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Global Eutrophication Spreads, Causes, Consequences and Control

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A R T I C L E I N F O

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A B S T R A C T

Eutrophication, the excessive nutrient enrichment of aquatic ecosystems, has become one of the most critical environmental challenges in modern times, affecting both freshwater and marine systems globally. This process, driven by elevated concentrations of nutrients such as nitrogen and phosphorus, leads to detrimental outcomes like algal blooms, oxygen depletion, and the creation of hypoxic "dead zones." Eutrophication is caused by both natural and anthropogenic factors, with human activities like agricultural runoff, urbanization, wastewater discharge, and deforestation playing major roles. These nutrient overloads trigger significant ecological disruptions, including the loss of biodiversity, oxygen depletion, and the proliferation of harmful algal species that pose risks to aquatic life and human health. In addition, cyanobacterial blooms have become a major concern due to their toxicity, which can lead to the death of aquatic organisms, contamination of drinking water, and health hazards to humans and animals. Globally, the prevalence of eutrophic water bodies has significantly increased, with the number of affected systems continuing to rise due to factors like urbanization, agricultural intensification, and climate change. This review explores the causes, consequences, and geographical spread of eutrophication, highlighting the urgent need for effective management and mitigation strategies to protect aquatic ecosystems and the services they provide.

Causes of eutrophication

Nutrient over enrichment in water ecosystems may stem from human activities or occur through natural phenomena. Natural events like flooding can increase nutrient levels in bodies of water, leading to a process called natural eutrophication. The following are some instances of this phenomenon.

Major Causes of Eutrophication

1. Agricultural Runoff: Excessive use of fertilizers in agriculture leads to nutrient runoff into nearby water bodies, contributing to increased nutrient levels (Pericherla et al., 2020). Fertilizers contain high amount of nutrient like nitrogen and phosphorus it leads to eutrophication. After flooding all agriculture water collect in lake or natural resources, it contains high amount of nutrient. Mostly during monsoon season agriculture runoff done and its lead to eutrophication.

2. Urban Runoff: Urban areas contribute to eutrophication through stormwater runoff carrying pollutants, such as nutrients, from paved surfaces and sewage systems (Tota-Maharaj et al., 2010). Urban runoff is a nonpoint source. These nutrients typically originate from sources like fertilizers, pet waste, and sewage from urban areas. When these nutrients accumulate in aquatic ecosystems, they promote the rapid growth of algae, leading to algal blooms. This process depletes oxygen levels in the water, harms aquatic life, and disrupts the balance of ecosystems, resulting in eutrophication (Smith, 2003).

3. Wastewater Discharge: Improperly treated or untreated sewage discharges introduce nutrients into water bodies, promoting eutrophic conditions. (Akpor et al., 2011). Wastewater discharge, including both municipal and industrial effluents, plays a pivotal role in the process of eutrophication. These discharges often contain elevated concentrations of nutrients, particularly nitrogen and phosphorus, which are commonly found in household and industrial wastes, detergents, and fertilizers. When these nutrient-rich effluents enter water bodies, they stimulate the rapid growth of algae, leading to algal blooms. The subsequent decay of these blooms depletes dissolved

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oxygen levels, creating hypoxic conditions that disrupt aquatic ecosystems, harm fish populations, and degrade water quality. This nutrient enrichment process is a significant driver of eutrophication in many freshwater and coastal ecosystems (Carpenter et al., 1998).

4. Deforestation: Removal of natural vegetation can lead to increased soil erosion, transporting nutrients into water bodies (Zheng et al,. 2005). Deforestation contributes to eutrophication by increasing the amount of nutrients, particularly nitrogen and phosphorus, that are carried into water bodies. When forests are cleared, the protective vegetation that naturally filters and absorbs nutrients is lost. This leads to an increase in soil erosion, causing more sediment and nutrients to wash into rivers, lakes, and coastal areas through runoff. The excess nutrients promote the growth of algae, which can result in algal blooms. As these blooms decay, they deplete oxygen levels in the water, creating hypoxic conditions that harm aquatic organisms and disrupt ecosystems, a key characteristic of eutrophication. (Vitousek et al., 1997).

