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Microalgal bloom and cyanotoxin proliferation in freshwaters: cycle and dynamics, impacts and remediation strategies

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ABSTRACT
The intense growth of microscopic algae and cyanobacteria in our freshwaters eventually results in a colored scum on the surface and thus termed as "Microalgal or Cyanobacterial Bloom." This bloom can emerge in both saltwater and freshwater habitats, and it can inflict people, harm microflora and fauna, and damage the environment in a variety of ways. In this study, we gathered and investigated relevant data on microalgal bloom and cyanotoxin proliferation in freshwaters. We analyzed and presented an insightful notion of eutrophication and its natural and man-made drivers. The eutrophic cycle and processes of microalgal and cyanobacterial blooms, as well as their consequences, were critically explored in this research. In order to achieve a sustainable and incredibly simple remediation strategy, we thoroughly studied and discussed the many ways of algal bloom cleanup and control instruments. Finally, we highlighted the potential prospects for nitrogen and phosphorus pollution mitigation measures against microalgal blooms and cyanotoxin proliferation in freshwaters.

KEYWORDS
Microalgal bloom;
hypoxia and hyperoxia;
cyanobacteria; nitrate and phosphate;
aphotic condition

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INTRODUCTION
Over the past century, there has been a dramatic increase in the presumption that environmental pollution is increasingly wreaking havoc on our ecosystem more than any other category of devastation. When people think of environmental pollution, they usually focus on fossil fuels and carbon emissions since they are major contributors to climate change. However, many other silent contributing variables majorly contribute to environmental pollution. There has been a plethora of research on chemical pollution in bodies of water and how it contributes to so many health and environmental issues [1, 2]. Compared to deforestation, land pollution, smog, and other ecological challenges, eutrophication is one of the few considered. It is the process of adding nutrients to an ecosystem's water body, either artificially or naturally, to stimulate the bountiful growth and development of aquatic plants. It is characterized by dense algal and plant growth owing to the enrichment of nutrients needed for photosynthesis. As a result, it recurrently enables the generation of massive mats of floating plants [3, 4]. And thus, the rapid growth of phytoplankton is linked to eutrophication (algal blooms), as shown in Figure 1.

