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High pollution loads engineer oxygen dynamics, ecological niches, and pathogenicity shifts in freshwater environments

Nuraddeen Bello Ahmad [a,b], Mohammed Sani Jaafaru [c], Zaharaddeen Isa [d], Yusuf Abdulhamid [f], Rahanatu Adamu Kakudi [g], Adamu Yunusa Ugya [a,e,*], Kamel Meguellati [a,*]

[a] School of Pharmacy, Jinan University, 855 Xingye Avenue East, Guangzhou, 511436, China
[b] Department of Biological Sciences, Kaduna State University, Kaduna State, Nigeria
[c] Medical Analysis Department, Faculty of Applied Science, Tishk International University, Erbil, Kurdistan Region, Iraq
[d] Geography department, Kaduna State University, Kaduna State, Nigeria
[e] Department of Environmental Management, Kaduna State University, Kaduna State, Nigeria
[f] Department of Plant Science and Biotechnology, Federal University Dutsin-Ma, PMB 5001, Dutsin-Ma, Katsina State, Nigeria
[g] Department of Integrated Sciences, Federal College of Education Kano, Kano State, Nigeria

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ABSTRACTS

The current study comprehensively reviews the ecological niche and pathogenicity shift in the freshwater microbial community in response to the stress induced by a high pollution load. The study provides a unique understanding of how a change in oxygen level tends to affect the survival of aquatic biota by delving into how an increase in pollutant load affects freshwater stability. The review indicated that high pollution loads alter the balance of freshwater resources such as organic matter, dissolved gases, light penetration, and essential nutrients. This causes oxygen dynamics and a species-dependent change in the community and niche of microorganisms in freshwater environments. This oxygen dynamics also causes the alteration of the genome of freshwater microorganisms, leading to the development of antibiotic resistance genes and thereby increasing the pathogenicity of freshwater microorganisms. The oxygen dynamic created lowers the natural defence strategies of the freshwater environment, thereby increasing the efficacy of the pathogens to infest the respective host. A detailed study of the mechanisms involved in freshwater exotoxins production and interaction with microorganisms will give an important insight into the niche shift in response to the effect of the exotoxin. The effect of the change in the pathogenicity of freshwater microorganisms is of importance to both environmental and medical interests. This is because the change in pathogenicity is not only detrimental to aquatic organisms but also resists improperly treated drinking water. Such water could retrogress wellness and quality of life when used continuously. An extensive study on how specific pollutants cause a shift in the niche and pathogenicity of freshwater microbiota will provide a detailed understanding of the impact of pollution on the stability of freshwater environment.

1. Introduction

Freshwater ecosystem is an environment with high species richness, with different organisms occupying various ecological niches (Sagova-Mareckova et al., 2021). In this ecosystem, sustainability is highly dependant on the biota, which are specialised in different roles across the diverse food chain and food web in the freshwater environment (Gbair and Alshamsi, 2022). These peculiar roles and niches favour the transfer and utilisation of energy and nutrients, respectively, within the freshwater environment (Cantonati et al., 2020). The ability of freshwater organisms to occupy different niches reduces interspecific competition and increases specialisation. The specialisation increases the resilience of freshwater organisms towards global climate change and increases their ability to adapt to changing environments caused by human anthropogenic interferences (Simon and Townsend, 2003). Freshwater organisms are able to develop different mechanisms to counteract the effects of environmental changes. These mechanisms range from physical to biological responses involving the activities of enzymes, which are largely dependent on the ecological role of the organism in the environment (Mugwanya et al., 2022).

Microorganisms are the most important organisms in freshwater due to their role in the processes of decomposition, nutrient cycling,

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* Corresponding authors.
E-mail addresses: ugya88@kasu.edu.ng (A.Y. Ugya), kamel2021@jnu.edu.cn (K. Meguellati).

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photosynthesis, and water remediation. Some microorganisms provide critical ecological services involving symbiotic associations with other organisms for the sustainability of the ecosystem. The incessant pollution caused by human activities affects the quality of freshwater, which in turn affects the ecological role played by microorganisms. Other factors, such as climate and the inversion of freshwater by different species of organisms, also hinder the positive ecological role of microorganisms (Labbate et al., 2016). This is because the variation in the climatic conditions has a direct effect on freshwater chemistry due to an increase in temperature, which lowers the microorganism's diversity due to the depletion of important indicators such as oxygen and nutrients (Polazzo et al., 2022). Also, the inversion of invasive species tends to stimulate the presence of oxygen-depleting bacteria, which also has a negative impact on the sustainability of freshwater ecosystems (Gallardo et al., 2016).

The sustainability of the freshwater ecosystem depends largely on several factors, with dissolved oxygen being one of the key factors (Banerjee et al., 2019). This is because growth indicators, behavioural changes, and organisms survival rates are largely affected by the level of dissolved oxygen in aquatic ecosystems (Martins et al., 2012). The dynamics of oxygen in aquatic ecosystems are due to activities such as photosynthesis and respiration, with the former having a positive effect and the latter having a negative impact (Prasad et al., 2014). This is because during the process of photosynthesis, a large amount of oxygen is released into the aquatic environment to sustain the sustainability of the aquatic biota, but the process of respiration increases the freshwater carbonation and reduces the level of oxygen present in the aquatic environment (Pedersen et al., 2013). Another important factor that alters the rate of dissolved oxygen in aquatic environments is sunlight, which leads to the variation of water temperature, which directly alternates with the dissolved oxygen level of aquatic environments (Vallero, 2019). Human anthropogenic activities increase the pollution load of freshwater ecosystems, leading to intense accumulation of nutrients that stimulate the formation of intense algae blooms (Nwankwegu et al., 2019). This favours the depletion of oxygen due to the decomposition reaction caused by the action of bacteria on the dead cells of the microalgae biomass formed (Dang and Lovell, 2016). The oxygen dynamics are critical for the distribution of microorganisms in freshwater ecosystems because oxygen is an important element needed for survival and reproduction (Liu et al., 2020). The decrease in the level of oxygen tends to affect the basic metabolic pathways of microorganisms and their ability to utilise nutrients, which in turn narrows their survival rate. Despite the difficulty of surviving in a low-oxygen zone, some microorganisms are able to adapt and occupy a niche in the oxygen-depleted freshwater zone (Kapinusova et al., 2023). There is a pool of studies on the effect of pollution on freshwater organisms, but scanty literature shows how it affects ecological niches and pathogenicity. Several key pathways are involved in the disruption of cellular functions in freshwater ecological environments by harmful bacteria-based exotoxins. These include inhibition of cellular protein synthesis leading to death with consequent alteration of the structure of the microbial community (Gu et al., 2024). Interference with membrane integrity and function is another pathway through which exotoxins disrupt cellular function, exotoxins such as hemolysins create pores with the plasma membrane resulting in cell lysis with consequent death of the cells (Verma et al., 2021). Moreover, disruption of the functions of the nerve synapses is considered amongst the key pathways that destroy cellular function in freshwater ecosystems. Botulinum neurotoxin is an example of exotoxins that inhibit the release of neurotransmitters such as acetylcholine for the continuation of communication between nerve cells and muscles in the peripheral nervous system, thereby affecting the survival and behaviour of aquatic organisms (Sejvar, 2020). Likewise, some toxins disrupt cell functions via metabolic interference, causing a cellular homoeostatic imbalance that results in absolute cellular dysfunction with eventual death (Kim and Choi, 2021).

