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Eutrophication: A Multifaceted Examination of Processes, Impacts, and Remedial Approaches in Contemporary Aquatic Environments

KUMAR MANOJ[1] AND PRANAY PUNJ PANKAJ[2]

[1] Department of Botany, Marwari College, Bhagalpur, Tilka Manjhi Bhagalpur University, Bhagalpur, 812007, Bihar, India

[2]Department of Zoology, Nagaland University, Lumami - 798627, India,

Corresponding author: **PRANAY PUNJ PANKAJ**

Email: pranaypunj@gmail.com

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ABSTRACT

Eutrophication, propelled by excessive anthropogenic activities, has become a pressing global concern. This phenomenon entails the enrichment of water ecosystems with nutrients, predominantly nitrogen and phosphorous, fostering excessive biomass production and culminating in the development of hypoxic and anoxic conditions within aquatic habitats. While historically confined to freshwater bodies like ponds, lakes, and rivers, eutrophication has progressively encroached upon marine environments, notably coastal ecosystems, affecting freshwater and saline realms globally. This paper delves into the contemporary landscape of eutrophication, elucidating its principal drivers, deleterious repercussions, and prospective mitigation strategies. The study underscores the imperative of adopting comprehensive measures to curb eutrophication at a global scale for the sustainable management of water resources.

INTRODUCTION

Eutrophication, the excessive nutrient enrichment of water habitats, is a major global environmental issue because of its substantial effects on aquatic environments. Anthropogenic activities, like agricultural runoff, industrial discharges, and urbanisation, are the main drivers of this phenomenon, leading to the rapid buildup of nutrients in water bodies (Xu *et al.*, 2019; Yang, 2022). Eutrophication has seriously endangered aquatic environments' ecological equilibrium and biodiversity globally. Eutrophication has increased in recent decades, along with other significant environmental problems such as climate change and resource depletion. These interrelated concerns pose major hazards to global environmental sustainability (Xia *et al.*, 2016). Eutrophication has become a significant problem due to its widespread presence and harmful impacts on aquatic environments and other environmental challenges.

Extensive scholarly research has shown the eutrophication problem, emphasising its tendency to worsen in emerging nations compared to industrialised ones. Brönmark and Hansson (2002) and Odum and Barrett (2005) highlighted the significant effects of eutrophication on areas with scarce resources and insufficient environmental laws. Developing countries frequently undergo swift population expansion, urban development, and industrial growth, intensifying nutrient contamination and eutrophication in aquatic ecosystems. This study paper attempts to systematically examine eutrophication processes, repercussions, and solutions in modern aquatic habitats due to the urgent need to address this issue and its interactions with other environmental concerns. This study aims to establish effective strategies for reducing eutrophication and promoting sustainable water resource management globally by combining existing knowledge and investigating new alternatives.

Eutrophication - Origins and Definitions:

Eutrophication is the process of water ecosystems being overly enriched with nutrients, such as nitrogen and phosphorus, which can negatively affect the environment. This phenomenon involves the rapid growth of cyanobacteria, algae, and other aquatic plants caused by abundant nutrients, reducing oxygen levels and degrading water quality (Odum and Barrett, 2005).

In 1907, German scientist C. A. Weber introduced the word "eutrophication" to characterise nutrient-rich marshes in Europe that were absorbing runoff from adjacent areas (Schindler, 2006). Since then, it has been commonly utilised to depict the process of nutrient enrichment in aquatic environments.

It is essential to comprehend the origins and meanings of eutrophication in order to tackle this worldwide environmental issue and create successful solutions to reduce its effects on modern aquatic ecosystems. Closely associated with the eutrophic concept are the concepts of mesotrophic and oligotrophic water bodies (Dasmohapatra, 2011). Both nitrogen and phosphorous are often essential limiting or controlling factors for the abundance of organisms. In recent times, however, both these elements have created severe adverse effects on a global scale due to overfertilisation. Based on productivity, water bodies are often designated as either oligotrophic, which means low in nutrients or eutrophic, which means high in nutrients (Odum and Barrett, 2005).