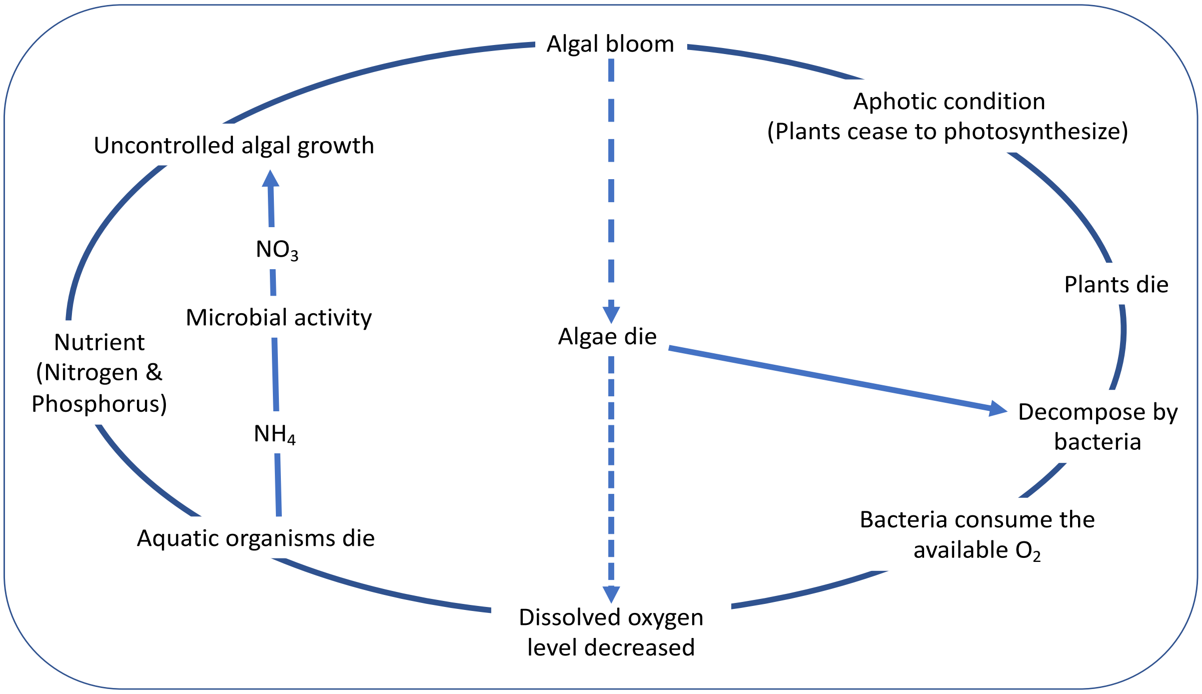

FIGURE 1: schematic diagram of eutrophication cycle and dynamics

The presence of specific species of cyanobacteria within blooms has constantly been shown to be of great importance since they can produce hepato- and neurotoxins that can seriously harm human and animal health [5, 6]. Eutrophication appears and sounds to be a regular thing but is not. It is accelerated by various human activities, more specifically by adding phosphates and nitrates to water bodies, which are the limiting factors for plant and algal growth [7, 8]. An excess supply of phosphates and nitrates can enter the hydrological cycle through detergents, fertilizers, sewage disposal systems, etc. (Figure 2). Nonetheless, eutrophication could be a natural phenomenon resulting from senescence over geological time, usually in temperate grasslands.

Because phosphate easily mixes with soil, the primary mode of phosphate transport is erosion, such as that caused by deforestation, which ultimately leads to surface runoff and eutrophication. Plants absorb more oxygen (O2) from water due to high phosphate concentration, allowing them to grow disproportionately in aquatic habitats. Excessive plant growth results in excessive plant decomposition, mainly algae, resulting in hypoxia (Figure. 1). Hypoxia refers to low oxygen levels in water or low dissolved oxygen (DO) in a medium, whereas hyperoxia occurs when DO levels in the water exceed saturation [9, 10, 11]. Due to excess plant growth, the O2 content of water is usually taken up by the plants and microalgae, resulting in a lower O2 range than is required for aquatic life to exist.

However, a reverse mechanism induces meiotrophication, which causes the lake to be somewhat nutrient-deficient over time [12, 13]. This process occurs more frequently in coastal waters than in a freshwater system. Moreover, the extra nutrients are supplied in coastal areas by deposition from estuaries, while in the case of brackish water, the amount of nitrogen present in the water is the primary nutrient limiting factor. The use of synthetic nitrogenous fertilizers changed the magnitude of productivity in the aquatic environment, necessitating the emergence of a special term, “eutrophication” [14, 15]. Concerns about this pressing issue are a relatively recent development in the scientific literature [16].