5. Atmospheric Deposition: Airborne pollutants containing nutrients, such as nitrogen compounds, can settle into water bodies through atmospheric deposition (Weerasundara and Vithanage, 2015). These compounds, including nitrogen oxides (NOx) and ammonia (NH_3), are released into the atmosphere from sources such as fossil fuel combustion, agricultural activities, and industrial emissions. Once in the atmosphere, these nitrogen compounds can be carried by wind over long distances and eventually deposited onto land and water bodies through rain, snow, or dust. The excess nitrogen that is deposited into aquatic ecosystems acts as a nutrient, fueling algal growth and leading to eutrophication. (Galloway, 2004)

6. Aquaculture: Intensive fish farming and aquaculture activities may release excess nutrients, exacerbating eutrophication. (Datta, 2012). The nitrate and phosphate content in aquaculture effluent, concentrated, concentrated fish feed and organic matter are regard as a primary source of nutrients that are leached into water bodies through flooding during rainfall (Knight, 2021). Direct discharge of waste water from aquafarm content high amount of nutrients it leads to eutrophication in natural water bodies.

7. Natural Sources: While often overshadowed by anthropogenic sources, natural processes also contribute to nutrient loading in aquatic ecosystems. These include: The decomposition of organic matter, which releases nutrients back into the water. Weathering of phosphorus-rich rock formations, which can naturally leach phosphorus into water systems. Coastal upwelling, where nutrient-rich deep waters are brought to the surface, contributing to nutrient enrichment in coastal areas.

Consequences

Eutrophication can lead to a range of effects on water bodies. These impacts span from increased growth of water plants and algae – including green algae, diatoms, and cyanobacteria (also called blue-green algae) – often resulting in algal overgrowth, to more severe consequences. In extreme cases, eutrophication can render water sources unsafe for human consumption and recreational use, while also creating an environment that's inhospitable for aquatic organisms to survive. (Costa, 2018). Eutrophication causes water to become murky and take on a greenish tint, which blocks sunlight from reaching deeper levels. This light reduction hampers the photosynthesis process for underwater plants. Moreover, as algae die off and decay, they deplete oxygen levels in the water. This oxygen scarcity is particularly harmful to aquatic organisms living in the lower depths of water bodies, often leading to their demise (Sonaghare et al., 2020; Rathore et al., 2016; Kim et al., 2020; Hwang, 2020). When algal blooms deplete oxygen in the water, fish populations dwindle. This reduction in fish numbers triggers a chain reaction in the ecosystem. Mammals like sea lions and wading birds such as herons lose a vital food source. As a result, many shore birds and marine animals that rely on fish for nourishment face starvation, ultimately leading to their death. This illustrates how the effects of oxygen depletion can ripple through the entire food web of coastal and marine environments. (Sonaghare et al., 2020, Kim et al., 2020). After algal bloom crash bacteria decompose deceased algae, their respiratory process has two major effects. First, it uses up oxygen, leading to hypoxic (low-oxygen) conditions in the water. Second, it releases carbon dioxide as a byproduct. This CO_2 combines with water to form carbonic acid, increasing the water's acidity. In estuaries and lagoons severely affected by eutrophication, scientists have recorded significant spikes in water acidity levels. A key indicator of eutrophic water systems is the shift towards a prevalence of cyanobacteria. These microorganisms produce harmful toxins, effectively creating dead zone within the aquatic environment. (Rathore et al., 2016)

Since the mid-20th century, cyanobacterial blooms in freshwater ecosystems have emerged as one of the most detrimental forms of algal growth. These blooms cause a wide range of environmental and health issues, including: 1. Formation of dense surface scums 2. Production of potent liver and nerve toxins 3. Mortality of livestock and wildlife 4. Occasional human fatalities. The proliferation of these harmful algae has led to significant ecological disruption and poses serious risks to both animal and human health (Huisman et al., 2018) Furthermore, eutrophication hampers the passage of sunlight through water, which is crucial for photosynthesis in aquatic plants like sea grasses. This light blockage ultimately leads to the disappearance of sea grass beds from affected areas (Sonaghare et al., 2020; Kim, 2020; Almanasara et al., 2021).

The cyanobacterial toxin most frequently mentioned is microcystin (MCs), a hepatotoxin known to be produced in higher concentrations compared to other toxins. It has been observed to bioaccumulate more readily in aquatic animals, such as fish. When humans consume aquatic animals that have accumulated harmful levels of MCs, there is a significant health risk due to the toxin's movement up the food chain from lower to higher trophic levels (Usman et al., 2022). Scientific studies have shown that microcystin (MCs) are highly toxic to various organs, including the kidneys, heart, gastrointestinal tract, nervous system, and gonads of invertebrates. However, the liver remains the primary target of MCs (Usman et al., 2022; Lone et al., 2015).The consumption of water from rivers with high concentrations of microcystin (MCs) has been linked to an increased risk of colorectal cancer. Studies have suggested that prolonged exposure to MCs through contaminated drinking water may contribute to the development of this type of cancer, highlighting the significant public health risks associated with eutrophication and the presence of cyanobacterial toxins in freshwater sources (Xia et al., 2017).

