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Toxicological Examination and Environmental Impact of Water Pollution

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Abstract: This article investigates the issue of water pollution and its detrimental effects on human health and aquatic ecosystems. Sources of contamination, including industrial effluents, agricultural runoff and untreated sewage are explored. Understanding the detailed ecotoxicological parameters through water analysis is crucial in our efforts to protect and restore aquatic ecosystems. By examining the complex interaction of chemical, physical, and biological factors, we gain valuable insights into the health of water bodies and the impacts of human activities. With this knowledge, we can implement informed policies, enforce regulations, and promote sustainable practices to reduce pollution and safeguard water quality. Ongoing monitoring and research will be vital in addressing emerging threats and ensuring the resilience of aquatic environments for future generations. It is only through unified global efforts that we can maintain the integrity of our water resources and promote a balanced coexistence with nature.

Keywords: Metals, Pharmaceuticals, Physico-chemical, Pollution, Water

1. Introduction

A simple chemical consisting of two hydrogen atoms and one oxygen atom is called water [1]. One common solvable and main source of infection is water. 80% of diseases have been reported by the World Health Organisation (WHO) to be water-borne. Any change to the chemical, biological, or physical attributes of water that could have a negative impact on human and marine life is referred to as water pollution [2]. The water utilised for drinking in many countries does not follow WHO regulations. 3.1% of fatalities is due to unclean and poor-quality water [3]. Highly contaminated water is one of the leading causes of severe health problems [4].

From the past few decades, the majority of natural rivers worldwide had become depleted [5]. Process industries such as tanneries, steel mills, thermal power plants and mining operations that release harmful substances into the environment pose a significant threat due to declining water quality [6]. Recently, the utilisation of industrial effluents for irrigation has emerged as a prominent approach for recycling waste water. There are both advantages and disadvantages to utilising this waste water for irrigation purposes [7,8].

Approximately 1.1 billion people lack access to clean drinking water. With the rapid increment in the growth rate of human, anthropogenic and climatic factors, the rate of accumulation of pollutants in the surface water is drastically increased that lead to gradual change of the water source quality. This review provides an overview of water contaminant sources, assessment methods as well as impact on various organism health. Therefore, the aim of this review is to examine the occurrence of different water contaminants, various water quality monitoring parameters, toxicity effects on organisms in different ecosystem, and mitigation strategies and future directions to improve water quality.

2. Sources of Water Pollution

A multitude of sources contribute to the presence of chemical and microbial contaminants. These sources include municipal pollution, agricultural chemicals, arsenic, fluoride, selenium, uranium, iron, manganese, and selenium. Fig. 1 represents different means through which pollutants enter the environment. Pollutants are chemical contaminants that accumulate to the point where they pose a threat to life or negatively affect the environment. There are currently thousands of industrial chemical products that are potentially hazardous to both humans and the environment [9]. The primary origins of natural pollutants, which are predominantly detected in groundwaters, are chemical disposal sites for buried solid waste, runoff from chemical applications and the disposal of effluent from homes [10]. Microbial infections, which are the leading cause of mortality among children, are predominantly detected in potable water sources located in developing countries. Prominent pathogens that cause harm to the intestines include *Escherichia coli*, *Campylobacter jejuni*, *Vibrio cholerae* O1, and *Shigella* species. Microorganisms are predominantly observed in surface water sources, including reservoirs, lakes, and rivers unless they exhibit direct contamination of groundwater.