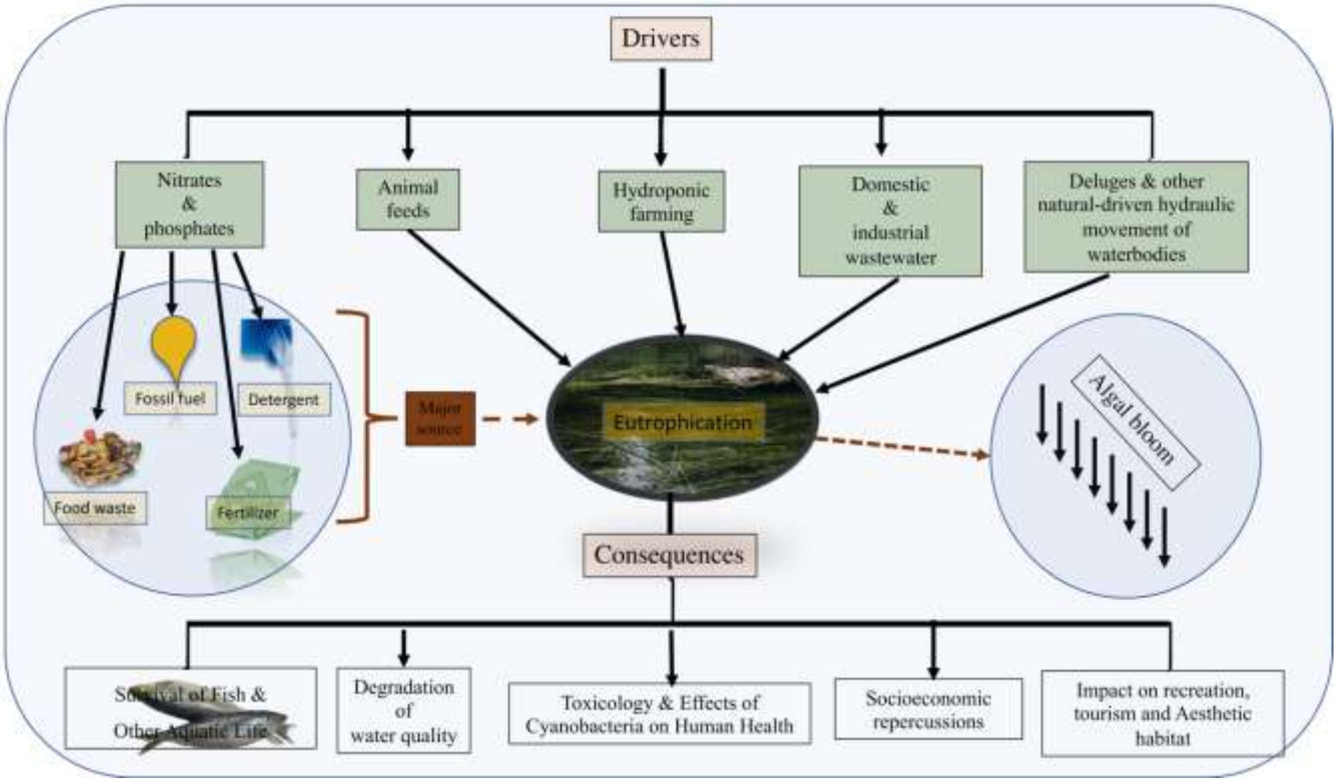

FIGURE 2: Schematic illustration of the drivers and impacts of microalgal bloom and cyanotoxin proliferation in freshwaters

Aside from natural processes that result in the sedimentation of lotic and lentic aquatic environments over time, the runoff of fertilizers, sewage, and animal wastes from both point- and non-point sources are still an essential source of nutrients into water bodies [17, 8].

NITRATES AND PHOSPHATES IN FRESHWATERS

In freshwaters, nitrates and phosphates are precursors to microalgal blooms and cyanotoxin proliferation. These may be organic and inorganic compounds used as fertilizers for the fastest plant growth and viable crop yields that are, to some extent, detriment to other aquatic lives. Anthropogenic activities are the primary cause of eutrophication because of our overdependence on nitrate and phosphate fertilizers. These fertilizers are commonly used in regular agriculture practices and the upkeep of recreational turf, lawns, golf courses, and other pitches and give rise to phosphate- and nitrate-nutrient concentrations in the process [18, 19].

According to Coates' (2004) research, more chemical fertilizer is utilized per grass surface area than on an equivalent surface area of cultivated farmland [20]. The nutrients are transported into diverse water bodies by surface runoff during rainstorms and serve as essential macronutrients to neutrophilic phytoplankton, microalgae, and other aquatic plants to activate their photosynthetic activity. This condition causes microalgal blooms and additional micro and macrophytes, such as water hyacinths, to grow uncontrollably in aquatic environments [3, 11].

(1) Animal feeds

Eutrophication, one of the ecological problems, occurs for a variety of reasons, including the operations of concentrated animal feeding practice by experts in the field of Animal husbandry. The United States Department of Agriculture (USDA) described the practice as an intense animal feeding operation (AFO) that confines over 1000 animal units for a minimum of 45 days per year. One thousand pounds of "live" animal weight equals one animal unit. A thousand animal units are equivalent to 1000 cows, 700 dairy cows, 2500 pigs weighing more than 55 pounds, 125 thousand chickens, or 82 thousand egg-producing hens or pullets [21].

Concentrated animal feeding practice is also a more prominent source of phosphate- and nitrate-nutrients, which nourish aquatic micro and macrophytes vis-a-vis the proliferation of eutrophication. When excess nutrients are discharged from the operations, they flow into various water bodies where they accumulate in high concentrations, causing cyanobacterial and microalgal blooms to occur continuously [3].

(2) Domestic and industrial wastewater

Domestic wastewater (sewage), industrial discharge, inflow, and infiltration are all discharges into a sanitary sewerage system. The last two contribute to the total volume of wastewater, but they are usually insignificant in wastewater disposal [22]. Due to the direct release of sewage water, aquatic bodies receive enormous volumes of organic and inorganic pollutants, notably nutrients, from domestic wastewater. This mindset persists in several parts of the world, particularly in underdeveloped countries.

Though some countries treat their domestic and industrial wastewater before discharging it into rivers, oceans, and other suitable water bodies yet, recent studies have found evidence of excess nutrients in the water bodies after treatment, resulting in the growth and propagation of unwanted micro and macrophytes on the water's surface, thereby supporting the spread of eutrophication [8, 23].

(3) Hydroponic farming

Hydroponic farming, including aquaculture, is the rearing of aquatic animals or cultivating aquatic plants in a medium containing dissolved nutrients under fully or partially controlled conditions. Aquaculture is often set up for aesthetic or recreational reasons [24]. Water quality imbalances can kill aquatic species, and they are more likely to be under stress, which makes them more susceptible to disease. Aquaculture is an ancient profession that has been practiced for generations, but it has been increasingly advanced by scientific approaches since the 18th century and continues till today [25]. According to a study by James & Bright (2019), aquaculture is one of the world's fastest-rising food-producing sectors. It is also one of the most efficient and low-impact means of generating high-quality protein for human consumption [26].

