrations, further exacerbating coastal eutrophication

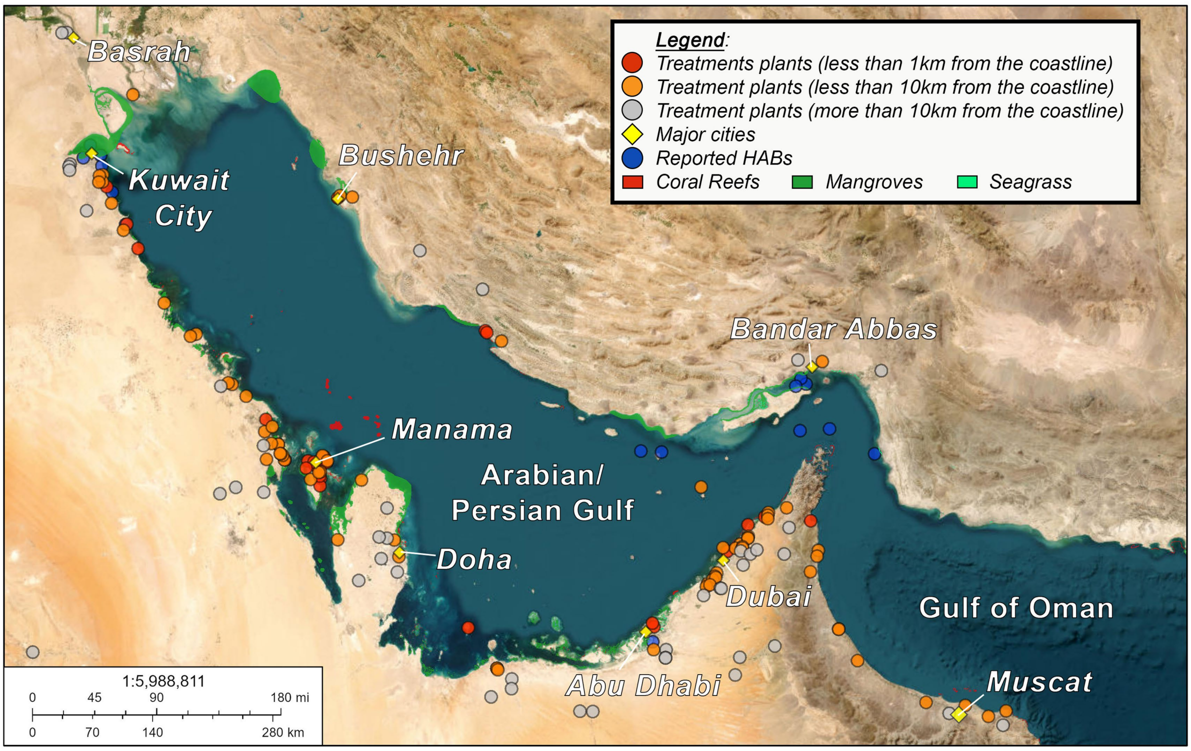

FIGURE 4
Map of the Arabian Gulf, denoting the major cities (yellow rhombus) and wastewater treatment plants. The plants have been identified using data from the World Resources Institute (Global Water Intelligence, 2023), Google Earth and peer-reviewed publications (Alhaj et al., 2017). Coral reef (dark red), mangrove (dark green) and seagrass (light green) cover was extracted from the Ocean Data Viewer dataset (Ocean Data Viewer, 2023). A high-resolution ArcGIS version of this map is available as Supplementary Figure 1.

(Akbarzadeh et al., 2023; Devlin et al., 2015; Dunia Frontier Consultants, 2013; Fatemi and Joolaei, 2020; Lyons et al., 2015; Todd, 2024).