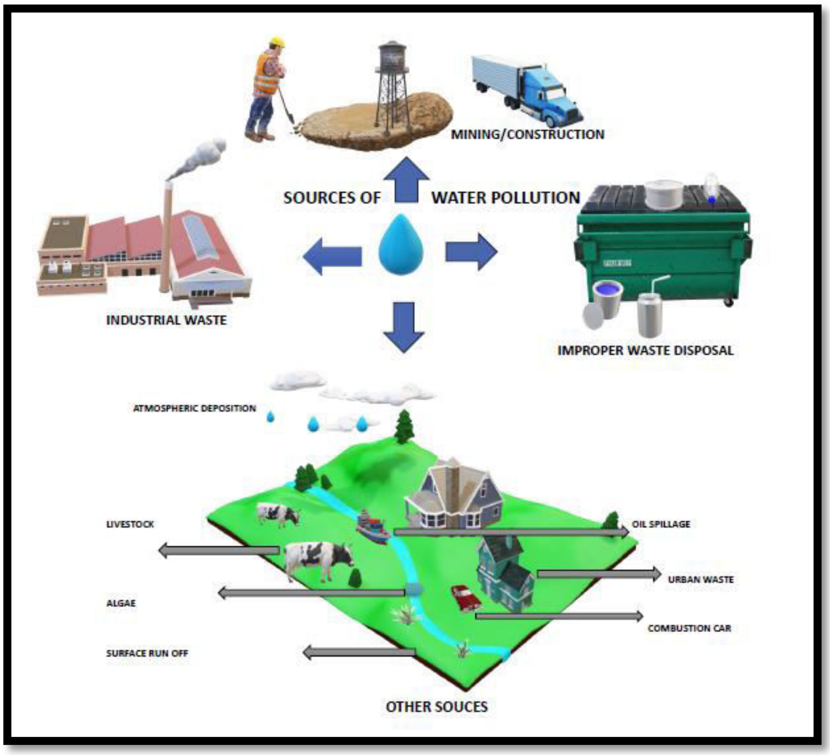

Fig.1: Various sources of water pollution

3. Methodologies for Toxicological Examination

Various ways were given by standard organizations to analyse the quality of the aquatic environment. It can be achieved through a combination of different assessment methods, including visual observations, species inventories, odour analysis, and various measurements such as physico-chemical determinations and biochemical/biological evaluations. To study water pollution using toxicological methods, experts utilize a range of biological, chemical and physical tests to assess the presence and impact of harmful substances. These methods aid in identifying contaminants, measuring their concentrations and comprehending their effects on living organisms and ecosystems. Among the different parameters, the measurements include physical, chemical and biological parameters.

3.1 Physical Parameters

Color: The presence of minerals like iron and manganese or organic substances like algae and weeds can cause discoloration in water. Testing the color of the water helps to assess the effectiveness of the water treatment system.

Temperature: Various paramater of water quality like viscosity, solubility, odour, BOD can be affected by variation in temperature

Turbidity: Turbidity in water occurs due to the presence of suspended solids and colloidal matter, which can result from soil erosion caused by dredging or the proliferation of micro-organisms . High turbidity increases the cost of filtration. If sewage solids are present, pathogens may be enclosed in the particles, making them resistant to chlorine disinfection.

Taste and Odor: It can be linked to the presence of living microscopic organisms, decaying organic matter such as weeds, algae, or industrial wastes containing ammonia, phenols, halogens, and hydrocarbons. This taste can affect fish, making them unappetizing. While chlorination can reduce odor and taste caused by some contaminants, it can produce a foul odor when added to waters contaminated with detergents, algae, and certain other wastes.

Total dissolved solids: The mass of anhydrous remains left in a sample vessel after evaporation and drying in an oven at a specific temperature is referred to as TDS [11]. The presence of inorganic salts and trace amounts of organic matter in water is commonly known as concentration [12]. According to WHO health guidelines [13], it is recommended to maintain TDS levels between 500 mg/L and 1,000 mg/L. The distribution of drinking water may be affected by the presence of total dissolved solids (TDS) or high salinity levels [11].

Electrical conductivity: As its name implies, electrical conductivity (EC) is a measure of a conductor's ability to carry an electric current. The total current-carrying capacity of an electrolyte or aqueous solution depends on the concentration of ions in the solution and the mobility of each ion when subjected to an electrical potential [14]. The recommended EC limit is set at 1,500 μS/cm [13]. Many industries rely on the electrical conductivity of water to assess its quality.