Global eutrophication

The impact of eutrophication is felt worldwide, affecting both freshwater and marine ecosystems. A survey conducted by the International Lake Environment Committee (ILEC) from 1988 to 1993 revealed varying levels of eutrophication across global regions. The study found that eutrophic conditions affected 54% of lakes in the Asia Pacific region. Similar percentages were observed in other continents: 53% in Europe, 48% in North America, 41% in South America, and 28% in Africa (Greenhalgh and Selman, 2012). The proportion of eutrophic lakes worldwide increased significantly from 41% to 61% between the late 1970s and the late 1990s (Gibson et al., 2000). As of 2012, 63% of the world's inland water bodies were classified as eutrophic, with these eutrophic areas accounting for 31% of the total surface area of all water bodies (Lu et al., 2012 and Zhou et al., 2020). The dramatic growth in global population over the past century has transformed eutrophication from a localized problem into a widespread environmental concern. More studies suggest that the problem has only worsened. the number of coastal "dead zones" –

areas of hypoxia (low oxygen) resulting from eutrophication – had been doubling every decade since the 1960s, with over 400 systems affected worldwide by the early 2000s. (Diaz and Rosenberg, 2008).

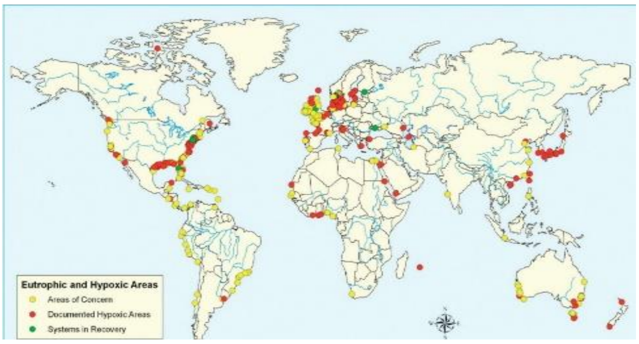

Figure 1: World hypoxic and eutrophic area (world resources institute, 2008)

A comprehensive global assessment has identified 415 coastal systems worldwide affected by eutrophication and hypoxia. Of these, 169 are scientifically documented hypoxic areas, 233 are areas of concern, and 13 are systems showing signs of recovery (Selman et al., 2008).

In 2008, Research had identified 20 eutrophic coastal zones across the African continent. Of these, 8 have been scientifically documented to experience hypoxic conditions, while 12 were classified as areas of concern due to various symptoms of eutrophication. In Europe, 168 coastal areas have been identified as affected by eutrophication and hypoxia. Among these, 59 are scientifically documented hypoxic zones, 106 are classified as areas of concern, and 3 were systems showing signs of recovery. In North America and the Caribbean, 131 coastal zones have been identified as affected by eutrophication and hypoxia. Of these, 62 have scientifically documented hypoxic conditions, 59 are classified as areas of concern, and 10 were showing signs of recovery. In South America, 25 coastal zones have been identified as affected by eutrophication and hypoxia. Among these, 3 have scientifically documented hypoxic conditions, while 22 were showing recovery. In Australia and Oceania, 36 coastal zones have been identified as affected by eutrophication. Of these, 9 have scientifically documented hypoxic conditions, while 27 were classified as areas of concern. In Asia, 33 coastal areas have been identified as affected by eutrophication. Among these, 24 have scientifically documented hypoxic conditions, while 9 were classified as areas of concern (World Resource Institute, 2008).

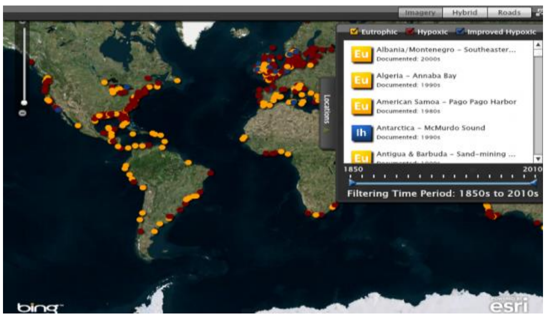

Figure 2: Map of Eutrophication 2013 (World Resources institute, 2013)