3 The role of wastewater effluents in nutrient enrichment

The Gulf's arid climate, limited water exchange, elevated temperatures, and hyper-salinity create a naturally stressful setting for marine organisms. Over the past five decades, rapid coastal population growth has led to accelerated land reclamation and infrastructure expansion, resulting in a significant increase in municipal wastewater generation and discharge (Burt, 2014; Burt et al., 2013). Inadequate collection, limited treatment capacity, and insufficient reuse result in large volumes of nutrient-rich effluent entering the basin on a daily basis, raising concerns about both the immediate and long-term ecological consequences of anthropogenic nutrient enrichment.

Effluent standards along the Gulf are heterogeneous and primarily formulated at the national level, with limited cross-border coordination. Thresholds for nutrients (total N and P) and heavy metals vary widely among states (Conley et al., 2009; Ngatia et al., 2019), and guidelines for reuse are often more stringent than those governing direct discharge (Supplementary Table 2). Oman permits total threshold concentrations up to 50 mg L^{-1} and Iran up to 30 mg L^{-1}, values that exceed European and US limits for comparable population equivalents (p.e.[2]; 0.7 mg L^{-1} and 2–6 mg L^{-1}, respectively). In contrast, Saudi Arabia and Kuwait stipulate 2 mg L^{-1} and Iraq 0.4 mg L^{-1}, which are below European and US standards of 10 mg L^{-1} for 10,000 p.e. and 1 mg L^{-1}, respectively (European Commission, 2024). Such disparities weaken regional efforts to curb nutrient inputs and complicate opportunities for effluent reuse.

Recent monitoring programs provide direct evidence linking wastewater outfalls to elevated nutrient concentrations. For instance, total nitrogen and phosphate concentrations in nearshore areas adjacent to major discharge points, such as the Mussafah South Channel (UAE) and Doha Bay (Kuwait), are often 2–5 times higher than offshore reference sites, demonstrating a clear link between wastewater discharge and nutrient build-up in the water column (Alkhalidi et al., 2024; Environmental Agency Abu Dhabi, 2021; Rajan et al., 2020; Rajan et al., 2022). Similarly, a recent study on the algal community in Yas Bay (Abu Dhabi) suggested that nutrient variation in the water column correlates with anthropogenic input from the

2 Population equivalent: the organic biodegradable load has a 5-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day (Article 2(6) of the Directive). This term reflects organic pollution generated at agglomeration level by local inhabitants and other sources, such as non-resident population and industries under Articles 11 or 13 (Directorate-General for Environment; European Commission, 2024).

surrounding urban area (Moreno et al., 2025). Devlin et al. (2019b) identified a heightened increase in ammonium concentrations along the Kuwait coastline between 2009 and 2011. This increase has been traced back to the direct discharge of untreated wastewater due to pump malfunctions in 2009, after the commissioning of the Sulaibia wastewater treatment plant which could treat all the domestic wastewater generated in Kuwait in 2004 (Saeed et al., 2015).

Although wastewater discharge and eutrophication are broadly recognized as related issues, direct empirical evidence connecting effluent outflow, nutrient enrichment, and ecological impacts remains limited in the Arabian Gulf. This warrants further targeted research in this rapidly developing and environmentally sensitive region. Regulatory inconsistencies directly translate into spatially uneven nutrient loads, which trigger eutrophication stimulating harmful algal blooms and promote hypoxic events (Devlin and Brodie, 2023; Saeed et al., 2015). Over the past three decades, the Gulf recorded an average of three HAB outbreaks per year, many of which caused large-scale mass mortalities of fish and invertebrates (Al-Yamani et al., 2020; Alkhalidi et al., 2022, 2024). Figure 5 illustrates pronounced HAB hotspots at Bandar Abbas (Iran), Kuwait Bay, and along the Bahrain and UAE coast. Following the extensive 2008–2009 red-tide event, the number of blooms recorded in Bandar Abbas tripled, with 213 incidents between 2009 and 2019, mainly in nearshore waters (Mirza Esmaeili et al., 2021). Similar upward trends in bloom frequency and intensity are evident elsewhere in the Gulf.

