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Eutrophication in freshwater bodies: Causes and consequences

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Abstract
The excessive nutrient enrichment of freshwater ecosystems, or eutrophication, has become a major worldwide water quality concern endangering aquatic biodiversity and human well-being. The several causes of eutrophication are examined in this paper, with a focus on anthropogenic nutrient inputs from industrial discharges, residential sewage, agricultural fertilizers, and urban stormwater runoff as the main contributing contributors. The effects show up as distinctive ecological cascades: dense algal blooms are caused by enhanced phytoplankton growth, which is followed by microbial decomposition that reduces dissolved oxygen, resulting in hypoxic zones that kill fish and disrupt benthic communities. The growth of dangerous cyanobacterial toxins, the loss of water clarity and submerged macrophytes, the disturbance of nutrient cycle, and the deterioration of ecosystem services like the availability of drinking water and recreational opportunities are further effects. In addition to discussing mitigation measures ranging from point-source controls to watershed-scale best management practices, the study summarizes current knowledge of eutrophication mechanisms and assesses monitoring and evaluation methodologies. Integrated strategies that address nutrient reduction, ecological restoration, and sustainable land-use planning are necessary for effective eutrophication management.

Keywords: Eutrophication, freshwater bodies, Causes, consequences, management

Introduction

The Greek term eutrophos, which meaning well-nourished, is where the word "eutrophic" comes from. According to Bali and Gueddari (2019) [5] and Sonarghare *et al*. (2020), eutrophication is the state of an aquatic network with excessive concentrations of nutrients, such as phosphorus and nitrogen, which cause algal blooms and deteriorate the water quality in aquatic ecosystems. Over-enrichment of nutrients, particularly phosphorus, causes eutrophication of aquatic bodies (Schindler 1977) [29]. This is followed by unchecked primary producer development and periods of oxygen deficiency due to algal organic matter breakdown. According to Zhang *et al*. (2023) [38], eutrophication is defined as the excessive development of plants and algae brought on by a rise in the availability of limited growth elements (such as sunlight, carbon dioxide, and nutrient fertilizers) necessary for photosynthesis. Due to its significant contributions to socioeconomic and environmental health issues, eutrophication caused by nitrate and phosphate runoff from farmlands, aquaculture pond effluent, and municipal and industrial discharge is a serious problem (Carpenter, 2008; Akinnawo, 2021) [1]. Water bodies are in a condition of oligotrophy at their early phases of formation, supporting a meager amount of aquatic life due to nutrient deficiencies. Water bodies change from an oligotrophic to a mesotrophic, eutrophic, and ultimately hypertrophic stage when they are enriched with mineral nutrients like nitrogen (N) and phosphorus (P). Because phosphorus is typically coupled to soil components, it typically contains a lot more nitrogen. Large amounts of nutrients, especially nitrogen, are found in agricultural runoff as a result of extensive fertilizer use. Due to their water-soluble nature, nitrates are easily transported into rivers by surface runoff or into the groundwater below by water seeping through the soil profile. Since phosphate sticks to soil particles and is not water soluble like nitrate is, it simply moves with the soil. Urban and industrial sources of nutrient losses include storm water runoff, nitrogen leaching from underground septic tanks, and municipal wastewater treatment plants and industrial wastewater discharges. 50% of the phosphorus dumped into lakes from human settlements comes from industrial wastes and household sewage, which together are the main urban sources of nutrient overload (Smith *et al*. 2006). Large-scale fish deaths, hazardous algal blooms, and hypoxic occurrences have all expanded locally, regionally, and eventually even globally as a result of rapid industrialization and urbanization (Diaz and Rosenberg 2008; Rabalais *et al*. 2009; Kahru *et al*. 2020). On a global scale, Cloern (1991) [6, 8, 18, 26] demonstrated the connections between nutrient loading and long-term ecological responses in both the sedimentary and pelagic systems. We now know that the increasing global climate change can threaten the ecosystem's potential resilience and ability to recover from the detrimental effects of eutrophication (Meier *et al*. 2012), which has a greater impact on arctic and boreal coastal systems than other aquatic ecosystems (Halpern *et al*. 2008 [13]; Reusch *et al*. 2018). Developing successful mitigation solutions requires an understanding of the intricate relationships that exist between nutrient supplies, hydrological processes, biological responses, and socioeconomic forces. The ecological effects of nutrient over-enrichment are examined, management strategies are assessed, and the current understanding of eutrophication mechanisms is summarized. This paper attempts to offer a thorough framework for tackling one of the most urgent threats to the health of freshwater ecosystems and the essential services these systems provide to human communities around the world by combining knowledge from limnology, biogeochemistry, ecology, and environmental management.