This study is vital because it provides an in-depth understanding of why ecological niches and pathogenicity are crucial indicators for explaining the overall ecological consequences caused by a high pollution load in freshwater. This is because by investigating how high pollutants load impact an organism's ecological niche, we can gain insights into the broader implications for ecosystem health and functioning. whereas understanding the relationship between high pollutant loads and pathogenicity can provide valuable information for developing strategies to mitigate the spread of diseases in both human and animal populations. The current review is aimed at showing the ecological niche and pathogenicity shift in freshwater microbial community in response to the stress induce by high pollution load.

2. Methodology

An in-depth assessment of the literature was done to investigate the current trend on how different pollutants affect oxygen dynamics, cause ecological niches, and cause pathogenicity shifts in aquatic ecosystems. Keywords such as pollution, biogeochemical cycle, pathogenicity, aquatic ecosystem, water pollution, and hypoxic zone were searched in Google Scholar, Scopus, and Web of Science databases. The keywords were used to refer to literature that focuses on the effects of different pollutants on the biota of both freshwater and marine water in order to make a proper inference. Articles that were published between 2010 and 2024 were evaluated in order to ascertain the most recent information. The relevant articles were thoroughly studied, and some information was also extracted from articles with keywords that are directly related to the marine environment. The only referenced work that is outside the timeframe selected for the current review is the study conducted by Simon and Townsend (2003). This work was selected because it provides information on ecological organisation in freshwater, which is vital for the current review.

2.1. *Potential sources of pollution in the freshwater environment*

The amount of chemicals and nutrients released into the freshwater environment causes an increase in pollution. These pollutants, which broadly originate from industrial discharge, agricultural runoff, and sewage discharge, are associated with different ecotoxicological effects due to their various compositions (Mishra et al., 2023). For example, industrial activities lead to the release of chemicals such as heavy metals, volatile organic compounds (VOCs), and persistent organic compounds (POPs) during different industrial processes such as manufacturing, mining, distillation, electrolysis, cutting, metalworking, etc. (Kumar et al., 2021). Agricultural runoff leads to the release of pollutants such as fertiliser and pesticides as a residual of agricultural activities into aquatic ecosystems (Pericherla and Vara, 2023). Whereas sewage discharge leads to the release of various pollutants such as organic matter, nutrients, pathogens, and different pharmaceutical products (Hassan et al., 2023). The thresholds of nitrate at < 10 mg/L, phosphate at < 0.1 mg/L, ammonia at < 0.02 mg/L, heavy metals at < 0.01 mg/L, dichlorodiphenyltrichloroethane at < 0.0001 mg/L, biological oxygen demand at < 5 mg/L, polychlorinated biphenyls at < 0.0005 mg/L, dioxins, and furans at < 0.0000003 mg/L are considered elevated levels in an aquatic ecosystem.

The elevated level of these pollutants tends to affect overall productivity due to disruptions in the eco-balance and health of the freshwater environment. This causes a reduction in the resilience of freshwater biota to environmental stressors, leading to increased vulnerability, impaired growth, reduced reproduction, and possible death due to the destruction of aquatic habitat (Pelletier et al., 2020). For instance, the elevated level of pharmaceutical waste in freshwater leads to an increase in the presence of bacteria strains that are resistant to antibiotics. This is due to the occurrence of antibiotic resistance genes (ARG) caused by the high levels of antibiotics in the freshwater environment.

This ARG is transferred to bacteria, leading to the development of antibiotic-resistant strains that tend to exert negative effects on aquatic biota (Okoye et al., 2022). ARG tends to alter the natural environment by disrupting the eco-balance and health of freshwater, thereby exerting negative effects on aquatic organisms. The issues of ARG extend beyond the aquatic environment because the rise of pathogens with ARG leads to an increase in the spread of drug-resistant infections, making it difficult to effectively treat infections. Hence, it is an issue of public health concern because it affects both humans and animals. Copiuous number of studies revealed that high pollution loads result in the alteration of freshwater microbial genome which leads to the increase in pathogenicity through the development of antibiotic-resistance genes in the organism (Quillaguamán et al., 2021). Several mechanisms are involved in the genomic changes of the microorganisms including horizontal gene transfer which is the main mechanism of mediating the transfer of genetic materials amongst microorganisms using either bacteriophages or transposons (Blakely, 2024). Another mechanism was believed to be through the induction of mutation in the microbial genome, which results in resistance gene development (Ghosh et al., 2020). Pressure selectivity by pollutants and many antibiotics was also considered one of the mechanisms that enhance the survival of some resistant organisms via the resistance genes spread (Maurya et al., 2020). Table 1 summarises the ecotoxicological effects of other pollutants on human and aquatic ecosystems.

2.2. *Effect of high pollution load on freshwater resources*

The increased release of toxic pollutants into freshwater environments tends to increase the pollution level in the environment (Szymańska and Obolewski, 2020). These elevated pollutants tend to alter the balance of the freshwater ecosystem, particularly its resources. These resources, which include organic matter, dissolved gases, light penetration, and essential nutrients, are key factors for the sustainability of freshwater ecosystems (Fig. 1). Alteration of these resources leads to drastic dynamics that affect the composition, structure, and function of the ecosystem (Gavrilescu, 2021). For example, high pollution loads tend to affect the quality and composition of organic matter in freshwater environments, making it persistent and less biodegradable due to the change in its overall chemical structure (Xenopoulos et al., 2021).

An increase in pollutant load in freshwater environments leads to the enrichment of organic matter and nutrients, triggering eutrophication. This results in the growth of algae and other aquatic plants, which consume oxygen during decomposition, leading to oxygen depletion in the water. The reduced oxygen levels create hypoxic or anoxic conditions, impacting the composition and activity of microbial communities. Anaerobic microorganisms become dominant, leading to shifts in ecosystem functions and nutrient cycling. Additionally, changes in oxygen dynamics can affect the concentrations of other dissolved gases, such as methane and hydrogen sulfide, with ecological implications. Understanding these processes is crucial for managing the impacts of pollutant loading on freshwater ecosystems.

The persistence of these organic matters and the presence of more nutrients from the intense pollution favour the growth of algae blooms, which prevent the penetration of adequate light into freshwater ecosystems and also lead to the decrease of important dissolved gases such as oxygen and carbon dioxide (CO_2). (Häder and Gao, 2015) These occurrences of CO_2 in low concentration in freshwater environments lead to an increase in the acidity of the water, which exerts a negative effect on aquatic organisms, particularly microbial communities, whose composition and diversity are affected in response to the acidic dynamics. The decrease in the level of CO_2 leads to low availability of food sources for the freshwater ecosystem due to the fact that CO_2 is an important resource used by aquatic producers for the manufacture of aquatic food (Lefcort et al., 2015). This excessive CO_2 concentration also facilitates the decrease in freshwater dissolved oxygen, which in turn has negative effects on the aquatic organisms that are dependent on it (Griffith and Gobler, 2020). Water pollution tends to hinders the penetration of light into the freshwater environment to a level that is detrimental to resource availability in the environment. This is because water pollution increases the level of contaminants and sediments, which in turn prevent light penetration and restrict activities in the photic zone of freshwater. The photic zone is the centre for energy productivity in freshwater, so the conversion of this zone to an aphotic zone by pollution limits resources flow of important materials such as nutrients and oxygen across the trophic level (Bashir et al., 2020). Fig. 1 also shows the contribution of climate change to the dynamics of oxygen and freshwater resources. This is because temperature causes an increase in the water temperature, which leads to an increase in the rate of evaporation, which contributes to the deficiency of oxygen in freshwater environments (Brkić, 2023). This is because the increase in water temperature leads to the warming of the water, which results in a decrease in the availability of oxygen because warmer water holds less oxygen compared to cold water (Chapra et al., 2021). A change in climate due to increased anthropogenic emissions results in a change in the pattern of rainfall, leading to environmental problems such as drought, floods, and erosion, which negatively affect the chemistry of freshwater and resource availability (Okon et al., 2021).