3.2 Chemical Parameters

Hardness: When the water's hardness is increased, it tends to reduce the toxicity of metals. This is likely due to the competition between calcium and the cell's surface. When salt levels increase, changes in chemical speciation and an organism's physiological characteristics can also impact toxicity [15]. Excessive utilisation of calcium and magnesium may lead to an increased risk of coronary artery disease, insulin resistance, colorectal cancer, stroke, hypertension, osteoporosis, and nephrolithiasis.

Alkalinity: This method is employed to measure the levels of carbonate, bicarbonate, and hydroxide ions in water. It is important to ensure that the alkalinity levels in potable water do not exceed 200 mg/l. If the levels go beyond this threshold, it can result in an unpleasant taste [16]. As the acidity increases after neutralisation, the concentration of hydrogen ions steadily rises. It has been shown that achieving a well-defined pH during neutralisation can be done successfully by titrating alkalinity concentrations with the use of methyl orange and mixed indicators. In a study [17], Gran titration is a widely accepted method for measuring alkalinity, while other studies have employed end point titration to pH 4.5 [18].

Free CO_2: The drainage basin's lithography, runoff, temperature swings, vegetation, and terrain all play a role in influencing the rate of weathering from chemicals and the resulting CO_2 consumption [19]. Rivers play a crucial role in determining the amount and direction of gas exchange at the air-water interface.

The partial pressure of aqueous carbon dioxide (pCO_2) is a key factor in this process, indicating whether rivers act as sources or sinks of atmospheric CO_2 [20].

PH: Variances in CO_2 levels resulting from variations in respiration and photosynthesis rates can lead to significant fluctuations in the pH of a water body within a 24-hour time frame.

BOD: Microorganisms, such as bacteria, utilize organic matter as a food source, and as they metabolize this matter, they consume oxygen [21]. In an aquatic environment, the process of organic matter decomposition can significantly deplete the dissolved oxygen in the water. High levels of organic matter in water can lead to the consumption of large amounts of dissolved oxygen, which is essential for the survival of aquatic plants and animals. The level of dissolved oxygen consumed by organic matter decomposition can be measured using the dilution method to determine the biological oxygen demand (BOD). Elevated BOD levels indicate water contamination. BOD is high in water rich in organic material while it is low in water where there is poor organic matter [21].

Dissolved Oxygen: Once dissolved, oxygen becomes a transparent, flavourless, and scentless gas that does not directly impact human health. Therefore, guidelines for drinking water have generally not taken into account restrictions on oxygen content [22]. Assessing water quality in different watersheds and reservoirs often involves using the indices dissolved oxygen (DO) and dissolved oxygen deficiency. Physical, chemical, and biological properties of streams play a crucial role in influencing various factors such as algal biomass, dissolved organic matter, ammonia, volatile suspended solids, and sediment oxygen demand [23]. It plays a crucial role in the balance of aquatic ecosystems, with the concentration of certain solutes such as iron and manganese being affected by the level of oxygen in the surrounding air. Surface water bodies with low dissolved oxygen (DO) concentrations can indicate potential problems with water quality that concern both managers and users [24].

Nitrate: Given its high solubility in soil and its association with development, the presence of nitrate as a groundwater contaminant is a matter of great concern. The primary contributors to nitrate contamination in groundwater are fertiliser and residential on-site sewage disposal [25]. The presence of nitrate in drinking water can be attributed to the use of inorganic fertilisers in agriculture [26]. Surface water generally contains a low level of nitrate concentration (0–18 mg/litre). However, when there is runoff from farms, trash dumps, or animal or human waste, it can lead to elevated nitrate concentrations. Fluctuations in the concentration can lead to an increase in situations where the river is supplied with water from a nitrate-rich aquifer [27]. Due to an excessive supply of nitrate, plants accumulated high levels of nitrate, negatively impacting both plant growth and human health [28].