A coastal time-series between 2012 and 2024 from Sharjah identifies wind-driven sediment resuspension and episodic sewer overflows as the dominant proximate triggers of HABs (Ahmed et al., 2025). The semi-enclosed nature of many lagoon areas, where wastewater is released, can also exacerbate these conditions (Cavalcante et al., 2021). Together, these findings support and extend the proposed hotspot mechanism, demonstrating its applicability to semi-enclosed urbanized coasts subject to both physical forcing and infrastructural stress.

This sustained acceleration in HAB occurrences is not symptomatic of a broader regional pattern in which wastewater-derived nutrient enrichment is emerging as a dominant ecological stressor. Unless nutrient inputs are reduced and regulatory frameworks are harmonized, eutrophication-driven blooms and their associated hypoxic events are likely to further intensify across the Gulf (Table 1).

4 Eutrophication and its consequences: short- and long-term effects of HABs and nutrient imbalance on marine ecosystems and society

Eutrophication compounds the Gulf's existing biological stressors, including rapid urbanization, extensive land reclamation and climate-driven rising sea temperatures (Burt, 2014; Burt and Paparella, 2024; Mirza Esmaeili et al., 2021). The convergence of natural extremes and anthropogenic pressures exacerbates biodiversity loss and jeopardizes ecosystem services such as fisheries, carbon sequestration and coastal protection.

Nutrient enrichment produces distinct temporal effects. In the short term, HAB proliferation and the onset of hypoxia can kill fish and invertebrates within days, with reported values of thousands of

FIGURE 5
Overview of the HABs records along the Gulf coastline over the last 40 years based on the literature cited in the main text and reported in Table 1. Satellite close-ups of the most critical areas impacted by the HABs are presented.

TABLE 1 **Comparison of the eight countries surrounding the Gulf.**

Nation (2020 data)	Population (Food and Agriculture Organization of the United Nations (FAO), 2020)	Treated municipal wastewater (Qureshi, 2020)	Reused municipal wastewater	Effluent concentration		Reported HAB/ hypoxia records
	Million	% of produced	% of treated	Nitrogen	Phosphorous	
Bahrain	1.48	46.7	90	No data	No data	from the 80s to the present–government monitoring (General Directorate of Environment Bahrain, 2009; Supreme Council for Environment Bahrain, 2020)
Iran	87.29	54.2	No data	1–2.5 mg L^{-1} (NH^{4+}) 10 mg L^{-1} (NO^{2-}) 50–10 mg L^{-1} (NO^{3-}) (Akbarzadeh et al., 2023)	6 mg L^{-1} (PO_4^{3-}) (Akbarzadeh et al., 2023)	August 2008–May 2009 (Fatemi et al., 2012; Rajan et al., 2021; Richlen et al., 2010; Samimi et al., 2010)
Iraq	42.56	52.3	No data	15 mg L^{-1} (NO^{3-}) (Noor and Alanisi, 2022)	0.4 mg L^{-1} (PO43-) (Noor and Alanisi, 2022)	February 2016 (Al-Shehhi and Abdul Samad, 2022)
Kuwait	4.36	86.2	61	3 mg L^{-1} (NH^{4+}) 30 mg L^{-1} (NO^{3-}) 5 mg L^{-1} (Organic N) (Environmental Public Authority Kuwait, 2001)	2 mg L^{-1} (Environmental Public Authority Kuwait, 2001)	September–October 1999 August–September 2001 June–July 2011 in Kuwait Bay (Al-Yamani et al., 2020; Devlin et al., 2019a; Glibert et al., 2002; Saeed et al., 2012; Saeed et al., 2015)
Oman	4.54	63.6	100	10 mg L^{-1} (Organic N) 50 mg L^{-1} (Total N) (Ministry of Environment and Water Resources Sultanate of Oman, 1986)	30 mg L^{-1} (Ministry of Environment and Water Resources Sultanate of Oman, 1986)	August 2008–May 2009 (Fatemi et al., 2012; Rajan et al., 2021; Richlen et al., 2010; Samimi et al., 2010)