the map eutrophication 2013 identifies 762 impacted coastal zones worldwide: Active hypoxic zones: 479 sites currently experience hypoxia (low oxygen levels), Recovering areas: 55 sites that previously suffered from hypoxia are now showing signs of improvement, other eutrophication symptoms: 228 sites exhibit various effects of eutrophication such as: Algal bloom occurrences, Loss of species diversity, Degradation of coral reef ecosystems. This detailed mapping illustrates the global extent of eutrophication and hypoxia in coastal environments, highlighting the need for continued monitoring and mitigation efforts (World Resources Institute, 2013). Between 2008 to 2013 there were 347 costal zones, 310 hypoxic zones and 42 recovery sites increased. Between 2008 and 2013, the number of impacted coastal zones, hypoxic zones, and recovery sites showed a noticeable increase. Coastal zones grew by an average of 69.4 zones per year, hypoxic zones by 62 per year, and recovery sites by 8.4 per year. Based on these trends, we can project the situation for 2030. Over the 17 years from 2013 to 2030, it is estimated that the number of coastal zones affected by eutrophication will rise to approximately 1,528, reflecting a total increase of about 1,180 zones. The number of hypoxic zones is projected to reach approximately 1,364, with an estimated rise of 1,054 zones. Similarly, recovery sites, although increasing at a slower rate, are expected to grow to around 184, with an increase of approximately 143 sites. These projections assume the continuation of the current trends, although they could be influenced by changes in environmental policies, mitigation efforts, and global conditions that impact eutrophication and hypoxia.

Control of Eutrophication

Eutrophication, caused primarily by an excess of nutrients such as nitrogen and phosphorus, leads to harmful algal blooms, oxygen depletion, and the degradation of aquatic ecosystems. Effective management of eutrophication requires a combination of preventative, in-situ, and restorative approaches. One of the primary strategies is reducing nutrient inputs at the source, particularly from agricultural runoff and wastewater discharge. Best management practices (BMPs) in agriculture, such as precision farming, controlled fertilizer application, and crop rotation, can help minimize nutrient runoff into nearby water bodies (Carpenter et al., 1998). Upgrading wastewater treatment plants with advanced technologies like biological nutrient removal (BNR) can significantly reduce nutrient concentrations before discharge into water bodies (Smol et al., 2006). In areas with septic systems, proper maintenance and system upgrades can prevent nutrient leakage into the environment. In-situ management methods also play an essential role in controlling eutrophication. For instance, aeration of hypoxic waters can help restore oxygen levels, preventing fish kills and promoting the breakdown of organic matter. In some cases, the introduction of algae-eating species or zooplankton (biomanipulation) has been used to control algal blooms and improve water quality (Shapiro et al., 1975). Additionally, the restoration of wetlands is an effective way to naturally filter nutrients from water before they reach larger water bodies (Mitsch and Gosselink, 2015). Wetlands absorb and process excess nitrogen and phosphorus through plant uptake and sedimentation, helping mitigate eutrophication. The creation of constructed wetlands is another viable solution, particularly in urban or agricultural areas where natural wetlands have been lost.Moreover, public education and policy play a critical role in controlling eutrophication. Educating stakeholders, such as farmers, industries, and local communities, about the causes and consequences of eutrophication can lead to better practices and behaviours that reduce nutrient pollution. Government regulations, such as nutrient management plans for agriculture and stricter wastewater treatment standards, are essential for reducing nutrient loads entering water bodies (Nixon, 1995). Regular monitoring of water quality and nutrient concentrations is also crucial for assessing the success of these control measures and identifying areas in need of further intervention.

Conclusion

Eutrophication is a pervasive and escalating environmental challenge with profound impacts on aquatic ecosystems and human health. Primarily driven by anthropogenic activities such as agricultural runoff, urbanization, wastewater discharge, and deforestation, it results in the excessive enrichment of water bodies with nutrients, particularly nitrogen and phosphorus. This nutrient overload leads to widespread algal blooms, oxygen depletion, and the formation of hypoxic zones, degrading water quality, disrupting food webs, reducing biodiversity, and posing significant risks to both aquatic life and human populations. The global extent of eutrophication is alarming, with a marked rise in the number of eutrophic and hypoxic coastal and freshwater systems worldwide. While natural processes contribute to nutrient loading, human activities have accelerated this phenomenon, making it one of the most critical environmental issues of the 21st century. The increasing prevalence of harmful algal blooms, particularly toxin-producing cyanobacteria, further exacerbates the problem by threatening ecosystems and public health. To address eutrophication effectively, enhanced monitoring and global collaboration are essential to mitigate its impacts and safeguard aquatic ecosystems. As the global population grows, implementing effective management strategies is crucial to preserving the resilience of these ecosystems and the vital services they provide in the face of mounting environmental pressures.

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