Natural Eutrophication

Freshwater bodies gradually amass nutrients through geological weathering, atmospheric deposition, organic matter breakdown, and natural discharge over the centuries-long process of natural eutrophication. Lakes eventually convert to terrestrial ecosystems through natural succession as a result of this gradual enrichment, which sustains moderate biological production and permits ecosystems to adapt without disruptive algal blooms or oxygen depletion. The accumulation, movement, and addition of nutrients to water bodies, which leads to primary compositional changes in the production and community species, is known as natural eutrophication, and it has been occurring for millennia (Knight, 2021) [20]. Because they get nutrients from watersheds and tidal currents from upstream areas, estuaries are naturally eutrophic and extremely productive. Furthermore, lakes fall into the same category since they are big, hold organic matter and sediments, and need time to become rich in nutrients (Engelhardt *et al*., 2011) [11]. A study on the cultural eutrophication was done by Bhandarkar, (2015, 2017), Bhandarkar and Paliwal, (2019) [3, 4, 5] in the eutrophied water bodies in eastern Maharashtra. These studies confirmed the role of rotifers and other zooplankton as indicators of trophic status and ecological conditions. A diverse assemblage of 46 rotifer species belonging to 15 families and three orders was reported from Dhukeshwari Temple Pond whereas the broader zooplankton research recorded 83 species with Rotifera being the leading group. The dominance of rotifer is connected with the favourable environment and high food supplies due to organic enrichment.

Anthropogenic Eutrophication

Urban rainwater, sewage discharge, industrial effluents, and agricultural fertilizer runoff are some of the human activities that cause anthropogenic eutrophication, which happens quickly over decades. Fish fatalities, oxygen deprivation, explosive algal blooms, and ecological collapse are all caused by excessive nitrogen and phosphate inputs. When natural absorption capacity is exceeded by this increased nutrient enrichment, water quality deteriorates severely and biodiversity is lost. Human activities that raise the rate of nutrient intake in a water body can dramatically accelerate water eutrophication because of growing urbanization, industrialization, and escalating agricultural output (Yang *et al*., 2008) [37].One of the reasons for the expanding human population and its consequences on the environment is the accelerated rates of nitrogen (N) and phosphorus (P) entering the biosphere, which are predicted to continue rising in the next decades (Glibert, 2017 [12]; Sutton *et al*., 2013).

Mechanisms and Process of Eutrophication

When too many nutrients mainly nitrogen and phosphorus from fertilizers, sewage, and agricultural runoff enter water bodies, they cause eutrophication, which leads to rapid algae growth. Bacterial breakdown reduces dissolved oxygen when algae die, resulting in hypoxic "dead zones." Aquatic life is suffocated, ecosystems are upset, biodiversity is decreased, and human-use water quality is deteriorated. Runoffs that transport down excessive fertilizers from agroecosystems and/or human waste that has been dumped into communities cause this nutrient enrichment (Khan and Ansari, 2005) [19]. This interaction between the aquatic plants and the nutrients in the sediment promotes eutrophication, which deteriorates water quality and highlights the mechanisms underlying eutrophication (Sonarghare *et al*., 2020).

Ecological Consequences

Ecological harm cascades as a result of eutrophication. Fish and other bottom-dwelling species suffocate in hypoxic "dead zones" created by the death and decomposition of excessive algal blooms. As food webs disintegrate and oxygen-sensitive animals go extinct, biodiversity falls precipitously. In addition to producing poisons that are harmful to humans and wildlife, harmful cyanobacteria prevent submerged plants from receiving sunlight. Fish spawning habitat is lost as aquatic vegetation disappears. Diverse communities give way to simpler systems dominated by species that can withstand contamination. Increased turbidity, unpleasant smells, and contamination of drinking water sources all contribute to a decline in water quality. Both wildlife and human populations are impacted when fisheries fail, recreational areas close, and important ecosystem services like natural water purification are seriously jeopardized. Large-scale fish deaths, hazardous algal blooms, and hypoxic occurrences have all expanded locally, regionally, and eventually even globally as a result of rapid industrialization and urbanization (Diaz and Rosenberg 2008; Rabalais *et al*. 2009; Kahru *et al*. 2020) [8, 18, 26].