Nutrients like phosphorus and nitrogen are the most important cause of water bodies' eutrophication. Phosphorus is probably the primary pollutant contributing to eutrophication as it cannot be completely recycled. River bottom pollution is among the major causes of water eutrophication, which is mostly caused by unreasonable human activity, particularly the expansion of agricultural practices. The process of eutrophication occurs when pollutants enter water bodies through surface runoff. Fertiliser usage in agricultural areas, the areas around planting and aquaculture, livestock farming, animal husbandry, rural domestic waste, land use, atmospheric sedimentation, and runoff all contribute to the release of nutrients into water bodies. A significant amount of nitrogen and phosphorus components enter the water channel through runoff due to fertiliser application. Agricultural non-point source pollution emissions have grown due to overexploitation of rural areas. The primary causes of the rise in phosphorus concentration in river substrates are human-caused soil erosion and siltation. Wastewater from industries is another important source of phosphorus and nitrogen. The wastewater released by agricultural enterprises, processing, animal husbandry, and others has a higher nitrogen content, whereas the wastewater released by chemical industry facilities has a higher phosphorus content. The crucial causes of eutrophication include raising animals and conducting agriculture in the higher upstream reaches of water bodies. In addition, there is the outflow of sanitary wastewater. Unnecessary phosphorus entering rivers can result from using pesticides, fertilisers, and detergents containing phosphorus. Nutrient levels in the water are further raised by the artificial feed used in the high-density aquaculture sector (Yang, 2022).

During intermittent rainfall events, a significant amount of nitrogen and phosphorus are carried to coastal zones by rainwater runoff from urban catchments. Increased emissions of nutrients, including phosphorus and nitrogen, into the surrounding ecosystem, can result from rapid urbanisation in coastal zones. Urban pollutants (mainly nitrogen and phosphorous) have the potential to enter natural water bodies by storm runoff, become dissolved by it, and eventually cause eutrophication of lakes, rivers, and coastal waters. Urban storm runoff is the primary factor influencing nutrient movement and conversion in urban environments. During days without rain, the nutritional salts build up in the soil, water bodies, and on the rough surface of the earth due to pollution emissions, air dry deposition, etc. Aerosol particles act as cloud nuclei to enter cloud droplets during rainfall events. Brownian diffusion, interception, impaction, and turbulent diffusion are the processes by which the descending rain droplet particles clash with aerosol particles. Ultimately, surface flow and the sewage system release the nutrient salts into the adjacent coastal environment through leaching and wash-off. The estuary region and the inner bay are most affected by storm runoff pollution regarding eutrophication and seawater quality (Xu *et al.*, 2019).

Eutrophication - Classification and Impacts:

Eutrophication can be categorised as natural or cultural based on the rate of nutrient enrichment and human involvement in water bodies (Schindler, 2006). Natural eutrophication develops slowly over many periods due to natural processes, including weathering and organic matter decomposition (Brönmark and Hansson, 2002). Cultural eutrophication is caused by human activities, causing a sudden rise in nitrogen levels and the growth of algal blooms in water bodies (Radojević and Bashkin, 2006). Agricultural runoff, sewage discharge, and industrial effluents inject excessive nutrients into aquatic habitats. Natural eutrophication mainly occurs in regions where geological processes lead to nutrient enrichment, including volcanic areas or areas with significant sedimentation rates. On the other hand, cultural eutrophication is caused by anthropogenic actions such as agricultural runoff, sewage discharge, and phosphorus-based detergents. These activities deliver abundant nutrients into aquatic habitats, hastening eutrophication (Schindler, 2006). The categorisation of eutrophication into natural and cultural categories offers insights into the root causes of this phenomenon. It aids in identifying appropriate remedial strategies to reduce its effects on modern aquatic ecosystems.

Change in ecosystem structure, function and biodiversity: Eutrophication can adversely affect the aquatic ecosystem's quality and cause significant changes in its structure, function and diversity (Khan and Ansari, 2005). Anthropogenic disturbance of water bodies, in the form of eutrophication, may drastically alter their abiotic environment and thus change the position of the abiotic frame of these water bodies. Due to this change, the niche of several aquatic life forms will fall outside the abiotic frame, resulting in their extinction from that specific system. Both abiotic and biotic factors determine biodiversity. On a smaller spatial scale, water chemistry, for example, is a background abiotic environmental factor which affects the biodiversity of all freshwater bodies, including ponds and smaller lakes (Brönmark and Hansson, 2002). About eutrophication, a sudden shift in aquatic ecosystems may occur after long-lasting water pollution.