Pollutants in freshwater environments can lead to low oxygen conditions through processes like eutrophication, organic pollution, and

Table 1
Toxicological effects of different freshwater pollutants.

SN	Pollutant	Concentration range in surface water	Aquatic toxicology	Human toxicology	Reference
1	Pesticide	The range of pesticides in surface water is dependant on factors such as location, agricultural practices, and weather conditions. The concentration reported ranges from a trace amount to a level exceeding the regulatory limit of 0.1 μg/L set by the Groundwater Directive.	Pesticides enter aquatic environments via agricultural runoff due to improper management and exert negative effects on fish, amphibians, and other aquatic organisms. For example, pesticides disrupt the reproductive system and cause impaired growth and development in fish.	Human exposure to pesticides is associated with acute or chronic effects; acute effects include nausea, rashes, blisters and dizziness, while chronic effects include cancer, reproductive disorders, and beurological damage.	(de-Assis et al., 2021; Mas et al., 2020)
2	Fertilizer	The concentration range of fertiliser in surface water is dependent on agricultural practice and proximity. Studies have shown that nitrate concentrations range from 0.1 to 100 mg/l in surface water, with higher concentrations found in regions with intense agricultural activities.	Fertilisers contain important elements such as nitrogen and phosphorus, which, in nutrient form, cause the excessive growth of algae, leading to a decline in oxygen levels and negatively impacting freshwater biodiversity.	The possible exposure of humans to fertiliser via ingestion, inhalation, and skin absorption has been associated with chronic effects including skin irritation, respiratory issues, and cancer.	(Ahmed et al., 2017; Suresh et al., 2023)
3	Heavy metals	The range of heavy metals in surface water is dependant on the location and proximity of anthropogenic activities and geological processes. In Bangladesh, the concentration range of heavy metals reported in surface water is between 3.98 ppm and 0.004 ppm.	Heavy metals tend to interfere with the physiological processes of aquatic organisms, leading to impaired growth and reproductive dysfunction, which leads to biodiversity declines.	Human exposure to heavy metals through ingestion, inhalation, and dermal contact has been linked to chronic effects such as neurological disorders, kidney damage, cardiovascular diseases, developmental abnormalities in children, and even cancer.	(Hossen and Mostafa, 2023; Jaishankar et al., 2014)

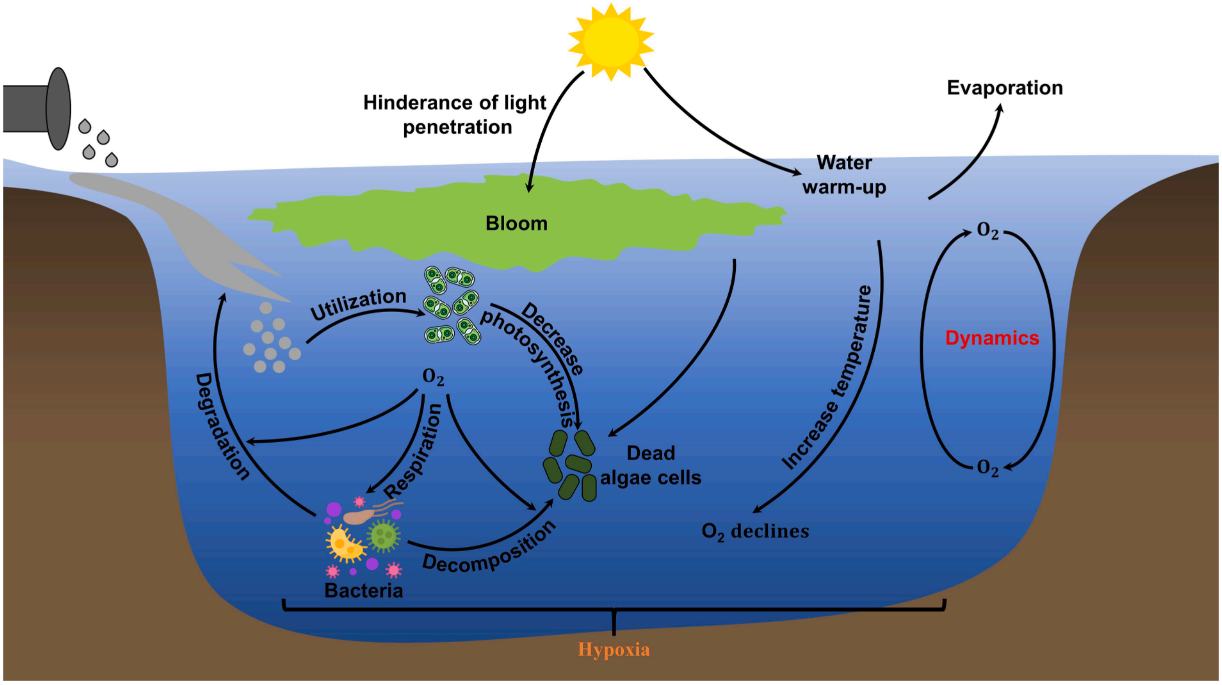

Fig. 1. How pollution and climate induce oxygen dyanamics in freshwater.

toxic substances. Excessive nutrients and organic pollutants promote the growth of algae and bacteria, increasing oxygen demand during decomposition and depleting oxygen levels (Lefcort et al., 2015). These low oxygen conditions favour the proliferation of harmful bacteria, disrupt ecological functions performed by microorganisms, promote harmful algal blooms, and alter trophic interactions within the microbial community (Eriksen et al., 2022b). Understanding the impacts of pollutants on oxygen levels and microbial communities is essential for effective pollution management and preserving the health and functioning of freshwater ecosystems. More so, Pollutants contribute immensely to the anoxia stimulation in freshwater ecosystems via eutrophicating the water. Nitrogen and phosphorus from agricultural runoff or sewage increase algae growth in waterways called algal bloom, which blocks sunlight, preventing other plants from photosynthesizing and oxygen generation. Algae decompose, deplete dissolved oxygen, and cause hypoxic or anoxic environments (Altieri and Diaz, 2019). Anoxia affects freshwater microbial populations in numerous ways. Anaerobic bacteria may survive without oxygen, outcompeting aerobic germs. Botulism-causing anaerobic bacteria can multiply rapidly in a polluted environment. Anoxic environments can equally upset ecological equilibrium by shifting microbial processes from aerobic to anaerobic metabolic pathways including denitrification and methanogenesis (Cox and Gillis, 2020). When that happens, water quality, aquatic organism's health, and ecosystem services like water purification and recreation can be affected by the changes, which can ripple through the ecosystem. Similarly, low-oxygen circumstances can make some bacteria more virulent or toxic, which can endanger aquatic life and human health at large (Schuster et al., 2021; Gao et al., 2023).