(Continued)

TABLE 1 (Continued)

Nation (2020 data)	Population (Food and Agriculture Organization of the United Nations (FAO), 2020)	Treated municipal wastewater (Qureshi, 2020)	Reused municipal wastewater	Effluent concentration		Reported HAB/ hypoxia records
	Million	% of produced	% of treated	Nitrogen	Phosphorous	
Qatar	2.76	66.7	100	Not required (Qatar Petroleum, 2020)	Not required (Qatar Petroleum, 2020)	August 2008–May 2009 (Al Muftah et al., 2016)
Saudi Arabia	35.99	100	16	1 mg L^{-1} (NH_3) (Saleh A. A. S. et al., 2021)	1–2 mg L^{-1} (Saleh A. A. S. et al., 2021)	80s (Al Shehhi et al., 2014)
United Arab Emirates	9.29	100	55	150 mg L^{-1} (Organic N) (Department of Energy UAE, 2022)	50 mg L^{-1} (Department of Energy UAE, 2022)	August 2008 – May 2009 (Fatemi et al., 2012; Rajan et al., 2021; Richlen et al., 2010; Samimi et al., 2010) 111 algal bloom events between 2006 and 2019 (Rajan et al., 2020)
GCC countries total	58	38.6				
Regional Total (including Iran and Iraq)	188	63.5				

Population and wastewater data are presented together with the legal threshold for effluents and the reported HABs events. For further details, refer to the cited documents. Total generated wastewater for each nation can be found in Supplementary Table 1.

tons in the Gulf. For example, between September and October 1999, an extensive dinoflagellate bloom in Kuwait Bay, linked to untreated wastewater input, caused a massive mortality event, with over 30 tons of dead fish (Al-Yamani et al., 2020). Three years later, in 2002, another massive HABs caused a major fish kill in the same location (Al-Yamani et al., 2020; Glibert et al., 2002). In 2011, an important hypoxic event, with DO level below 1.93 mg L^{-1} at 1 meter and 0.08 mg L^{-1} along the bottom, induced another significant fish mortality event within the marina of the Kuwait Bay. The cause of the hypoxia can once again be attributed to organic loading from municipal wastewater effluent (Al-Yamani et al., 2020). Over more extended periods, sustained nutrient surpluses alter water quality chemistry, disrupt food webs, and may precipitate large-scale ecosystem reorganization or collapse (Horta et al., 2021).

Empirical evidence from the Gulf underscores the severity of these acute effects. In Tubli Bay, Bahrain, chronic overloading of the national wastewater treatment plant (100,000 m^3 d^{-1}) has, over the past two decades, produced recurrent HABs and mass mortality events (Abdulla and Naser, 2021; Aleisa and Al-Zubari, 2017). The Mussafah South Channel, Abu Dhabi, recorded 111 HABs in 12 years, coinciding with nitrate and phosphate levels that consistently exceeded local guidelines (Rajan et al., 2020). Kuwait Bay, which receives effluents from 50 outfalls, experienced hypoxia in 2011 (DO < 0.08 mg L^{-1}) and frequent fish kills, trends documented by a long-term monitoring program (Al-Yamani et al., 2020). Such eutrophication-linked mass mortality events have become increasingly common across the Gulf since the 1990s (Al-Muzaini et al., 1999; Devlin et al., 2019a; Saeed et al., 2015).

HABs also pose socio-economic risks (Al-Rawajfeh et al., 2023; Alotaibi et al., 2022). During the 2008–2009 bloom of *Cochlodinium polykrikoides* across the Gulf of Oman and eastern Arabian Gulf, algal toxins threatened public health and forced the closure of at least five UAE desalination plants due to membrane fouling (Al-Rawajfeh et al., 2023; Richlen et al., 2010). Such interruptions jeopardize the potable-water supply in a region heavily dependent on seawater desalination, representing a water security risk for regional nations (Al-Rawajfeh et al., 2023).