When a threshold is surpassed, the aquatic system undergoes a transformation, leading to an alternate state that remains unresponsive to reduced pollution levels until pollution burdens significantly drop below the specified threshold. However, the response of the aquatic system to the cessation of pollution and return to the initial conditions will not retrace the same trajectory. In this case, if biodiversity losses injure the egg and seed bank, the return of the aquatic system to its original state will never occur. Thus, preservation of natural sites should be preferred over later recovery of degraded ecosystems (Miracle *et al.*, 2010).

The two immediate responses shown by an aquatic system to an increase in the content of nutrients are an increase in photosynthetic rate and an abundance of plants. These outcomes can cause productivity to increase at all levels of the food chain, including fish at higher trophic levels. However, during eutrophication, alteration can occur in the organisms that inhabit aquatic ecosystems, disrupting energy transfer up the aquatic food chain. The epilimnion layer is the chief site for producing algae and other aquatic plants. However, as algae and other aquatic biota die in the epilimnion, they sink to decompose in the deeper hypolimnion, which is an oxygen-consuming process. An increase in supplies of nutrients causes an increase in organic matter content, leading to severe depletion of oxygen concentration in the hypolimnion. At such low oxygen concentrations, survival of air-breathing organisms becomes impossible in the deeper layers of water bodies. As the water body becomes more eutrophic, the species of bottom-inhabiting invertebrates and fish fauna change from those that require high oxygen concentration to those that are tolerant to low oxygen (Schindler, 2006). A rise in the anoxic boundary layer, a rise in the bottom water oxygen demand, and a more considerable attenuation of light are possible outcomes of eutrophication on sedimentation.

Consequently, the euphotic zone will be shallower. The availability of fish habitats may decrease due to these changes, which could be better for fisheries. The species makeup of phytoplankton may also shift (Msomphora, 2008).

Harmful algal bloom (HAB): All across the world, harmful algal blooms (HABs) are marked by the growth of poisonous and destructive algae and cyanobacteria (blue-green algae). Any occurrence that negatively affects aquatic systems, socio-economic interests, or human health is categorized as a health-related obstacle. Wide-ranging effects of HABs include the generation of potentially dangerous or fatal toxins, the development of hypoxic or anoxic zones, increased expenses associated with water treatment, and a reduction in the quality and usefulness of water bodies (Phys.org, 2024).

HABs have been linked to a growing trend of pollution-related issues in many aquatic environments. The presence of HAB in fresh and marine waters has resulted in the mass mortality of wild and farmed fish and shellfish, human illnesses, and, in some cases, fish or shellfish contamination-related deaths, as well as the death of marine mammals, seabirds, and other animals. Additionally, the alteration of marine habitats or trophic structure through shading, overgrowth, or adverse effects on fish and other marine organisms' life history stages has hampered the sustainability of fisheries and aquaculture. The emergence of Harmful Algal Blooms (HABs) can detrimentally affect industries such as aquaculture, which rely on clean water for their operations, by inducing dead zones in water bodies and increasing the cost of treating drinking and clean water (Eong and Sulit, 2017). Table 1 exhibits a roster of microorganisms accountable for Harmful Algal Blooms (HABs).

World Health Organization underscores that one of the numerous ramifications of eutrophication is the proliferation of toxic cyanobacteria in water. Cyanobacterial toxins have recently garnered widespread recognition as a threat to human health. Exposure to cyanotoxins through ingestion and recreational contact may lead to waterborne diseases. Several countries, including the USA, England, Australia, as well as some BRICS nations such as Brazil, China, and South Africa, have reported health issues stemming from cyanotoxins in water (WHO, 2003).

In the case of blue-green algal blooms, several cyanobacteria species can cluster in lakes and streams and create toxins for people and aquatic life. They constantly threaten the world's supply of potable water and water bodies. Large algal blooms are typically observed in the summer, and cyanobacteria are thought to be heat-loving organisms. However, cyanobacterial blooms can also happen in colder climates-even beneath ice. These blooms have drawn attention because greater water temperatures above 25 degrees Celsius encourage the growth of cyanobacteria, particularly in light of climate change. However, at relatively low water temperatures (below 15 degrees Celsius), cyanobacterial blooms may also happen in lakes-even beneath a layer of ice (Phys.org, 2023).