In contrast, Rinkesh (2019) considered aquaculture a technology that qualifies to be one of the top contributors to eutrophication [3]. "If not adequately controlled, the unconsumed food particles, in combination with fish waste, can considerably raise the levels of nitrogen and phosphorus in the water, resulting in a dense growth of microscopic floating plants," the report stated. Horlacher (2012), on the other hand, discovered that fish in an aquaculture system might absorb a considerable amount of the nutrients and convert them to productivity [27]. Hence, the prospect of aquaculture is questionable in the eyes of environmental and ecological scientists due to incapacitation in nature-based sustainability, which requires the attention of concerned bodies to address the menace [28].

(4) Deluges and natural-driven hydraulic movement of waterbodies

In addition to human causes of eutrophication, natural events play a substantial role in the intrusion of excess nutrients into water bodies. Water bodies' deluges and other natural-driven hydraulic movements can wash away nutrient-rich soil and deposit them in streams, lakes, and rivers. As a result, the water bodies become significantly nutrient-rich, hastening the excessive growth of microalgal and other phytoplankton.

Because the process is temperature-sensitive, natural eutrophication can be sped up or slowed down. However, it is generally a slower phenomenon. For instance, as the lakes age, the sediments containing nitrogen and phosphorus elements responsible for the rapid growth of cyanobacterial blooms and other aquatic macrophytes accumulate [3, 29].

IMPACTS OF MICROALGAL BLOOM AND CYANOTOXIN IN FRESHWATERS

(1) Survival of fish and other aquatic organisms

Increased nutrients availability in aquatic environments causes eutrophication, and eutrophic microalgal blooms reduce the amount of O2 required for the survival of aquatic animals. Aquatic hypoxia is a particularly intricate condition that results from this situation. Dong (2011) perceives aquatic hypoxia as a situation in which DO levels are less than 2-3 mg/L in marine and estuarine waters and less than 5-6 mg/L in freshwater [9]. On the other hand, the hypoxic threshold varies depending on the organism's species.

When DO levels fall below a certain point, aquatic plants and animals may suffocate and die, resulting in O2 depletion. Then the planktons, particularly macroalgae, die and decompose in anaerobic or hypoxic circumstances (Figure 1). In a complex scenario, marine vertebrates and invertebrates are killed by toxins produced by a few other aerobes in an anaerobic approach that stimulates their growth.

In general, eutrophication promotes aphotic conditions (increased turbidity) by stimulating the growth of phytoplankton, which blocks light penetration into the benthic zone (Fig. 1). This zone becomes an "aquatic dead zone" for a vast number of benthic species, including bacteria and fungi, resulting in biodiversity loss.

(2) Deterioration of water quality

As one of the most basic requirements for life, water plays a critical role in metabolic regulation. The water bodies have the potential for self-purification, use for human consumption, and support aquatic life. According to a study by Robert (2019), "Eutrophication enhances biological productivity to the extent that the ultimate death and degradation of biological material creates an overwhelming demand on the O2 content, resulting in O2 depletion in the worst circumstances." [30] Excess nitrates and phosphates in aquatic ecosystems have a significant impact on the functions of lakes, rivers, and oceans.

Nutrient enrichment by excessive nitrate addition and the growth of macrophytes and algal species that contribute to physical changes such as taste and odor nuisances can significantly impact water quality for human consumption. Nutrient enrichment harms water biotas by releasing toxic chemicals; ammonium toxicity and alterations in the chemistry of aquatic ecosystems affect DO levels, causing water quality to deteriorate and, as a result, the supply of potable drinking water to be compromised [31].

Microalgal blooms and photosynthetic bacteria can clog water systems, restricting the availability of piped water. Toxic algal blooms have shut down several water supply systems throughout the world in this regard. For example, in 2007, due to catastrophic algal blooms on Lake Taihu, more than 2 million people of Wuxi, China, were restricted from piped-drinking water for more than a week.

(3) Toxicology & Effects of Cyanobacteria on Human Health

Cyanobacteria primarily cause eutrophication's toxicologically detrimental impacts on human health. Cyanobacteria or Cyanophyta (blue-green algae) are microscopic organisms, a phylum of photosynthetic bacteria and plastids that are particularly abundant in aquatic habitats such as freshwaters, coastal water bodies, and seawaters, according to Whitton & Potts (2000) [32]. Eutrophic conditions encourage this type of bacteria to secrete very powerful biotoxins, commonly known as "cyanotoxins," into the aquatic medium with significant toxicity levels, even in little doses. Cyanotoxins are harmful or poisonous chemicals released by Cyanophyta during metabolic activities.