Chronic nutrient loading further destabilizes ecosystems (Jessen et al., 2015; Lan et al., 2024). This effect was observed during the 2008 *C. polykrikoides* bloom along the Qeshm Island in Iran, where corals experienced increased fouling by serpulid worms (Samimi et al., 2010). The same *C. polykrikoides* bloom was also associated with an anoxic event that extended along the UAE coast that resulted in substantial coral and fish mortality (Bauman et al., 2010).

Nutrient enrichment around coral reefs is also associated with direct effects on the coral holobiont physiology (Wiedenmann et al., 2013). For already climate-vulnerable corals, elevated nutrients disrupt the coral-algal symbiosis, impair photosynthetic function, and lower heat tolerance, while endorsing hypoxic stress, thereby increasing bleaching susceptibility and disease prevalence (D'Angelo and Wiedenmann, 2014; Morris et al., 2019; Thurber et al., 2014; Wang et al., 2018; Wiedenmann et al., 2013). Aquarium studies indicate that increased nitrogen can lower thermal tolerance of some Scleractinian corals, particularly when phosphate is limited (Wiedenmann et al., 2013). Interesting, some data show also how nutrient loads can also be tolerated by the coral holobiont as long as the essential nutrients are available for the symbiont, ensuring a chemically balanced growth (Wiedenmann et al., 2013). This may explain why not all the eutrophication events result in catastrophic bleaching, especially if other stressors, such as high temperature triggered by climate change, are absent (D'Angelo and Wiedenmann, 2014; DeCarlo et al., 2020; Donovan et al., 2020). Nitrate seems to have the most significant impact on both branching and massive corals when combined with even moderate thermal stress, triggering bleaching up to 100% for *Acropora* and 80% for *Pocillopora* on the French Polynesian reefs (Burkepile et al., 2020). Interestingly, Burkepile and collaborators also observed that with a high level of nitrate, the corals remain bleached even after the end of the thermal stress, tripling *Pocillopora* mortality (Burkepile et al., 2020). Nevertheless, interactions between high nutrients and elevated temperatures remain poorly understood, highlighting the need for regional studies, especially on thermally resistant corals.

Beyond corals, nutrient enrichment also affects seagrass meadows and mangroves. In seagrass meadows, phytoplankton and epiphytic algal overgrowth reduce light availability, suppressing shoot growth and canopy cover (Al-Mansoori and Das, 2024). Long-term effects on Gulf mangroves remain less certain owing to limited long-term monitoring, but studies elsewhere suggest that initial growth stimulation by nutrients may be offset by reduced resilience to climatic extremes (Erftemeijer et al., 2021; Mack et al., 2024).

Collectively, the evidence suggests that eutrophication has both immediate and lasting impacts on Gulf ecosystems and their associated human activities. Nevertheless, these observations underscore that direct evidence connecting ecological changes to socio-economic effects in the region remains limited, highlighting the need for targeted research to understand better and manage these linkages. Wastewater-derived nutrients are a principal driver underscoring the urgency of coordinated, basin-wide management measures aimed at reducing effluent loads, harmonizing nutrient standards, and strengthening ecological monitoring.

5 Challenges for the wastewater management in the Gulf

Recent global estimates place annual municipal wastewater production at 359 billion m^3, or approximately 50 m^3 per capita (Jones et al., 2021). Of this volume 63% is collected and 52% receives at least secondary treatment (Jones et al., 2021). The eight Gulf countries produced 8.6 billion m^3 in 2020, accounting for 2.4% of the global total, despite comprising only 1.7% of the worldwide population (Supplementary Table 1; World Bank Group, 2024b). Within the six GCC nations 7.6 billion m^3 were generated, 4.0 billion m^3 were collected (53%), and only 2.9 billion m^3 (38% of production) were treated at >300 public plants; a mere 39% of this treated fraction was reused, mainly for landscaping (Qureshi, 2020). Hence, the GCC lags the global average for both collection and treatment, and recovers far less reusable water than is technically possible.