"cyanotoxins" refers to a complex class of substances that differ in their physicochemical properties, structures, and toxicity levels. Examples of these substances include teratogenic poly-methoxy-1-alkenes, cytotoxic alkaloids (cylindrospermopsins), hepatotoxic cyclic peptides (microcystins), neurotoxic alkaloids (anatoxin and saxitoxin analogues), and parts of their cell walls, such as lipopolysaccharides (Wejnerowski *et al.,* 2018). Worldwide, cyanobacteria are phototrophic microorganisms that live in a variety of settings. Cyanobacterial harmful algal blooms, or cyanoHABs, are dense biomass accumulations that occur seasonally in many eutrophic lakes that are affected by excess nitrogen and phosphorus. Several particular adaptations that contribute to their domination in eutrophic lakes are nitrogen and phosphorous concentrating mechanisms, nitrogen fixation, colony formation that deters predators, vertical transportation via gas vesicles, and synthesising poisonous or decomposition lead to a significant reduction in dissolved oxygen levels within water bodies. Eutrophication induces the formation of anoxic environments, resulting in biodiversity decline and hindering the agricultural functionality of water ecosystems. The emergence of anoxic conditions promotes the growth of anaerobic organisms at the expense of aerobic ones. Eutrophication poses a grave threat to freshwater systems, compromising essential water qualities due to profound oxygen depletion. This directly impacts aquatic fauna, leading to premature and considerable fish mortality rates. Eutrophic waters exacerbate challenges in fishing and navigation, render swimming unsafe, promote the proliferation of pathogenic other bioactive chemicals. Certain compounds have been studied for their potential medical uses, but others are classified as cyanotoxins and are potent poisons that are dangerous to people, animals, and other creatures. CyanoHABs and cyanotoxins in lakes make it challenging to keep aquatic recreational areas safe and produce potable drinking water (Miller *et al.,* 2017). It is also known that cyanobacteria can create hepatotoxic or neurotoxic substances. Cyanobacterial neurotoxins are categorised into three primary categories, each with a unique action method. A commonly found secondary amine is anatoxin-a. *Planktothrix agardhii*, *Planktothrix rubescens*, *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, *Anabaena spiroides*, *Anabaena planctonica*, and *Cylindrospermum* sp. are the organisms that make anatoxin-a. Natural organophosphates include anatoxin-a(s). *Planktothrix agardhii*, *Anabaena flos-aquae*, and *Anabaena lemmermannii* are cyanobacteria species that are reported to generate anatoxin-a(s). Freshwater habitats are the only ones where cyanobacteria may create anatoxin-a and -a(s). Although they are more frequently linked to marine habitats, cyanobacteria in freshwaters can create the paralytic shellfish poisons (PSPs), saxitoxin and neo-saxitoxin. The dinoflagellates *Protogonyaulax tamarensis* and *Protogonyaulax catenella* create PSPs in the marine environment. *Cylindrospermopsis raciborskii*, *Anabaena circinalis*, *Aphanizomenon flos-aquae*, *Aphanizomenon issatschenkoi*, *Lyngbya wollei*, *Planktothrix* sp., and *Anabaena lemmermannii* are among the cyanobacteria species that make PSPs. Microcystins, nodularin, and cylindrospermopsin are examples of cyanobacterial hepatotoxins. *Aphanizomenon ovalisporum*, *Umezakia natans*, and *Cylindrospermopsis raciborskii* produce the alkaloid cylindrospermopsin. Microcystins are thought to be the most prevalent of all the cyanobacterial hepatotoxins in the world. *Nostoc* sp., *Microcystis*, *Anabaena*, *Planktothrix*, and *Anabaenopsis* are among the cyanobacteria that have been shown to generate microcystins. *Aphanizomenon* also produces ß-N-methylamino-L-alanine (BMAA), a new neurotoxic amino acid that may cause ALS/PDC in humans (Kotak and Zurawell, 2007). A summary of cyanotoxins is given in Figure 1.

Early onset of succession: Algal bloom is not the only outcome of eutrophication. It also affects other wetland plants and promotes the early onset of the process of natural succession in water bodies at a relatively rapid rate. Uncontrolled eutrophication of smaller freshwater bodies may lead to their rapid upwelling and reduced water storage and recharging capacity by silting. It may cause ponds or lakes to become terrestrial and lose their aquatic entity (Khan and Ansari, 2005).