Oxygen Depletion

Massive algal blooms in aquatic bodies are caused by an excess of nutrients (phosphorus and nitrogen) from fertilizers, sewage, and agricultural runoff. Large volumes of dissolved oxygen are consumed by aerobic bacteria that break down the organic matter when these dense algae communities die and descend to the bottom. Oxygen availability is significantly decreased by this microbial respiration more quickly than it can be restored by photosynthesis or atmospheric diffusion. In stratified seas, where warm surface layers obstruct oxygen mixing to deeper zones, the issue gets worse. Additionally, dense algal mats obstruct sunlight, which kills submerged plants that typically produce oxygen through photosynthesis. This exacerbates oxygen loss and results in hypoxic conditions. The system's turbulence determines the hypoxic and anoxic conditions brought on by the organic matter's growing rate of breakdown. Opportunist species like Enteromorpha, Ulva, Cladophora, and others gradually supplanted the long-lived and slow-growing species. Dense layers are created by this shift in species composition, which results in severe degradation and oxygen scarcity, ultimately creating anoxia conditions (Raffaelli *et al*., 1998) [27]. Thus, the presence of toxins (such as anatoxina and microcystin) that produce noxious blooms has a negative impact on that water system. Numerous neurotoxins that impair creatures with complex neurological systems and raise fish mortality rates are frequently produced by harmful algal blooms. In nutrient-rich environments with low N/P ratios, low light levels, and high temperatures, cyanobacteria that produce toxins, such as Anabaena, Cylindrospermopsis, Microcystis, and Oscillatoria, exhibit dominance (Paerl *et al*., 2012) [24]. Both aquaculture and municipal drinking water systems include cyanobacteria, which cause significant financial losses (Crews *et al*., 2007) [21]. As a result, many tanks and small waterbodies gradually lose their aquatic identity and turn into permanently terrestrial environments (Diaz and Rosenberg, 2008) [8]. According to laboratory research, cyanobacteria are low-quality food for the majority of zooplankton grazers, which reduces the effectiveness of energy transmission in aquatic food webs (Wilson *et al*., 2006; Tilmanns *et al*., 2008) [32, 36].

Socio-Economic and Human Health Impacts

Communities and economies that depend on freshwater are negatively impacted by eutrophication. Microcystins and other toxins from toxic cyanobacterial blooms contaminate drinking water, resulting in gastrointestinal problems, neurological conditions, and liver damage. In order to address taste and odor issues and eliminate pollutants, municipal water treatment expenditures have skyrocketed. As lakes and rivers become unfit for boating, fishing, and swimming, recreational industries collapse, wreaking havoc on areas that depend on tourism. Livelihoods are lost when commercial freshwater fisheries diminish or vanish completely. Affected shorelines see a sharp decline in property values. When animals drink tainted water, agricultural operations suffer losses. Beach closures and public health advisories interrupt community activity and lower lakefront inhabitants' quality of life. The quality of fresh water resources is declining on a regional, national, and even worldwide scale. As a result of this drastic change in ecology, water resources are becoming a topic of debate in many developing countries (Heisler, 2008 [14]; Sondergaard *et al*., 2003). Episodes of harmful algae blooms (HABs) are a natural freshwater and marine hazard, and they have a substantial influence on human health and socioeconomic systems. The primary industries impacted by these changes include public health, commercial fishing, tourism, recreational activities, monitoring, and management. These changes may have major socioeconomic ramifications (Anderson 2000). Excessive nutrient loading promotes the growth of unwanted associated algae in streams and rivers and causes an increase in toxin-producing algal blooms like cyanobacteria and dinoflagellates in lakes, reservoirs, estuaries, and coastal waterways (Dodds, Carney, & Angelo, 2006; Lewis *et al*., 2011) [7, 9].

Prevention, Mitigation and Management Strategies

Use buffer strips, cover crops, and precise fertilizer application to cut down on nutrient inputs. Facilities for treating wastewater should be upgraded to eliminate phosphate and nitrogen. Wetlands should be restored to naturally filter runoff. Adopt watershed management strategies that have stringent discharge restrictions for nutrients. Manage algae by using biological controls, such as herbivorous fish. Aerate impacted water bodies to promote ecosystem recovery by raising oxygen levels and preventing stratification. Aquatic ecosystems were under risk from changes in water quality, mostly brought on by an increase in pesticides and nutrient inputs (Rabalais *et al*., 2009) [26]. Lakes are one of the primary inland water resources used for irrigation, industry, and residential reasons; therefore, it is essential to avoid and regulate lake water contamination and to have accurate information about lake water for more efficient ecosystem management (Lim *et al*., 2011). For example, control efforts in industrialized nations limit the amount of phosphates in detergents and remove phosphate from wastewater at the municipal wastewater treatment plant in order to reduce P loading to aquatic bodies (Rast and Thornton, 1996).