2.3. Persistent organic pollutants causes oxygen dyanamics in freshwater

The presence of persistent organic pollutants (POP) tends to cause a disruption in the balance of the freshwater environment, triggering a change in the biogeochemical cycles that impacts the freshwater biota negatively (Borgå et al., 2022). This pollutant causes a reduction in dissolved oxygen, which disrupts the metabolism of freshwater biota, leading to suffocation and a reduced reproductive rate, which affects the overall survival of freshwater biota (Perhar and Arhonditsis, 2014). The ability of POP to accumulate and magnify in freshwater interferes with the process of oxygenation due to its inhibitory effect on the growth of oxygen-producing organisms such as microphytes and macrophytes. This is because POP tend to magnify to a level that interfere with the synthesis and proper funtioning of chlorophyl leading to the reduction in the ability of aquatic flora to utilize light energy to perform photosynthesis which is the most important pathway that supply oxygen to freshwater environment (Ghosh et al., 2022).

The increase in the level of POP tends to affect the availability of nutrients such as nitrogen, phosphorus, and magnesium, which are important elements vital for the synthesis of chlorophyll by freshwater flora. Also, POP tends to interfere with biogeochemical cycles, causing an alteration in the microbial community that alters the nutrient status of freshwater, leading to eutrophication, a process that causes the depletion of dissolved oxygen (Xia et al., 2020).

The increase in the level of POP tends to disrupt the processes of nitrogen fixation and nitrification, leading to nutrient runoff, which causes an elevated level of nutrients leading to eutrophication (Kakade et al., 2021). An increase in POP also tends to cause a reduction in the availability of magnesium, which causes a reduction in the photosynthetic potential and survival of freshwater flora. This reduction of magnesium occurs due to the ability of POP to bind to magnesium ions via the formation of complexes or ligation, thereby making them unavailable for plant utilisation (Rutkowska-Zbik et al., 2013). This reduction in the photosynthetic potential of freshwater flora causes oxygen dynamics, which in turn affects the avialability of resources in the freshwater ecosystem (Akinnawo, 2023).

2.4. Oxygen dynamics drive resource partitioning in a freshwater environment

The impact of a high pollution load is responsible for oxygen dynamics in freshwater, particularly with the decrease in sunlight penetration, which leads to a reduction in photosynthetic activities and low dissolved oxygen production. The lack of sunlight at night also contributes to oxygen dynamics since oxygen production is lower than the oxygen used up during decomposition and respiration (Eriksen et al., 2022b). In freshwater environment resources are partition according to oxygen dynamics because dissolved oxygen is a vital element in freshwater environments because it is critical for the sustainability of freshwater ecosystems. This is because the level of dissolved oxygen in different regions of freshwater determines the population and diversity of organisms in the region (Yin et al., 2021). The studies conducted by Zhang et al. (2023) show an increase in the trend of dissolved oxygen between 2011 and 2020 due to a reduction in anthropogenic emissions into the Chinese coastal seas.

The studies further show that this trend favours an increase in species diversity based on the tolerance level of each species to dissolved oxygen (Zhang et al., 2023). Similarly, in freshwater ecosystems, the low population and diversity of organisms in some regions with low dissolved oxygen is due to the increased pollution load that favours the growth of toxic algae blooms and bacteria that use up the available dissolved oxygen at the expense of the sustainability of the ecosystem (Liu et al., 2022). The study conducted by Spietz et al. (2015) shows a link between bacterial community and variation of dissolved oxygen, with a significant change in community occurring between dissolved oxygen concentrations of 5.18 and 7.12 mg O_2/l (Spietz et al., 2015). The decrease in dissolved oxygen restricts the proper functioning and productivity of aquatic flora, thereby negatively impacting faunal resources such as fish, amphibians, reptiles, mollusks, and crutaceans (Cantonati et al., 2020).

The high diversity of organisms in regions with high levels of dissolved oxygen is due to the intense availability of food, which favours different trophic levels and food webs due to the high concentration of photosynthetic organisms (Trombetta et al., 2020). For example, a detailed review of ecosystem services by B-Béres et al. (2023) links the proper functioning of the freshwater environment to diatoms due to their role in primary production, food provision, and nutrient cycling via the process of photosynthesis, which is also dependant on the availability of dissolved oxygen (B-Béres et al., 2023). The process of photosynthesis is also dependant on the dynamic of oxygen because important nutrients such as carbon, nitrogen, and phosphorus are products needed for aquatic plants growth and development (O'Hare et al., 2018). These nutrients are produced through the biogeochemical cycle and are aided by the process of decomposition, which is dependant on the availability of dissolved oxygen (Carey et al., 2022). This process of decomposition, which is aided by aerobic microorganisms, is oxygen-dependant and essential for freshwater resources. This is because the processes facilitate the reduction of organic pollutants, leading to increased water transpirancy (Xu et al., 2023). This increase in transparency increases the amount of sunlight penetration, which leads to an increase in the productivity of the freshwater environment. This increase in productivity leads to an increase in diversity due to the direct dependence of freshwater food chains and the food web on the photosynthetic process. Also, dissolved oxygen is an important aquatic tool in the neutralisation of acidic compounds in water and also facilitates the growth of aerobic bacteria, which aid in biogeochemical processes that supply photosynthetic organisms with the needed nutrients (Gobler and Baumann, 2016).

Table 2
High pollutants induce microbial community shift under different biogeochemical cycle.

SN	Biogeochemical Cycle	Pollutants and Condition	Community diversity	Community Shift	References
1	Nitrogen cycling	Organic matter (Plant decomposition)	Benthic bacterial and archaea community	The influence of the release of nitrogen in the form of ammonia, nitrite, and organic nitrogen alters the assembly of the microbial community, with more effect on the benthic archae than the bacterial community	(Gu et al., 2021)
2	Nutrient cycling	Organic matter (aquatic plant decomposition aided by *E. coli* invasion)	Epiphytic bacterial and archaea community	The process of decomposition leads to nutrient release, which causes a shift in the epiphytic microbial community with more effect on the archaeal community due to the role of E. coli in weakened methanogenesis.	(Wu et al., 2021)
3	Heavy metals	Effect of zinc and arsenic pollution	Water is highly diverse with fungi and bacterial communities	The microbial diversity of the bacteria and fungi was reduced in response to the pollutant stress. although only a few resistant species were detected and the mass of limnodrilus hoffmeisteri increased despite the pollutants stress	(McComb et al., 2014; Zhao et al., 2014)
4	Nitrogen cycling	Wastewater pollution induced stress	Riverine bacterial communities	The shift in riverine bacterial communities was based on the three concentration gradients denoted as high, medium, and low effluent concentrations. The study reported a replacement of some species at the effluent concentration above medium.	(Ruprecht et al., 2021)
5	Stochastic processes	Pollution gradient	Pond bacterial community	The composition, structure, and diversification of the bacterial community were altered with increasing pollution levels.	(Tai et al., 2020)
6	Heavy metal Nitrogen cycle	Combined pollution load	Riverine bacterial communities	The study shows how exposure to heavy metals and other pollutants causes a shift in riverine bacterial structure, composition, and diversity upstream and midstream compared to downstream.	(Yuan et al., 2023)
7	Nutrient cycle	Nutrient pollution	Pond bacterial community	The abundance of the bacterial community was affected by the increasing nutrients, showing the involvement of the bacteria in the transport and transformation of the nutrients, leading to the self-purification of the lake water.	(Zhu et al., 2022)
8	Carbon cycle	Microplastics and detergent	Bacterial communities.	The interactions between the microplastic and detergent exert a multi-stress effect that causes a shift in the relative abundance of bacterial communities.	(Varg and Svanbäck, 2023; Zhu, 2021)
9	Nutrient cycle	Nutrient pollution	Riverine microbial communities	The use of micro-nanobubble technology improved the dissolved oxygen in the water, leading to a shift in the riverine microbial community. This indicates that the pollution load on the river has a negative effect on the dissolved oxygen, which in turn has a direct effect on the microbial community of the river	(Wu et al., 2019)
10	Nitrogen cycle	Nitrogen pollution	Riverine bacteria community	The bacterial richness and diversity change in response to the high pollution load of nitrogen compounds due to the presence of high concentrations of NH_4^+ and NO_3^- in the freshwater. The dynamic bacteria community in the nitrogen-polluted water is evidenced by the decrease in the abundances of some phyla, such as Firmicutes and Nitrospirae, and the increase of some phyla, such as Bacteroidetes, Verrucomicrobia, and Spirochaetes.	(Lin et al., 2019)