In the same vein, Carmichael (1992), as referenced by (Otten, 2015), noted that "cyanotoxins" are cyanobacterial metabolites that have a higher likelihood of negatively harming human health; this includes five classes of molecules that are particularly prevalent in an aquatic ecosystem influenced by eutrophication [33]. These complex compounds include microcystin, which is known to be toxic to the liver and cause severe hepatotoxicity; nodularin, which also directly affects the liver and causes hepatotoxicity; and cylindrospermopsin, which has harmful effects on specific cells and is, therefore, cytotoxin and hepato-toxin due to its adverse impact on liver organs; Saxitoxin is a neurotoxin generated by some dinoflagellates that can accumulate in mollusks and cause food poisoning in humans.

Nutrient enrichment entails the development of anaerobic conditions, making water bodies more conducive to cyanobacteria growth. Humans are exposed to the detrimental effects of cyanobacterial metabolites in various ways when this happens. Recreational activities nearby cyanobacteria-infested waterbodies are the most common source of exposure. Similarly, skin contact with blooms can cause severe dermatitis, and inhaling suspended particle droplets of cyanotoxified water can aggravate pre-existing respiratory diseases such as asthma [34]. Generally, the most common way to get cyanotoxins is to drink contaminated water or ingest edible aquatic organisms, including fish, shellfish, and seaweed contaminated with biotoxins due to the biomagnification process [35].

Furthermore, when nitrogen levels in drinking water exceed the maximum allowable limit, it might impair newborn babies' blood circulation and produce a blue baby syndrome, a hazardous health issue. Although no study has linked the effects of cyanotoxin on human health as susceptibility to sudden lethality based on the available literature, some symptomatic disorders such as inflammation of the stomach and intestine mucous membranes, breathing difficulties, or dermatitis manifestations have been reported [8].

(4) Socioeconomic repercussions

The repercussions of eutrophication pose a significant threat to human social life and professional activity. For instance, the presence of macroalgae on the surface of freshwaters frequently results in the closure of pools, bays, and beaches, which harms commercial opportunities. And obviously, the treatment of cyanotoxins-infected waters is growing more expensive; fish and other seafood are becoming unsafe for ingestion, affecting sales and limiting fishing markets. Due to this situation, the diversity of cyanobacteria inhabiting different aquatic habitats has been the focus of several recent pieces of research [36, 37].

In addition, the microalgal blooms and other planktons floating on the surface of water bodies can considerably impede the fishing process, making it harder to catch fish with netting, preventing canoes from moving, and increasing the risk of contracting waterborne infections caused by cyanotoxins.

(5) Impact on recreation, tourism, and aesthetic habitat

The addition of nutrients to an aquatic environment, particularly nitrogen and phosphorus, boosts the bulky growth of macroalgae and other planktons. The physical appearance of waters changes from colorless to yellowish-green due to macroalgae, planktons, and their activities, which are usually accompanied by unpleasant odors. Knockaert (2019) attributed the associated smell to bacterial activities; when anaerobic bacteria degrade macroalgae or seaweed, a gas called hydrogen sulfide (H2S) is generated, and this gas has a highly unpleasant rotten egg stench [38].

Furthermore, the presence of algae obstructs accessibility, navigation and renders the water unusable for leisure activities such as swimming, boating, and other water sports. When visiting an area afflicted by eutrophication, many tourists are advised to exercise caution.

WAY FORWARD

Since the impacts of lake eutrophication are so severe and are increasing at an alarming rate, this concern should decisively be addressed. Phosphorus and nitrates in domestic and animal wastewaters can cause eutrophication in aquatic ecosystems, and these pollutants can be recovered using various methods [39]. Experimentation with restoration approaches takes time, and monitoring for extended periods comes at a hefty price. According to Estrada et al. (2011), the design and implementation of ecological water models in conjunction with optimization approaches can aid in formulating and evaluating management plans for both short- and long-term schemes [40, 41].

In addition, the elimination of phosphorous, an essential component of detergents, could remove about 50% of the total phosphorous entering the lakes. Many technologies in the tertiary treatment process may involve a separate or a hybrid chemical, physical, and biological removal, all of which could be applied to phosphorous sewage treatment.

(1) Nutrient limitation, recycling, and recovery

Since nitrate and phosphate fertilizers somewhat contribute to eutrophication, composting technology can be considered a practically promising remedy [42, 8]. Composting is turning organic materials such as leftover food and decaying vegetation into compost manure.

The nutrients in compost manure lack the high concentrations of nitrates and phosphates that algae and other bacteria in water bodies need to bloom. All of the essential elements in compost fertilizer are broken down and synthesized by the plants, preventing the occurrence of eutrophication. Nutrient limitation is the name given to this approach of eutrophication control.