Loss of aesthetic values: The excessive and undesirable growth of aquatic flora, especially phytoplanktons, and their subsequent death give rise to a greenish slime layer over the water body surface. This development of algal bloom or growth and slime layer reduces sunlight's penetration and restricts water re-oxygenation through air currents. Thus, eutrophication enhances the death and decay of aquatic biota, giving rise to foul smells and an increase in water turbidity (Khan and Ansari, 2005). The decaying of organic matter causes the development of unwanted colour, turbidity, odour, and taste in water, which makes it unsuitable for domestic consumption (Dasmohapatra, 2011).

Depletion of oxygen and death of aquafauna: Uncontrolled proliferation of aquatic flora and excessive death and microorganisms, adversely affect hydroelectric power generation, and diminish water suitability for industrial and recreational purposes (Khan and Ansari, 2005). Recent attention has focused on sewage-induced eutrophication in coastal waters and its potentially detrimental effects on coral reef ecosystems (Radojević and Bashkin, 2006).

Cochlodinium polykrikoides	*Alexandrium minutum*	*Anabaena circinalis*	*Aphanizomenon flos-aquae*
Pyrodinium bahamense var. compressum	*Alexandrium ostenfeldii*	*Anabaena planctonica*	*Protogonyaulax catenella*
Anabaenopsis sp.	*Gambierdiscus toxicus*	*Protogonyaulax tamarensis*	*Umezakia natans*
Prorocentrum minimum	*Karlodinium veneficu*	*Planktothrix rubescens*	*Nodularia spumigena*
Karenia mikimotoi	*Nostoc* sp.	*Heterocapsa circularisquama*	*Cylindrospermopsis raciborskii*
Phaeocystis Globosa	*Gymnodinium catenatum*	*Heterosigma akashiwo*	*Cylindrospermum* sp.
Noctiluca scintillans	*Dinophysis fortii*	*Planktothrix agardhii*	*Microcystis aeruginosa*
Chattonella marina	*Dinophysis acuminate*	*Limnothrix redekei*	*Lyngbya wollei*
Alexandrium tamiyavanichi	*Anabaena flos-aquae*	*Aphanizomenon gracile*	*Lyngbya mujuscula*
Alexandrium tamrense	*Anabaena spiroides*	*Aphanizomenon issatschenkoi*	*Ostreopsis* sp.
Alexandrium catenella	*Anabaena lemmermannii*	*Aphanizomenon ovalisporum*	*Prorocentrum minimum*

Table 1: A list of some microorganisms responsible for harmful algal blooms

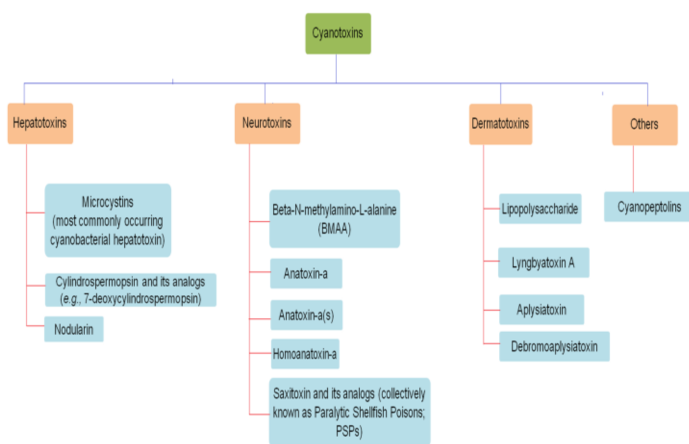

Figure 1: A summary of cytotoxins produced in algal blooms in eutrophic aquatic ecosystems

Contemporary Global Significance of Eutrophication:

An increase in nutrient inputs from activities in the upstream catchment areas, atmospheric deposition and local effluents cause nutrient loading of water bodies, including coastal waters. Eutrophication leads to increased biomass production in the coastal zone that disturbs its natural ecological balance, raising concerns over detrimental severe consequences. One of the biggest threats to the health of the marine ecosystem comes from the anthropogenic alteration of the nitrogen and phosphorous biogeochemical cycles at the global scale. Coastal regions throughout the world are affected by eutrophication. For example, within Europe, seas such as the Black Sea, the Baltic Sea, the Mediterranean Sea and the Wadden Sea currently suffer from severe impacts of eutrophication (Caitlin, 2019 for www.coastalwiki.org). The study by the European Environment Agency states that eutrophication is an issue in around 563000 km^2, or 23%, of the mapped regions of the 2400000 km^2 of Europe's seas. This includes areas in all regional seas. The Baltic Sea has the worst state, with 99% of the evaluated regions experiencing eutrophication, followed by the Black Sea with 53%. The studies indicate that eutrophication is also seen in some areas of the North-East Atlantic (7%) and some Mediterranean Sea coastal areas (12%), primarily along inhabited shores or catchments that are downstream of agricultural operations (European Environment Agency, 2019).

On the other hand, in the contiguous USA, about 65% of the estuaries and coastal waters are moderately to severely degraded due to excessive inputs of nutrients (NOAA, 2019). 415 coastal regions in the globe have been shown to be eutrophic, with 169 being hypoxic (WRI, 2008a). Likewise, eutrophication (Figure 2) has already occurred in 54% of Asian lakes, 53% of European lakes, 48% of North American lakes, 41% of South American lakes, and even 28% of African lakes (Wang *et al.*, 2013; ILEC, 1993).

About 22% of the world's population lives in the five South Asian maritime nations of Bangladesh, India, Pakistan, the Maldives, and Sri Lanka. These nations include just 4.8% of the world's land mass, 14% of its arable land, 2.73% of its forest area, and 4% of its coastline. Despite this, there is a significant danger of eutrophication in South Asian coastal environments because of nutrient enrichment from leaks in sewage, aquaculture, agriculture, industrial effluents, maritime commerce, and transportation (South Asia Cooperative Environment Programme online report).

Increased population density in Africa has led to burning, deforestation, and increased agricultural activity, all of which have detrimental effects on the Great Lakes area of East Africa. A few of the Great Lakes in Africa stand out due to their exceptionally long water residence times (more than 100 years). As a result, even if inputs are decreased, incoming nutrients will be held within the lakes, and recovery will be gradual For instance, Lake Victoria is already experiencing severe eutrophication, which has decreased the lake's biological diversity and may lead to human suffering. A qualitative phytoplankton study in Lake Victoria was delayed until significant alterations occurred. Within decades, the phytoplankton community had transformed into a eutrophic assemblage dominated by blue-green algae species that may be hazardous (Msomphora, 2008). According to analysis utilising satellite-measured chlorophyll-a or in-lake total phosphorus, between 41% and 76% of Africa's total storage is eutrophic or hypertrophic (Harding, 2015). African cities such as Abidjan, Cotonou, Lomé, Yaoundé, Ouagadougou, and Niamey have experienced eutrophication due to the invasion of water hyacinths in their well-known lakes, lagoons, dams, and rivers (Pare and Bonzi-Coulibaly, 2013). Lakes and reservoirs in sub-Saharan Africa are also susceptible to eutrophication. According to the analysis by Ndlela *et al.* (2016), seven countries from the Southern African region reported cyanobacterial blooms: four countries from Eastern, Western and Northern African regions each, and one country from the Central and Western Indian Ocean Islands each.