2.5. *Microorganisms' community shift under oxygen-dynamic condition*

Freshwater microorganisms are highly diverse and critical for nutrient cycling due to their role in biogeochemical cycles via the decomposition process. The fluctuation of oxygen in freshwater due to the increase in pollutants tends to alter the composition and diversity of freshwater microorganisms (Gu et al., 2021). These oxygen dynamics in freshwater environments tend to alter the metabolic pathways of microbial communities, leading to a change in the abundance and distribution of microbial constituents in freshwater (Bertagnolli and Stewart, 2018). The different biogeochemical cycles tend to stimulate a shift in microbial communities as presented in Table 2. This is due to the ability of microorganisms to utilise nutrients and energy via metabolic activities which is largely dependent on the availability of oxygen, although some microorganisms tend to utilise nutrients such as nitrate and sulphate in the absence of oxygen (Gupta et al., 2017). The oxygen dynamics tend to shift microbial community structure because biogeochemical cycles such as carbon, nitrogen, and phosphorus have an influence on the microbial metabolic activities (Camacho et al., 2022). This oxygen dynamic within the freshwater environment tend to interfere with the metabolic pathways of microorganism, hence the reason why some microorganism such as aerobic microorganisms tend to propagate in the presence of oxygen while other such as anaerobic microorganism propagate in anoxic condition (Gupta et al., 2017; Laso-Pérez et al., 2018).

This ability of microorganisms to evolve both aerobic and anaerobic mechanisms provides a perfect metabolic response to oxygen dynamics in freshwater, which persist due to the increase in anthropogenic input (Chen et al., 2021). This major shift in microorganisms after exposure to pollutants is directly linked to the reduction in dissolved oxygen due to the increased pollution load engineered by the utilisation of excess dissolved oxygen during the interaction of aerobic microorganisms with the pollutants (Révész et al., 2020). The aerobic microorganisms are able to use the Krebs cycle to oxidise these pollutants to produce energy used for other metabolic processes (Dang and Chen, 2017). This energy is produced during oxidative phosphorylation, which is a process in which energy is produced in the form of adenosine triphosphate (ATP) by the direct reduction of dissolved oxygen by the addition of electrons (Huang et al., 2019).

Anaerobic microorganisms are able to generate energy using processes such as fermentation and anaerobic respiration. During fermentation, ananerobic microorganisms are able to generate energy by converting complex organic pollutants into simpler organic pollutants in the absence of oxygen (Dai et al., 2023). During anaerobic respiration, microorganisms use other substances such as nitrate and sulphate as electron acceptors to generate energy needed for other cellular activities (George et al., 2020). The limitation of oxygen in freshwater causes aerobic microorganisms to revert to a facultative lifestyle, leading to a change from an aerobic metabolic strategy to anaerobic metabolic processes such as chemosynthesis and fermentation (Shan et al., 2012). Similarly, anaerobic microorganisms tend to reprogram their metabolic mechanisms under aerobic conditions in order to maximise the conservation of energy and maintain homoeostasis (Yasid et al., 2016). The inability of microorganisms to annul their metabolic strategies in response to oxygen dynamics is the reason for the shift in microorganism communities with either decreasing or increasing oxygen as a result of anthropogenic input (Spietz et al., 2015). Studies conducted by Guo et al. (2022) reported a change in the bacterial community in sediment collected from the Bohai Sea, leading to a switch in the functions of the microbiota. This implies that in a freshwater environment, an increase in the level of pollutants tends to cause a change in microbial communities and niches as a response mechanism to the decrease in the level of dissolved oxygen caused by the degradation of the pollutants.

Oxygen dynamics in freshwater ecosystems have significant implications for biogeochemical processes and ecological functions. Insufficient oxygen levels, known as hypoxia, can impede aerobic respiration, reducing the decomposition of organic matter and nutrient availability (Dai et al., 2023). Oxygen availability also affects nitrogen and phosphorus cycling, with fluctuations disrupting the balance between nitrification and denitrification as well as the bioavailability of phosphorus (Eriksen et al., 2022b). Additionally, oxygen levels influence methane production and the habitat suitability for fish and macroinvertebrates, as many aquatic organisms have specific oxygen requirements (Spietz et al., 2015). Understanding and managing oxygen dynamics are vital for maintaining healthy biogeochemical processes and sustaining the biodiversity of freshwater ecosystems.

Monitoring and mitigating factors contributing to oxygen depletion, such as nutrient pollution and excessive organic matter, are key to preserving the integrity of freshwater environments (Wu et al., 2021). Implementing measures to improve water quality, such as reducing nutrient inputs and promoting proper waste management, can help alleviate oxygen-related issues. Additionally, maintaining riparian vegetation and minimizing disturbances that can lead to sedimentation can contribute to healthy oxygen dynamics (Carey et al., 2022). By addressing these factors, we can support the ecological functions of freshwater ecosystems and ensure their long-term sustainability.