3.3 Biological Parameters

Assessment of water quality can also be done by indicating the presence or absence of a variety of organisms. A healthy aquatic ecosystem is one where there is availability of large number of aquatic organisms and this can be computed by species diversity index [29]. These organisms are termed biological indicators which can be bacteria, algae, fishes, macroinvertebrates *etc*. Most commonly tested bacteria is *E. coli*, an indicator of faecal contamination. Its high level in water ensures the presence of harmful pathogens which lead to serious human health issues on consumption.

4. Impact of Water Pollution on Environment

4.1 Impact of Pharmaceuticals on Aquatic life

Water pollutants can have a significant impact on the environment affecting aquatic ecosystems, human health and overall biodiversity. Now-a-days the aquatic ecosystem is affected by increase in the concentration of Emerging Contaminants (ECs), which have the potential to infiltrate the ecosystem and impose serious adverse effects on human health and ecology [30]. One of the major example of Emerging pollutants is pharmaceutical contaminant (PC) arising from different pharmaceutical industries. These are the biologically active compounds majorly used in the prevention and treatment of diseases [31]. Pharmaceutical chemicals are among the primary contaminants in aquatic environments and have also been shown to exert adverse effects on non-target organisms. These chemicals are constantly discharged into the environment and their chronic exposure even at less concentrations poses a serious risk to both aquatic ecosystems and human health. Aquatic animals can accumulate pharmaceuticals in their tissues through direct or indirect exposure [32]. Many pharmaceuticals may alter animal behaviour, even as side-effects of treatments like analgesics or hormone therapies [33]. Pharmaceuticals that originate from human activities can enter the aquatic environment through wastewater and contaminate various surface water bodies such as rivers, lakes, wetlands and oceans. These undigested pharmaceuticals and their metabolites are one of the significant classes of potentially hazardous aquatic pollutants which can pose a significant threat to food chains [34]. Notably, the presence of pharmaceuticals has also been reported in both surface and groundwater which comprises the main source of drinking water.

The pollution of aquatic environments has become a global issue, commanding attention from the public and prompting scientists and governments to intensify their efforts to prevent further environmental damage. Water bodies are exposed to various pollutants, including pesticides, heavy metals, polycyclic aromatic hydrocarbons, microplastic particles, and pharmaceuticals, due to human activities. These pollutants pose a threat to the health of plants, animals and humans due to their acute toxicity and potential accumulation risk, which can lead to chronic effects [35]. The chronic toxic effects of pharmaceuticals in non-target animal species can be related to various issues such as locomotive disorders, endocrine disruption, genotoxicity, reproduction disorders, oxidative stress, body deformations, teratogenic effects, and reductions in overall organism condition (vitality).

Emerging contaminants include various categories of compounds such as pharmaceuticals, personal care products, gasoline additives, endocrine disruptors, and illicit drugs [36]. Pharmaceuticals are the potentially hazardous substances that have been detected in the environment and natural streams for a relatively short period. Therefore, it is important to monitor them due to their potentially toxic impacts on non-target organisms [34]. However, monitoring of these contaminants can be complicated due to their various active chemical structures, the diversified influences they have on living organisms and the lack of environmental toxicity data [37].

Pollutants such as heavy metals, fertilizers, and organic compounds have a harmful impact on aquatic ecosystems. They can adversely affect fish, amphibians and other aquatic organisms, interfering with their growth, behaviour and reproduction, ultimately leading to a decline in their population sizes and loss of biodiversity.

Role of Pesticides

Any substance or mixture thereof, proposed for the prevention, elimination, mitigation, or weakening of any pest or weed, is classified as a pesticide. Pests encompass undesirable plants, destructive insects, nematodes, mammals, birds, fish, and microorganisms. These pests pose a competitive threat to human food resources, inflict harm upon resources, propagate diseases, or cause irritation. Insecticides, herbicides, fungicides, and rodenticides are commonly employed as pesticides. The utilization of pesticides constitutes a significant contribution to the degradation of water quality. Now-a-days the increased use of pesticides has raised concerns regarding their harmful effects on other organisms including humans [38]. As a result, this contamination has been linked to issues such as fish mortality, aquatic animal health problems and reproductive failure in birds.