(2) Pollution control and management

Limiting pollution strategies, like composting, is a simple and effective way to reduce the quantity of nitrates and phosphates discharged into water systems. If the polluters can limit waste discharge, nutrient content in water systems will be lowered, and eutrophication will be effectively controlled. For instance, phosphates can be precipitated with lime coagulants containing aluminum or iron compounds in sewage treatment plants. The precipitate is then separated in a sedimentation unit before mixed with the other sludge produced during sewage treatment. At the same time, biological cleanup relies on the ability of some microorganisms to absorb phosphorous over their immediate nutritional needs and store it as polyphosphates within their cells.

Phosphorous can also be eliminated by circulating water through treatment ponds, which is absorbed by particulate matter that settles at the bottom of the pond [43]. Thus, large manufacturing firms and municipalities should reduce the amount of waste containing organic nitrogen and phosphorus and refrain from discharging garbage into waterways to limit the number of toxins and nutrients ending up in the waters to feed the algae and other tiny organisms.

(3) Ultrasonic Irradiation

The world is constantly looking for new solutions to some of the world's most pressing environmental concerns. When it comes to eutrophication, ultrasonic irradiation is a technology that has been utilized to reduce and treat algal blooms. The process works by stimulating cavitation, which enables free radicals to be released and damaged the algal cells. Still, research is being conducted to determine the specificity of its application in combating eutrophication.

(4) Bioelectrochemical Technology

Since Michael Potter (1911) first studied the generation of an electrical current by several microorganisms that convert chemical energy into electrical energy by degrading various substrates, particularly organic compounds from wastewater, bioelectrochemical systems (BS) have been widely applied in the form of microbial fuel cells [44]. Many ecological scientists have been successful in removing nitrogen and phosphorus using BS. This promising technology can recover a large quantity of phosphate through precipitation, ammonia, and nitrate in the ammonia-rich wastewater using nitrifying and denitrifying bacteria, and recently by anammox bacteria in bioelectrochemical reactors [45].

(5) Law enforcement

Strengthening rules and regulations against non-point water source pollution can significantly control eutrophication. According to the EPA, the most crucial difficulty in managing nutrient intrusion into water bodies is non-point pollution. Eutrophication is thus reduced when nutrient sources are monitored. The control of detergent manufacturing might eliminate roughly half of the total phosphorus entering some lakes.

Ultimately, we can effectively reduce the amount of nutrients entering aquatic environments by carefully monitoring the non-point pollution sources. High water quality standards and zero tolerance for non-point solutions should be the priorities of the laws. With the support of legislators, pollution regulatory agencies, and all other stakeholders, we can seamlessly minimize the problem of eutrophication.

POTENTIAL PROSPECTS

Considering the fact that nitrate and phosphate pollution is the primary source of eutrophication, reducing it in many forms can aid in the prevention of potential water body deterioration. Reducing dependence on nitrogen and phosphates and adequately managing the discharge of these pollutants into water systems can help control eutrophication by lowering the nutrient density of the water system.

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REFERENCES

[1] Angela, A. D., Jennifer, M., & Ibrahim, M. (2019). Assessment of the Quality of Water from Rooftops (A Case Study of "Nkamponasi" in Tarkwa, Ghana). International Journal of Scientific and Research Publications (IJSRP), 9(5), p8941. https://doi.org/10.29322/ijsrp.9.05.2019.p8941

[2] Madaan, S. (2019). What is Environmental Pollution? Retrieved from Earth Eclipse: https://www.eartheclipse.com/environment/causes-effects-solutions-to-environmental-pollution.html

[3] Rinkesh. (2019). What Is Eutrophication? Retrieved from Conserve Energy Future: https://www.conserve-energy-future.com/causes-effects-and-solutions-to-eutrophication.php

[4] Khadija, B. U., & Ibrahim, M. (2019). Assessment of the Pollution extent of Sulphur Dioxide (SO2) and Nitrogen Dioxide (NO2) in Ambient air within Kano Metropolis, Kano State, Nigeria. Journal of Environmental Science, Computer Science and Engineering & Technology, 8(8), 396–404. https://doi.org/10.24214/jecet.A.8.4.39604.

[5] Estrada, V., RodriguezeReartes, S. B., SoledadDiaz, M. (2011). Determination of biorestoration strategies in eutrophic water bodies through the formulation of an optimal control problem based on a 3D ecological model. Computer Aided Chemical Engineering, ScienceDirect, 1281-1285.

[6] Ibrahim, M, Daniel, A. K., Kiyawa, S. A., & Kutama, A. S. (2017). Phyto-Accumulation of Lead and Chromium in Common Edible Green- Leafy Vegetables Consumed in Dutse Metropolis, Jigawa State, Nigeria. International Journal of Chemical, Material, and Environmental Research (Vol. 4, Issue 3).