2.6. *Microorganisms niche modification under oxygen-dynamic conditions*

The community response and competition between microorganisms on the distribution of resources in freshwater is a key function of microorganisms under oxygen dynamics (Arora-Williams et al., 2018). Pollution load alters the resource partitioning of freshwater, leading to changes in microorganisms ecological niches (Nguyen et al., 2022), as shown by various studies represented in Table 3. This ecological niche is species-dependent and tends to vary due to differences in freshwater resource utilisation. for example different heterotrophic and autotrophic bacterial play crucial role in freshwater nitrogen fixation. The diazotrophs are microorganisms that consist of bacteria and archaea and are able to occupy an important niche in freshwater due to their ability to convert gaseous nitrogen into usable ammonia in freshwater ecosystems (Fujita and Uesaka, 2022). Cyanobacterial which are the largest taxa of diazotrophs reported to perform nitrogen fixation in freshwater due to their ability to devise morphological, ecological and biochemical strategies to survive oxygen limitation (Paerl, 2017). These survival strategies by cyanobacteria under oxygen dynamics facilitate chemical interactions between the microorganisms and the freshwater environment, leading to biogeochemical cycling because these interactions favour the fixing of atmospheric nitrogen via nutrient cycling (Chen et al., 2022). Studies conducted by Li et al. (2023) show how pharmaceutical and phosphorus pollution cause a shift in the function of the microbial community in water collected from Lake Taihu, China. The studies show how exposure to these pollutants alters the function of the bacteria associated with nitrogen fixation, nitrification, and sulphate reduction (Li et al., 2023). Studies conducted by Zhang et al. (2019) also give an insight on how heterotrophic nitrifying bacteria occupy a different niche in black and malodorous water, leading to the effective removal of organic pollutants and ammonia nitrogen from the water (Zhang et al., 2019). Microorganisms such as archaea and bacteria in freshwater environments tend to occupy a niche that is vital for the regulation of organic and inorganic sulphur in the environment (Nosalova et al., 2023). The process of sulphur transformation in a freshwater environment by microorganisms is mediated by the processes of oxidation and reduction, leading to the transformation of sulphur compounds into different forms (Vigneron et al., 2021). The presence of a high pollutant load in freshwater tends to alter the niche of sulphur-transforming bacteria due to the oxygen dynamic created by these pollutants (Akhtar et al., 2021). Lack of oxygen in freshwater environment hinder the ability of microorganisms to transform sulphur via the process of oxidation thereby increasing the process of sulphur reduction (Ayangbenro et al., 2018). This process favours the

Table 3
Biogeochemical cycle drive a change in freshwater microbial niche.

SN	Cycle	Condition	Consortia Niche	Niche modification	References
1	Nitrogen cycling	Wastewater condition	The anammox consortia have organisms with different niches, including heterotrophic denitrification bacteria, anammox bacteria, Chloroflexi bacteria, nitrite-oxidising bacteria, and ammonia-oxidising bacteria.	The ecological niches of the two distinct anammox genera (Ca. kuenenia and Ca. brocadia) change due to the variation in the concentration of dissolved oxygen.	(Zhang et al., 2022)
2	Nitrite oxidation	Oxygen dynamics with zones	Marine oxidizing bacterial	Niche differentiation was observed for the marine nitrite-oxidising bacteria at different zones due to the difference in the tolerance level of oxygen.	(Sun et al., 2021)
3	Carbon cycle	Biofilm from pyrite mine site	pyrite-oxidizing microbes	Oxygen alters the distribution and causes differentiation in the ecological niche of bacteria and archaea in the biofilm. The fixation of CO_2 only occurs at the rim of the snottite and decreases with decreasing oxygen; as such, the niche of the archaea inhabiting the core of the snottite plays no role in primary production in the biofilm.	(Ziegler et al., 2013)
4	Sulfur cycle	hydrogen sulfide release due to the disturbance of brackish ecosystem	phototrophic blooms	The niuche differentiation occurred with variation in oxygen gradients, with aerobic phototrophic Cyanobacteria dominating the upper part while anoxygenic purple sulphur bacteria and green sulphur bacteria dominated the middle and lower parts, respectively.	(Bhatnagar et al., 2020)
5	Phosphorus cycle	phosphate enrichment	The diversity and richness of the bacterial community were higher, while the fungus community was lower in the pre-posphate dose sample.	The microbial niches shift with increasing concentrations of phosphate, favouring bacterial and fungus communities able to metabolise phosphate.	(Douterelo et al., 2020)

accumulation of hydrogen sulphide in freshwater, thereby exerting a negative effect on sulphur-transforming microorganisms with high concentrations of hydrogen sulphide accumulation (Pal et al., 2018). A study conducted by Wang et al. (2019) gave an insight on how the high pollution load on the river Ziya due to inflow from urban and agricultural wastewater causes a change in the niche of sulphur-oxidising microorganisms and sulphur-reducing microorganisms (Wang et al., 2019). Arora-Williams et al. (2022) also show how sulphur-oxidising microorganisms are able to undergo a change in niche in response to hypoxia conditions in Chesapeake Bay (Arora-Williams et al., 2022). The phosphorus cycle is another important cycle in which the mediation of microorganisms is critical for the breaking down of complex organic matter, thereby availing phosphorus for utilisation in freshwater ecosystems (Tian et al., 2021). This mineralization process, mediated by microorganisms, is an important biogeochemical process that provides nutrients for utilisation by freshwater biota for growth and development (Silva et al., 2023). The microorganisms are able to engineer the conversion of inorganic phosphorus into organic phosphorus and are able to use the process of immobilisation to mediate the conversion of organic phosphorus into inorganic phosphorus, thereby aiding phosphorus cycling (Feng et al., 2023; Yang et al., 2021). The presence of a high pollution load tends to change the niche of phosphorus-solubilizing microorganisms due to the accumulation of these pollutants to a level that is toxic and inhibits the growth of these microorganisms (Chen et al., 2023). This pollution induces an oxygen-dyamic condition that affects the efficacy of these microorganisms to solubilize phosphorus, leading to a shift in freshwater microbial community composition and diversity that affects the niche of phosphorus solubilizing microorganisms, thus affecting their role in phosphorus cycling (Zheng et al., 2019). Microorganisms also function in freshwater carbon cycling by acting as decomposers that facilitate the decomposition of dead organic matter, thereby availing carbon dioxide, which is utilised by freshwater photosynthetic organisms for nutrition and then serves as a food source for other freshwater biota (Dang, 2020). When the pollutant load in freshwater is intense, the ecological niche of carbon cycling microorganisms is altered due to the oxygen dynamics caused by the high pollutants load, which inhibit the ability of this microorganism to degrade carbon (Eriksen et al., 2022a). This is because oxygen is an important element that aids this microorganism in the degradation of carbon due to its role as an electron acceptor, which is vital for the microbial degradation of organic compounds (Mohapatra and Phale, 2021).

The increased pathogenicity of freshwater microorganisms in response to oxygen dynamics and pollutant-induced changes in microbial niches and communities has significant environmental and medical implications (Tian et al., 2021).. Environmentally, it can disrupt ecosystem balance, promote harmful algal blooms, and disrupt trophic interactions. Medically, it raises the risk of waterborne diseases, reduces water quality, and contributes to the emergence of infectious diseases (Yang et al., 2021). Addressing these implications requires comprehensive monitoring, surveillance, and mitigation strategies to protect both freshwater ecosystems and public health.

Rise in freshwater-based microbial pathogenicity as a result of alterations in oxygen dynamicity and pollution could possess crucial medical and ecological implications in many ways. Ecologically, pathogenic organisms could reduce the quality of freshwater when present, making it not safe for humans and other forms of life (Chakraborty and Bhadury, 2015). Also, the pathogenicity of such organisms in freshwater causes an intense disruption in the aquatic ecosystem, leading to an imbalance in the microbial community that could affect numerous processes such as nutrient cycling within the ecosystem (Bocanegra-García et al., 2023). On the other hand, freshwater pathogenic microbes are unequivocally implicated in disease outbreaks, antimicrobial resistance, and food safety-related matters. For instance, pathogens contaminated freshwater used in irrigation farming could be the source of numerous foodborne disorders and consequent disease outbreaks. The unavoidable presence of pollutants in freshwater could enhance antimicrobial resistance development leading to a series of complications in the choice of treatment (Egli et al., 2002; Bell et al., 2021). These and many other reasons indicate the need to carefully monitor the freshwater environment and apply actions through which pollution will be mitigated and the quality of the water will be preserved.