Three structural deficiencies perpetuate wastewater-driven eutrophication in the Gulf. First, is infrastructure capacity. Large volumes bypass effective treatment because many plants operate beyond design limits or provide only secondary processing. Second, there are low reuse rates. Reclaimed water is seldom used for agriculture or industry, forfeiting a strategic water resource and necessitating the disposal of surplus effluent. Lastly, there is regulatory fragmentation. Nutrient discharge limits vary widely among states, and enforcement under the Regional Organization for Protection of the Marine Environment (ROPME[3]) remains weak, reducing the incentive to upgrade treatment systems.

These deficiencies impose environmental and public health risks that no single state can resolve in isolation. The GCC and ROPME have provided a platform for dialogue and collective action since the 1980s (General Secretariat of the Gulf Cooperation Council, 1981; ROPME, 1979), yet tangible progress depends on more substantial legal harmonization, credible enforcement and sustained political commitment to finance modern infrastructure. Regional coordination is necessary to standardize nutrient thresholds, share monitoring data and align investment priorities.

Experiences from Mediterranean countries demonstrate the value of comprehensive national water strategies operating in a shared water body. The European Commission's (2024) directive recommending quaternary treatment for wastewater intended for agricultural reuse, together with long-term enforcement in Spain, has measurably improved river basin water quality (Mas-Ponce et al., 2021; de-los-Ríos-Mérida et al., 2021). Comparable initiatives in Morocco (157 new wastewater treatment plants; 50% treatment rate 50% in 2020) and Egypt (planned capacity of 5 million $m^3\ d^{-1}$) show that substantial gains are achievable outside the EU (Mateo-Sagasta et al., 2022). Adapting similar frameworks, by combining advanced treatment technologies with clear reuse targets, would enable Gulf states to curtail coastal nutrient inputs while increasing non-conventional water supplies.

By integrating upgraded infrastructure, aggressive reuse targets, and regionally harmonized nutrient standards, Gulf nations can reverse current deficits in wastewater management and mitigate the escalating ecological and socio-economic costs of eutrophication.

6 Recommendations

Fundamental for Gulf countries is to facilitate the recovery of nitrogen and phosphate from the wastewater treatment plant

3 ROPME enclosed eight coastal countries: Bahrain, I.R. Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. This framework represents the regional organization for protecting the marine environment in the area, including the Gulf of Oman and the Arabian Sea, which, together with the Gulf, constitute the ROPME Sea Area (ROPME 1979).

production. Incorporating nutrient recovery processes, such as struvite and ammonia stripping, into wastewater treatment represents an economic opportunity, aligning the resources recovery with cost recovery and agricultural resilience (Abeysiriwardana-Arachchige et al., 2020; Aguilar-Pozo et al., 2023; Zangeneh et al., 2021), with the captured nutrients having the capacity to be later reused in agriculture as fertilizer (Abeysiriwardana-Arachchige et al., 2020). Given the region's high dependency on fertilizer imports and the growing emphasis on wastewater reuse, nutrient recovery would not only enhance environmental sustainability but also improve the economic viability of wastewater treatment systems (Śniatała et al., 2024).

To achieve this objective, a coordinated regional response is necessary if Gulf states are to curtail wastewater-driven nutrient loading and its ecological and socio-economic consequences. Three mutually reinforcing priorities emerge from the evidence assembled in this review.

6.1 Upgrade and optimize treatment infrastructure

Advanced, tertiary-level technologies that remove residual nutrients must replace or be retrofitted to ageing secondary treatment plants. Such upgrades would significantly reduce effluent nutrient concentrations, thereby safeguarding coastal coral reefs, seagrass beds, and coastal fisheries from eutrophication-related impacts, while simultaneously increasing the supply of high-quality reclaimed water for agriculture, urban greening, and other non-potable uses. Capital investment should prioritize processes that minimize energy demand, operational costs, and carbon footprints, ensuring long-term economic sustainability across the region's diverse socio-economic settings.