[7] de Jonge,V.N. & Elliotte, M. (2001). Eutrophication. Encyclopedia of Ocean Sciences (Second Edition), 2, 306-323.

[8] Cihelio Alves Amorim & Ariadne do Nascimento Moura (2021). Ecological impacts of freshwater algal bloom on water quality, plankton biodiversity, structure, and ecosystem functioning. Science of the Total Environment, 758, 143605

[9] Dong X.Y., Qin, J.G. & Zhang, X.M (2011). Fish Adaptation to Oxygen Variations in Aquaculture from Hypoxia to Hyperoxia. Journal of Fisheries and Aquaculture, 2(2), 23-28.

[10] Ibrahim, M. (2019). Air Quality Analyses for Photochemical Smog Associated with Atmospheric Aerosol Particles and Ozone Precursors Using CMAQ and CAMx Modeling Systems. International Journal of Scientific Research in Science and Technology, 224–235. https://doi.org/10.32628/ijsrst196530

[11] Tang, Y., Zhang, M., Sun, G., & Pan, G. (2019). Impact of eutrophication on arsenic cycling in freshwaters. Water Research, 150, 191–199. https://doi.org/10.1016/j.watres.2018.11.046

[12] Walker, I. R. (2006). Chironomid overview (Vol. 1). U.S.A: 360–366 in S.A. Elias (ed.) Encyclopedia of Quaternary Science, Vol. 1, Elsevier.

[13] Akilu, M.S. & Ibrahim, M. (2021). An Assessment of Occurrences of Thunderstorms as an Indicator of Climate Change: A Case Study of Potiskum and its Environs, Yobe State, Nigeria. International Journal of Scientific Research in Science and Technology (IJSRST), Online ISSN: 2395-602X, Print ISSN: 2395-6011, Volume 8 Issue 4, pp. 526-533, July-August 2021. Available at DOI: https://doi.org/10.32628/IJSRST218480 Journal URL: https://ijsrst.com/IJSRST218480

[14] Korpinen, S., Bonsdorff, E. Crowe, T.P. & Frid, C.L.J. (2015). Eutrophication and hypoxia: impact of nutrient and organic enrichment. Marine Ecosystems, 202-243.

[15] Numafo-Brempong, L., Dawoe, E., & Ibrahim, M. (2019). Assessment of the Effect of Biochar and Leucaena Leucocephala on the Growth and Yield of Maize (Zea mays). International Journal of Scientific Research in Science and Technology, 34–45. https://doi.org/10.32628/ijsrst19641

[16] Lemley, D. A. & Adams, J. B. (2019). Eutrophication. Encyclopedia of Ecology (Second Edition), Elsevier. doi: https://doi.org/10.1016/B978-0-12-409548-9.10957-1

[17] Mairiga, N. M., & Ibrahim, M. (2021). Assessment of Indigenous Knowledge in Managing Environmental Challenges: A Case Study of Ringim Local Government Area of Jigawa State, Nigeria. International Journal of Scientific Advances 2(4), 606–611. https://doi.org/10.51542/ijscia.v2i4.25

[18] Thakur, V. (2018). What is eutrophication? What are its Causes & Effects? Retrieved from Science Samhita: https://sciencesamhita.com/what-is-eutrophication-its-causes-effects/

[19] Ibrahim, M., Chen, D., Ibrahim, S. S., Danjaji, H. A., Ibrahim, K. (2022a), Status of education and agricultural mechanization as a tool for poverty alleviation in Nigeria: a brief review, IRESPUB Journal of Agriculture, Food & Nutrition. Volume 2, Issue 1, Jan-Feb 2022, Page 1-6

[20] Coates, P. (2004). Emerging from the Wilderness (or, From Redwoods to Bananas): Recent Environmental History in the United States and the Rest of the Americas". Environmental & History, 10(4), 407–38.

[21] USDA, U. S. (2019). Animal Feeding Operations. The U.S.A.

[22] Peirce, J.J., Weiner, R. F. & Aarne, P. (1998). Wastewater Treatment. Elsevier Inc.

[23] Ibrahim, M., Chen, D., Ibrahim, S. S., Danjaji, H. A., Muazu, T. (2022b). A Concise Review on The Current Status of Agricultural Mechanization and Environmental Considerations in Nigeria. International Journal of Scientific Advances (IJSCIA), Volume 3| Issue 1: Jan-Feb 2022, Pages 147-151, URL: https://www.ijscia.com/wp-content/uploads/2022/02/Volume3-Issue1-Jan-Feb-No.231-147-151.pdf

[24] Boyd, C.E. (2009). Aquaculture, Freshwater. Encyclopedia of Inland Waters, Elsevier.