Nutrient Management

Utilize improved wastewater treatment and best practices in agriculture, such as riparian buffers and precision fertilization, to manage nutrient sources. To naturally filter runoff, restore wetlands. Use sediment dredging and phosphorus-binding compounds as in-lake treatments. Put aeration systems in place to stop nutrient leakage and stratification. Create thorough watershed management plans that include enforceable nutrient discharge restrictions and routine monitoring to monitor recovery status and assure compliance. This approach focuses on the nutrient supply that leads to eutrophication or algal blooms, as opposed to chemical control, which eliminates and eliminates algal blooms. Instead of killing the algae, it drastically reduces the delivery of vital nutrients, which allows for long-term control of algal biomass. In order to create flocculants that bind P and coagulate the algal cells, the process involves dispersing specific chemicals in the water body, such as lanthanum (Peterson *et al*., 1976; Reitzel *et al*., 2013a), zirconium (Kumar and Rai, 1978; Sanville *et al*., 1982), aluminum sulphate (alum) (Smeltzer, Kirn and Fiske, 1999; Rydin, Huser and Welch, 2000; Steinman and Ogdahl, 2008), and the most recent Phoslock, which is lanthanum modified bentonite (Haghseresht, Wang and Do, 2009; van Oosterhout and Lürling, 2013; Reitzel *et al*., 2013b). According to observations, the majority of studies favor using alum to deactivate P in the water column. This could be due to the fact that alum is less expensive than other salts (Jorgensen *et al*., 2005).

Bioremediation

By using biological processes to eliminate excess nutrients and restore ecological balance, bioremediation is a promising strategy to reduce eutrophication (Lu *et al*., 2014). Daphnia are effective grazers that can remove edible algae cells from the water column; as a result, Lake Washington's clarity unexpectedly increased dramatically (Edmondson 1994). It has been discovered that a number of plant species can lessen the excess of phosphorus and nitrogen in aquatic systems. *Salvinia auriculata* and *Eicchornia crassipes* are examples of aquatic macrophytes that significantly lower the levels of phosphorus and nitrogen in water. In order to prevent the eutrophication process in Imboassica Lagoon, this knowledge was thought to be helpful in creating an appropriate management strategy for aquatic macrophytes (Petrucio and Esteves 2000). According to Jiang *et al*. (2004), *Phragmitis communis* and *Zizania latifolia* are effective at absorbing N and P, and as a result, they were found to be crucial in the purification of wetlands that receive pollutants from nonpoint sources. According to reports, duckweed is a promising macrophyte for treating wastewater. They have been shown to successfully remove nutrients and high levels of ammonia from shrimp farm effluent (Ruenglertpanyakul *et al*. 2004).

Aeration

A physical method called aeration is used to raise the oxygen content of a pond in order to reduce stratification. By establishing an anoxic environment that can release P from the soil to promote internal cycling, oxygen is used connectively to reduce eutrophication. Therefore, by raising the oxygen content to slow down the rate of eutrophication, limited internal cycling can be achieved (Rathore *et al*., 2016) [28]. Extended aeration has allegedly been used in wastewater treatment to remove nutrients; results showed that total phosphorus and orthophosphate were removed from wastewater on average by 15 and 28%, respectively, while ammonia was removed by 98% (Sotirakou *et al*., 1999) [10].

Public Awareness and Legislations

Local residents' awareness of their surroundings and water sources has a significant and long-lasting effect on the environment. Only a collaborative community effort can more effectively reduce nutrient inputs to water bodies, as demonstrated in the case of Lake Washington, where public awareness led to a decrease in detergent use. Therefore, raising public awareness, educating residents about the environment, and creating an integrated plan to reduce eutrophication are important needs (Jorgensen 2001) [17]. Public education had a major role in Australia. Two public education initiatives were conducted, one in the Hawkesbury-Nepean Basin in Sydney's western suburbs and the other in the Murray-Darling Basin in the town of Albury-Wodonga. Positive outcomes led to the conclusion that, if eutrophication is addressed at its source and community support is built for an integrated strategy, initiatives like "Phosphowatch" can offer a long-term, economical solution (Howard and McGregor 2000) [15].

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