2.7. High pollutants load induce change in pathogenicity of potential microorganisms in freshwater ecosystem

The freshwater ecosystem is comprised of organisms that vary greatly in terms of compositions and genetic diversity (Sagova-Mareckova et al., 2021). Such differences are attributed to the factors like temperature, quality, nutritional availability, and the presence of other organisms in the water (Nonić and Šijačić-Nikolić, 2021). Amongst the potential pathogenic organisms found in freshwater ecosystem are bacteria, viruses, protozoans, helminths, fungi, algae, and many others. While infected humans are the primary reservoir of pathogenic organisms, it is crucial to acknowledge the fact that other animals such as sheeps, cattles, pigs, cats, dogs, and wild ones also play a key role in polluting freshwater sources through the deposition of faeces that increase pathogens and nutrient level (Klūga et al., 2021). The infective dose of pathogens required for transmission to human varies amongst different pathogenic organisms, with some requiring very little, while others need large doses of transmissible pathogens to for effective pathogenicity (Alegbeleye and Sant'Ana, 2020). Microbial organisms utilize various ways to invade, infect, and damage their vulnerable hosts, causing several forms of disease conditions at varying intensities as shown in the Table 4.

The main basis for judging the level of pathogenicity is the virulence of the pathogen, which refers to its ability to cause disease in a host organism. This can be influenced by various factors, such as the presence of specific virulence factors or the ability to evade the host's immune system. The level of pathogenicity can be compared under different aquatic environments, but it is important to consider the specific conditions and factors present in each environment. For example, in the case of Vibrio species, the pathogenicity appears to increase in cadmium and arsenic contaminated environments, while it is inhibited in mercury and zinc contaminated environments (Hanna et al., 2017). Similarly, in the

Table 4

Pathogenicity, mechanism of action and diseases caused by some selected potential freshwater pathogenic organisms.

SN	Microorganism	Level of Pathogenicity	Mechanism	Diseases caused	Reference
1	**Bacteria**				
	Cyanobacteria	Moderate	Toxins production, Adherence, Evasion, Damage	Liver damage, neurotoxicity, GIT disease	(Dhagat and Jujjavarapu, 2022)
	Actinobacteria	High	Toxins production, Adherence, Evasion, Damage	Tuberculosis, Nocardiosis, Leprosis	(Dhagat and Jujjavarapu, 2022)
	Proteobacteria	High	Toxin production, Adhesion, Invasion, Evasion	Salmonellosis, Cholera, Pneumonia, Gonorrhoea, Tularaemia, Whooping cough	(Dhagat and Jujjavarapu, 2022)
	Bacteroidetes	Low	Toxin production, Adhesion, Colonization, Invasion, Evasion	Inflammatory bowel disease, Obesity, and Metabolic disorders, Oral Disease	(Dhagat and Jujjavarapu, 2022)
2	**Protozoans**				
	Amoebae	High	Invasion, Evasion, Nutrient Acquisition, Damage.	Amoebic dysentery, Amoebic meningoencephalitis, Granulomatous amoebic encephalitis, Amoebic keratitis.	(Li et al., 2020)
	Ciliates	Moderate	Adhesion, Invasion, Enzyme secretion, Toxins secretion	Balantidiasis, Ichthyophthiriasis, Trichodiniasis, Oyster disease, Cryptosporidiosis.	(Li et al., 2020)
	Flagellates	Moderate	Invasion, Toxins production, Disruption of host immune response, Induction of inflammation, Transmission.	African trypanosomiasis, Chagas disease, Giardiasis, Trichomoniasis, Leishmaniases.	(Chaudhury and Parija, 2020)
	Sporozoans	High	Invasion, Replication, Immune evasion, Transmission.	Malaria, Toxoplasmosis, Babesiosis, Coccidiosis, Cryptosporidiosis, Theileriosis.	(Rai et al., 2023)
3	**Viruses**				
	Bacteriophages	High	Adhesion, Injection, Replication, Lysis, Inflammation, Horizontal gene transfer.	Diphtheria, Staphylococcal infections, Shiga toxin-producing E. coli infection.	(Akmal et al., 2020)
	Hantavirus	High	Infusion, Replication, Immune evasion, Endothelial cell damage.	Hantavirus Pulmonary Syndrome, hemorrhagic Fever with Renal Syndrome.	(Akmal et al., 2020)
	Rotavirus	High	Adhesion, Replication, Assembly and maturation, Cell damage and release.	Acute gastroenteritis, Dehydration, Malnutrition, Intussusception.	(Rashid et al., 2021)
	Adenovirus	High	Adhesion, Evasion, Replication, Invasion, Tissue damage.	Respiratory infection, Gastroenteritis, Conjunctivitis, Cystitis, Keratoconjunctivitis, Neurological complications.	(Rashid et al., 2021)
	Norovirus	High	Adhesion, Immune evasion, Replication, Invasion.	Acute gastroenteritis, Waterborne illness, Foodborne illness, Community outbreaks, Traveler's diarrhoea.	(Pasalari et al., 2022)
4	**Algae**				
	Brown algae	Low	Biofilm formation, Toxin production, Immune evasion, Enzyme secretion.	Eutrophication	(Molina-Grima et al., 2022)
	Blue algae	Moderate	Biofilm formation, Adhesion, Invasion, Immune evasion, Tissue destruction.	GIT illnesses, Hepatic disease, Neurotoxicity, Respiratory illnesses.	(Molina-Grima et al., 2022)
	Red algae	Low	Toxin production, Invasion, Colonization, Nutritional depletion, Immune evasion.	Amnesic Shellfish Poisoning, Ciguatera Fish Poisoning, Red Tide.	(Molina-Grima et al., 2022)
5	**Fungi**				
	Achlya	Moderate	Invasive growth, Appressorium formation, Production of Toxic metabolites, Evasion of immune system, Induction of hypersensitive response.	Skin and soft Tissue Infection, Respiratory Trac infection, Eye infection, Allergy.	(Magray et al., 2021)
	Oomycetes	Low	Invasive growth, Appressorium formation, Production of Toxic metabolites, Evasion of immune system, Induction of hypersensitive response.	Pythiosis.	(Magray et al., 2021)
	Rhodotorula	High	Adhesion, Colonization, Biofilm formation, Production of virulence factor, Evasion of the immune system.	Meningitis, Fungemia, Endophthalmitis, Skin and Soft Tissue Infection.	(Magray et al., 2021)
6	**Helminths**				
	Trematodes	High	Adhesion, Invasion, Nutrient absorption, Immunomodulation, Tissue obstruction, Damage, Allergenicity.	Schistosomiasis, Fascioliasis, Clonorchiasis, Paragonimiasis, Opisthorchiasis.	(Madsen et al., 2022)
	Cestodes	Moderate	Adhesion, invasion, Nutrient absorption, Immunomodulation, Tissue obstruction, Damage, Allergenicity.	Taeniasis, Diphyllobothriasis, Cysticercosis, Echinococcosis, Hymenolepiasis.	(Madsen et al., 2022)
	Nematodes	High	Molecule secretion, Feeding structure, Migration and tissue invasion, Induction of host cell modification, Immune evasion, Transmission.	Ascariasis, Strongyloidiasis, FilariasisTrichuriasis, Enterobiasis, Hookworm infection.	(Ziarati et al., 2022)

case of Flavobacterium columnare, high nutrient concentration in the outside-host environment can promote both the virulence and the growth of the pathogen (Sethi, 2014). Therefore, the level of pathogenicity can vary depending on the specific environmental conditions and factors present. The level of pathogenicity can be compared directly under different aquatic environments. Studies have shown that the presence and abundance of pathogenic microorganisms can vary in different hydro ecosystems of fish farms (Labella et al., 2013). Additionally, the presence of virulence genes in non-pathogenic bacteria, such as Vibrio alginolyticus, suggests that they may serve as reservoirs for these genes (Khouadja et al., 2022). Furthermore, the nutrient levels in the environment have been found to influence the virulence of opportunistic pathogens, such as Flavobacterium columnare, with higher nutrient concentrations promoting increased virulence (Hanna et al., 2017). The aquatic environment, including wastewater treatment plants, has also been identified as a route for the dissemination of virulence-associated genes and antibiotic resistance (Pérez-Etayo et al., 2020), the abiotic environment, specifically lake pH, has been found to be strongly related to the virulence of parasites in a coevolutionary system (Mahmud et al., 2017).