[25] Aqu96 (1996). Introduction to the Practice of Fishery Science, Aquacultural Sciences. Elsevier. doi: https://doi.org/10.1016/B978-012600952-1/50011-6

[26] James H. Tidwell, L. A. (2019). Freshwater Aquaculture. in Encyclopedia of Ecology (Second Edition), Elsevier.

[27] Horlacher, H., Heyer, T., Ramos, C.M. & da Silver, M.C. (2012). Management of Hydropower Impacts through Construction and Operation (Vol. 6). Comprehensive Renewable Energy, Elsevier.

[28] Buschmann, A.H., Hernendez-Gonzalez, M.C., Aranda, C., Chopin, T., Neori, A., Halling, C. & Troell, M. (2018). Mariculture Waste Management. Elsevier.

[29] Unknown. (2019). What Is Eutrophication? Retrieved from Chemistry: https://byjus.com/chemistry/eutrophication/

[30] Robert, K. L. (2019). Lake physical feature. Retrieved from Encyclopaedia Britannica: https://www.britannica.com/science/lake

[31] Bressler D.W. & Paul, M.J. (2007). Effects of Eutrophication on Wetland Ecosystems. Tetra Tech, Inc.

[32] Whitton, B.A. & Potts, M. (2000). The ecology of cyanobacteria. Dordrecht: Kluwer Academic Publishers.

[33] Otten, T. G. & Pearl, H. (2015). Health Effects of Toxic Cyanobacteria in U.S. Drinking and Recreational Waters: Our Current Understanding and Proposed Direction. Current Environmental Health Reports, 2(1), 75–84. doi: https://doi.org/10.1007/s40572-014-0041-9

[34] Stewart, I., Schluter, P.J. & Shaw, G.R. (2006). Cyanobacterial lipopolysaccharides and human health-a review. Environmental Health. PMID: 16563160, PMCID: PMC1489932. DOI: 10.1186/1476-069X-5-7

[35] Funari E. & Testai, E. (2008). Human health risk assessment related to cyanotoxins exposure. Critical Review on Toxicology, 38(2), 97–125.

[36] Charpy, L., Casareto, B. E., Langlade, M.J. & Suzuki, Y. (2011). Cyanobacteria in Coral Reef Ecosystems: A Review. Journal of Marine Biology, 2012, 9 pages.

[37] Young, A. C., & Ibrahim, M. (2021). Bioaccumulation of Heavy Metals in Lycopersicon Esculentum Grown with Tannery Sludge across Some Selected Farmlands in Dawakin Kudu LGA of Kano State, Nigeria. International Journal of Scientific Research in Science and Technology, 251–257. https://doi.org/10.32628/ijsrst218238

[38] Knockaert, C. (2019). Possible Consequences of Eutrophication. Retrieved from Wiki Coastal: http://www.coastalwiki.org/wiki/Possible_consequences_of_eutrophication

[39] Velvizhi, G. (2019). Chapter 4.1 - Overview of Bioelectrochemical Treatment Systems for Wastewater Remediation. Microbial Electrochemical Technology: ScienceDirect.

[40] Di Maggio, J., Estrada, V. & Soledad Diaz, M. (2015). Water Resources Management with Dynamic Optimization Strategies and Integrated Models of Lakes and Artificial Wetlands. Computer Aided Chemical Engineering, Volume 37, 2543-2548.

[41] Ibrahim, M., Young, A. C., Chen, D., & Mughal, N. (2021). Potential ecological risk, in-situ phytoextraction potential of Lycopersicon esculentum, and pollution indices of selected toxic metals in Hausawan - Kaba, Kano State, Nigeria. Environmental Challenges, 4(March), 100113. https://doi.org/10.1016/j.envc.2021.100113

[42] Abdallah, M. S., Ibrahim, M., & Warodi, F. A. (2017). Review on Some Plants As Bio - Pesticides. International Journal of Contemporary Research and Review. https://doi.org/10.15520/ijcrr/2017/8/07/203

[43] Lenntech (2019). Algae filtration from superficial water. Retrieved from Water Treatment: https://www.lenntech.com/eutrophication-water-bodies/algae-filtration.htm

[44] Zheng, T., Li, J., Ji, Y., Zhang, W., Fang, Y., Xin, F., Dong, W., Wei, P., Ma, J. & Jiang, M. (2020) Progress and Prospects of Bioelectrochemical Systems: Electron Transfer and Its Applications in the Microbial Metabolism. Front. Bioeng. Biotechnol. 8:10. doi: 10.3389/fbioe.2020.00010

[45] Kelly, P.T., He, Z. (2014). Nutrient removal and recovery in bioelectrochemical systems: a review. Bioresour Technol. Feb; 153: 351-60. DOI: 10.1016/j.biortech.2013.12.046. Epub 2013 Dec 18. PMID: 24388692