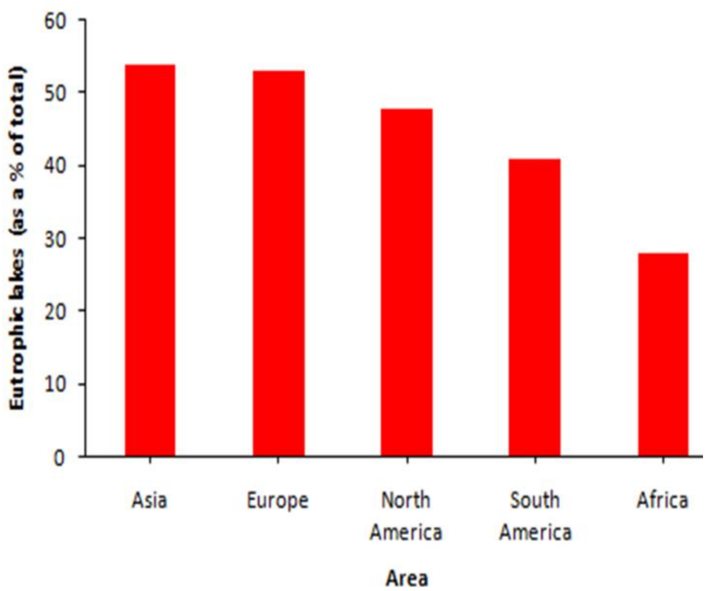

Figure 2: Eutrophic lakes worldwide as a percentage of total

Since an algal bloom in 1991 that killed hundreds of sheep and cattle and had an adverse effect on human health across 1000 km of the Baaka/Barka – Darling River, the consequences of eutrophication on Australia's rivers have been growing. Since then, the Murray has had four more comparable algal blooms: in 2007, 2009, 2010, and 2016. Three notable fish fatalities occurred in the Baraka/Barka-Darling River between December 2018 and January 2019, with eutrophication-related algal blooms being identified as one of the main reasons for the mortality of over a million fish. The likelihood of algal blooms and hypoxic blackwater formation has increased due to the 2019–20 bushfires, which burned more than 170000 km^2 areas. Large-scale forest fires have created ash-enriched soils, which are highly erodible and would flow into rivers and dams after heavy precipitation events. Deoxygenation and hypoxic blackwater occurrences are caused by the organic carbon in the ash biodegrading in the water. Burnt catchments mainly cause hypoxic blackwater episodes, although they can also happen when floods sweep organic materials like leaves into rivers. Any lowland river system can have hypoxic blackwater events, but the Murray-Darling Basin has seen many of these occurrences for the past ten years. Between October 2019 and May 2020, runoff from catchments affected by bushfires resulted in more than 65 incidents of fish mortality in the Murray-Darling Basin. These occurrences will persist as the early advantages of catchment reforestation will take time to manifest (Australia: State of the Environment Report, 2021).

131 eutrophic and hypoxic coastal zones in North America and the Caribbean have been investigated, according to data from the WRI (2008b). Ten systems are in recovery, 59 are regions of concern, and sixty-two have recorded hypoxia. The well-studied Chesapeake Bay system has twelve separate eutrophic and hypoxic zones. There are 25 eutrophic and hypoxic zones in South America. There are 22 regions of concern and three places with proven hypoxia. The majority are located in Peru, Chile, and Brazil. Given recent increases in nutrient supply to coastal waterways associated with rising industry, burning of fossil fuels, population expansion, and agriculture, this is probably an underestimate for the continent. In Latin America and the Caribbean, it is estimated that just 14% of wastewater—a vital source of nutrients—is treated. Enhancing water quality monitoring and evaluation is necessary to pinpoint issue regions and their origins, as well as to create plans to lessen eutrophication (WRI, 2008c)