The mechanisms used by freshwater microorganisms to invade host organisms include adhesion, invasion, evasion, and damage (Ribet and Cossart, 2015). The process of microorganisms adhesion involves the ability of pathogenic organisms to bind to the cell surfaces of the host organism by producing a protein called adhesin, which adheres to a specific receptor on the cells of the host (van Belkum et al., 2021). These bindings trigger the establishment of a site of infection by the pathogenic organisms and the resistance to get rid of the host body fluid system (Govindarajan et al., 2020). The process of microorganism invasion involves the ability of the pathogenic organisms to use bio-tools such as enzymes, toxins, or mechanical forces to infiltrate the host cell membranes from the bloodstream, skin, or mucous fluids. Some pathogenic organisms are also, in rare cases, able to outsmart the hosts' immune system and dominate the cells by initiating a self-replication process within the host (Khaneghah et al., 2020). The evasion process of microorganism involves the use of different strategies such as alteration of surface antigens, hiding inside cells, development of biofilms, immunosuppressive moles secretion, capsules production, or assuming host molecules shapes to avoid attack by hosts' immune system (Dhagat and Jujjavarapu, 2022). The process of host cell damage by microorganisms occurs due to the ability of pathogens to inhibits the structural and physiological functions of the host cell by using molecules such as enzymes, toxins, and other important bio-molecules (Lorrai and Ferrari, 2021). Addressing the adverse impacts of pollution on microbial habitats in freshwater environments requires comprehensive and multifaceted strategies which include remediation techniques, water treatment, public awareness campaigns, policy enforcement, and understanding the role of pollutants in the ecosystems through research and development programs (Tariq et al., 2024). Implementing these measures can facilitate the re-establishment of stability and productivity in ecosystems that have been impacted by minimizing the presence of detrimental contaminants (Mahmud et al., 2022).

Under high pollution loads, these mechanistic strategies used by pathogenic freshwater organisms are altered due to the distortion in the balance of the freshwater ecosystem caused by the high pollutant load (Chu and Karr, 2017). This pollutant load can either cause direct or indirect interference with the pathogenicity of freshwater microorganisms. For example, the presence of a high pollution load tends to alter the genome of freshwater microorganisms, leading to the development of antibiotic resistance genes and increasing the pathogenicity of these microorganisms (Fatimazahra et al., 2023). Also, the high pollutants load tends to cause an oxygen dyanamic situation, which lowers the natural defence strategies of the freshwater environment, thereby increasing the effectivity of the pathogens to infest the respective host (Xie et al., 2022).

The ability of microorganisms to attach to the host surface can be directly altered by an increase in pollutant load in freshwater, which causes a change in freshwater physico-chemical status that affects the ability of microorganisms to adhere to their host (Adesakin et al., 2020). This change in the physico-chemical status of freshwater also stimulates behavioural, and survival changes in microorganisms, which leads to the evolution of new genomes that aid in the development of new strategies to evade the host cell (Braga et al., 2016). The ability of microorganisms to invade and cause damage to the auqtic organism host cell increases with increasing pollutant load due to the weakening of the host immune system. This immune weakening is caused by the disruption in the food chain caused by the effect of pollutants on the availability of freshwater food resources (Kataoka and Kashiwada, 2021).

An increase in pollutant load in freshwater environments leads to the enrichment of organic matter and nutrients, triggering eutrophication. This results in the growth of algae and other aquatic plants, which consume oxygen during decomposition, leading to oxygen depletion in the water. The reduced oxygen levels create hypoxic or anoxic conditions, impacting the composition and activity of microbial communities (Gupta et al., 2017). Anaerobic microorganisms become dominant, leading to shifts in ecosystem functions and nutrient cycling. Additionally, changes in oxygen dynamics can affect the concentrations of other dissolved gases, such as methane and hydrogen sulfide, with ecological implications (Révész et al., 2020).

Exotoxins produced by harmful bacteria disrupt cellular functions in freshwater microorganisms through direct cell damage, interference with nutrient uptake and utilization, alteration of interspecies interactions, induction of stress responses, and disruption of trophic cascades (Ribet and Cossart, 2015). These disruptions lead to shifts in community structure, impacting ecological functions and stability. Understanding these pathways is essential for assessing the ecological impacts of exotoxins and implementing strategies to mitigate their effects, ensuring the health and sustainability of freshwater ecosystems (Braga et al., 2016).

2.8. *Future research directions*

The current review shows the effect of oxygen dynamics on the ecological niche of freshwater microorganisms with increasing pollution load, but the mechanisms by which these dynamics alter and hinder the ecological functions of various freshwater biogeochemical processes need to be fully studied. This will give a detailed insight on microbial interaction and nutrient cycling under oxygen dynamics in a freshwater environment.

A detailed study of the mechanisms involved in freshwater exotoxins production and interaction with microorganisms will give an important insight into the niche shift in response to the effect of the exotoxin.

The effect of the change in the pathogenicity of freshwater microorganisms is of importance to both environmental and medical interests. This is because the change in pathogenicity is not only detrimental to aquatic organisms but also resists improperly treated drinking water. Such water could retrogress wellness and quality of life when used continuously. Thus, extra measures must be taken to ensure a reasonable level of cleanness and purity of the water used either domestically or by nomadic animals, as the prevalence of zoonotic disease is on the rise.

More studies are needed to show how freshwater ecosystem oxygen dynamics result from the continuous trend in climate change. Also, to counteract the effect of pollutant and climate change on freshwater biogeochemical processes, more bio-engineering technology should be used for freshwater oxygenation.

Future research directions are needed to further explore the complex interplay between pollutant-induced changes in oxygen dynamics, microbial niches, and pathogenicity in freshwater environments. Key areas for investigation include mechanistic studies to understand molecular interactions and metabolic pathways, exploring microbial community dynamics and resilience, assessing the impacts on public health and waterborne diseases, fostering interdisciplinary approaches, and developing sustainable mitigation strategies. By advancing our understanding in these areas, we can develop effective and sustainable solutions to mitigate environmental degradation, protect public health, and ensure the long-term health and functionality of freshwater ecosystems.

3. Conclusion

The current study shows that increased pollution load stimulates oxygen dynamic conditions, which engineer the change in the microbial niches and community, leading to instability in the productivity of freshwater due to direct effects on the different cycling processes. This is because the oxygen dynamics created by the pollutants stimulate anoxia, or low oxygen conditions, which pathwa

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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No data was used for the research described in the article.

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