6.2 Adopt science-based, regionally harmonized discharge standards

Nutrient and related contaminant limits for marine outfalls should be aligned with international best-practice, yet calibrated to Gulf-specific conditions. Routine, standardized sampling of coastal water quality, coordinated through a pan-regional non-governmental institution like ROPME, is required to track compliance, detect emerging trends, and refine thresholds (United Nations Environment Programme, 1979). Where scientific uncertainty persists, the precautionary principle should be applied.

6.3 Strengthen governance, cooperation and public engagement

A legally binding nutrient reduction agreement negotiated through ROPME could establish standard monitoring methods, discharge limits, and progressive reduction targets. Annual scientific symposia would facilitate data sharing, enabling adaptive management. An integrated governance framework that links scientific evidence, regulatory enforcement and stakeholder participation must be supported by sustained finance from national governments. Ultimately, targeted public awareness and education campaigns can foster societal support for wastewater reuse and promote more effective water conservation strategies.

Collectively, these measures would move Gulf states towards a circular, resource-efficient wastewater economy, reduce eutrophication pressure on vulnerable marine ecosystems, and enhance regional water security.

7 Future research and remaining knowledge gaps

Effective implementation of the preceding recommendations will depend on a stronger empirical foundation than is currently available. Four priorities warrant immediate attention. First, process engineering studies should test and adapt advanced treatment technologies, such as ozonation, activated carbon, membrane bioreactors and advanced oxidation, for the extreme environmental characteristics of Gulf influents, with emphasis on removing nutrients and related contaminants and reducing energy demand.

Second, a region-wide, open-access monitoring network is needed to generate comparable long-term time series of influent quality, plant performance, coastal nutrient status and ecological condition. National agencies and ROPME should jointly define data standards and metadata requirements to facilitate seamless integration into a single Gulf wastewater database.

Third, targeted ecological experiments and modelling must quantify dose–response relationships between combined stressors (temperature, salinity, nutrients) and the health of biotic receptors such as microalgae, corals, seagrasses and commercially important fishes. Such studies would enable the determination of ecologically meaningful nutrient thresholds and refine tools for predicting harmful algal blooms and hypoxia.

Finally, socio-economic assessments must evaluate the costs and benefits of wastewater reuse, identify cultural and regulatory barriers, and explore incentives stimulating private investment in reuse schemes.

By closing these gaps, scientists and policymakers can develop evidence-based, regionally tailored strategies that secure both ecological integrity and water security across the Arabian Gulf.

8 Conclusion

Municipal wastewater discharge, rather than agricultural runoff, is the dominant source of anthropogenic nitrogen and phosphorus in the Arabian Gulf, making this region unique compared to much of the world, particularly in light of the extreme environmental conditions that characterize regional seas. The resulting eutrophication, which manifests in recurrent HABs, hypoxia, habitat degradation and socio-economic disruption, demands immediate, coordinated intervention. Priority actions include comprehensive modernization of sewage networks and treatment infrastructure, regionally harmonized, science-based nutrient standards, and strict regulation and enforcement. Establishing a Gulf-wide consortium dedicated to scientific, technical and logistic collaboration would accelerate technology transfer, streamline monitoring programs, and facilitate the adoption of legally binding nutrient reduction targets. Only through such collective effort can the Gulf states curb nutrient loading, safeguard vulnerable marine ecosystems, and secure the long-term sustainability of coastal resources and human livelihoods.

Author contributions

LG: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. AA-G: Data curation, Writing – review & editing. JAB: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Gen AI was used in the editing of the manuscript. Artificial intelligence tools (ChatGPT, OpenAI) were used during the manuscript preparation phase to improve grammar, clarity, and fluency of the English language. All conceptual content, analyses, and interpretation were developed entirely by the authors.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1702212/full#supplementary-material

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