In aquatic systems, phosphorous plays a critical role in eutrophication. Phosphorous is often in short supply and limits freshwater productivity (Odum and Barrett, 2005). An increase in phosphorous level is directly correlated to a rise in eutrophication. From 2002 to 2010, global anthropogenic activities emitted around 1.47 teragrams of phosphorous from the total of diffuse and point sources each year into the earth's major freshwater bodies. Asia contributes the most to the global anthropogenic phosphorous load (52%), followed by Europe at 19%, Latin America and the Caribbean at 13%, and North America at 7%. The maximum freshwater phosphorous load comes from China (30%), followed by India (8%), the USA at 7% and Spain and Brazil at 6% each. Domestic sewage contributes 54% to the global anthropogenic load in freshwater bodies, followed by agriculture (38%) and industrial activities at 8%. Phosphorus load exceeds the dilution or assimilation capacity of the freshwater ecosystems in nearly 38% of the earth's land surface area, which houses about 90% of the world's human population. The most acutely polluted freshwater basins include the Aral drainage basin in Central Asia, the Huang-He and the Yangtze in China, the Ganges and the Indus in India, and the river Danube in Europe. These basins are densely populated regions characterised by intensive agriculture. Less populated regions – Australia and Northern Africa – also have high pollution levels (phys.org, 2018; Mekonnen and Hoekstra, 2018). Over the previous 35 years, nutrient inputs have undergone significant modification. Between 1980 and 2015, there was an almost 40% rise in the worldwide nitrogen (from 308 to 430 teragrams/year) and phosphorous (from 31 to 45 teragrams/year) cycles. As per estimates, rivers transfer 43 teragrams/year of nitrogen and 5 teragrams/year of phosphorous to coastal hydroecosystems worldwide (Beusen *et al.,* 2022). In addition to fixing atmospheric nitrogen, rivers provide significant nitrogen to the open ocean and the coastal regions. As per the estimates of Mekonnen and Hoekstra (2015), anthropogenic sources, such as fertilisers and manure, accounted for 70% (24.4 million tonnes nitrogen/year) of the projected 35 million tonnes nitrogen/year of nitrogen leaching and runoff from croplands worldwide. Approximately 8.2 million tonnes of nitrogen were added annually to freshwater bodies worldwide from point sources, with 91% coming from domestic sources and 9% from industry. Thus, between 2002 and 2010, the annual worldwide human nitrogen load to freshwater systems from combined diffuse and point sources were 32.6 million tonnes. All anthropogenic nitrogen loads from diffuse and point sources are associated with a global greywater footprint of $13x10^{12}$ m^3/year. About 45% of this amount came from China, 7% from the USA, 6% from Russia, and 5% from India. In the Yangtze River basin, the agriculture sector contributes approximately 96% of the nitrogen load to the freshwater system, with the domestic sector contributing the remaining 3%. The domestic sector accounts for around 56% of the nitrogen load to freshwater bodies in the Ganges river basin, with the agriculture sector contributing another 39%. 1240 ktonne/year of anthropogenic nitrogen was added to the Xi Jiang river basin between 2002 and 2010. Every year, 1100 ktonne/year of nitrogen was added to fresh water in the Indus river basin. Freshwater bodies received 1000 ktonne/year of nitrogen emissions in the Yellow River watershed between 2002 and 2010. The Murray-Darling River basin's overall anthropogenic nitrogen load from 2002 to 2010 was 80 tonne/year. Untreated household sewage contributes seventy-five percent of the anthropogenic nitrogen load in the Aral Sea drainage basin. In the basin, 700 ktonne/year of emissions were produced.

Thus, comprehending the worldwide importance of eutrophication is essential for creating efficient solutions and strategies to tackle this urgent environmental problem in modern aquatic ecosystems.

Remedial Approaches and Mitigation Strategies:

Eutrophication is a complex phenomenon that requires a thorough investigation of its mechanisms, effects, and possible solutions in modern water ecosystems. Eutrophication, caused by excessive human activity, has become a primary worldwide concern, worsening with other critical environmental problems such as climate change and resource depletion (Radojević and Bashkin, 2006). Researchers have pointed out that its impact may be worse in developing countries than developed ones (Brönmark and Hansson, 2002). Remedial techniques and mitigation strategies are crucial to tackle this environmental concern. The suggested techniques include: (1) Exclude rapid input of phosphorous and nitrogen nutrients through sewage; restrict input of phosphorous and nitrogen from animal wastes. This can be done by limiting animal access or their products to the water bodies where possible; (2) Maintaining vegetation buffers in all areas where water flows to reach the water body. Buffers slow down water movement and filter it. This prevents nutrient enrichment and sedimentation; (3) Provision of a convenient shallow sedimentation pool at the water body inlet also captures sediments and prevents sedimentation; (4) Limit the use of fertilisers within the watershed area. It is beneficial because the number of fertilisers getting off the site will decrease; (5) Mechanical removal of the plant vegetation in the water body periodically encourages efficient wind action, which promotes better aeration and decay of waste material in water-based ecosystems (extension.psu.edu, 2015); (6) Enhancing water quality monitoring and evaluation. An all-encompassing and coordinated strategy for managing eutrophication is crucial for sustainable water management and ecosystem preservation in modern aquatic environments (Khan and Ansari, 2005).

CONCLUSION

Eutrophication is a significant environmental issue that requires immediate attention and collaborative efforts to address and prevent. Its various effects on aquatic habitats highlight the necessity for sustainable management solutions. It is clear from this analysis that tackling human-induced nutrient loading is crucial for maintaining the health and stability of aquatic ecosystems globally. Therefore, policymakers, researchers, and stakeholders must work together to implement effective strategies to avoid and regulate eutrophication. Global water resources and biodiversity can only be protected via collective action, securing a sustainable future for future generations.

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