4.2 Impact of Metals on Aquatic Environment and Fishes

From the few past decades, water is at threat of being polluted due to increasing human activities. Heavy metal elements that are present in the surrounding environment can enter into the water bodies and leads to severe toxic effects. One of major effect was observed in fish larvae. Metals have the potential to inhibit the fish larvae growth. Due to deposition of heavy metals into the water bodies, aquatic biota become toxic. In freshwater ecosystems, heavy metals can disrupt chemical communication, leading to behavioural and social changes in animal populations [39]. Heavy metals at a very less concentration can also induce chronic stress in fishes causing them to lose body weight and decreased ability to compete for resources [40]. Heavy metals have the ability to interfere the reproductive success, development process and survival of the fishes. Mercury (Hg) accumulation induces neurotoxicity [41]. Cd elevates blood pressure and causes cardiac malfunctioning. Increased metal accumulation in the fish body also leads to loss in fin structure, underdeveloped gills and non-functioning of liver and fins in fingerlings [42]. A number of studies observed serious impacts on the fish body including severe anemia and changes in hematological parameters, behavioural changes, cytoxicity [43], internal bleeding [44] and reduction in fish fertility and embryonic development [45]. Highly toxic metals like chromium, mercury, lead, cadmium and arsenic affect the distribution and population of benthic communities which are bioindicators of environmental stress [46].

4.3 Impact of Metals on Human Health

The presence of heavy metals in the environment has been linked to neuro-developmental issues, reproductive damage and behavioral disorders in children. Continuous exposure during perinatal and early childhood stages has also been associated with an increased risk of autism [47]. Additionally, heavy metals and persistent organic chemicals may affect the neurobiological processes and ultimately lead to the development of depressive symptoms [48]. Due to exposure to heavy metals and other inorganic contaminants in water conceiving females can also struggle with early-pregnancy miscarriage, accidental abortion, genetic defects, congenital malformations, intrauterine growth issues, and premature delivery [49]. Heavy metal pollution, primarily from industrialization and urbanization, significantly deteriorates water quality, rendering it unsuitable for human consumption and agricultural use. When water containing heavy metals is used for agricultural purposes, the metals can accumulate in crops, leading to crop contamination or enter the food chain through bio-magnification.

4.4 Impact of Metals on Terrestrial Animals

The accumulation of heavy metals in insects could alter their morphology and physiology, directly impacting food security, agricultural economy, and human welfare [50]. In terrestrial ecosystems, insects play vital ecological roles in maintaining ecosystem services such as food provisioning, pollination, dung burial, pest control and nutrition. Therefore, the eco-toxicological effects of heavy metals on useful insects, such as bees, butterflies, ants, and wasps, can have far-reaching consequences. The highly toxic impacts of heavy metals on diverse insect species are frequently documented, manifesting as growth inhibition, developmental irregularities, diminished reproductive capabilities, and reduced hatchability.

4.5 Impact of Metals on Plants

Heavy metals such as chromium, mercury, lead, cadmium, and arsenic are highly toxic as they have detrimental effects on plants by inducing physiological stress. This stress can lead to symptoms such as chlorosis, inhibited growth, reduced biomass production and generation of free radicals that damage ultimately affects plant structures [51]. Heavy metals accumulation also affects soil and crops. The risk of food security increases by accumulating heavy metals into crops (wheat, rice, maize), as they also affect rice production [52].

5. Mitigation Strategies and Policy Implications

Water pollution mitigation involves a wide range of strategies and interventions to protect and restore the quality of freshwater resources. First and foremost, regulatory frameworks are essential for effective pollution control. They establish the necessary legal and institutional structure to enforce pollution standards and monitor compliance. Dietz et al. [53] conducted research that emphasizes the importance of robust regulatory mechanisms in effectively managing water quality. Furthermore, wastewater treatment plays a vital role in addressing pollution caused by industrial, municipal, and agricultural activities. Various treatment technologies are used to eliminate pollutants from wastewater streams, including biological, chemical, and physical processes. These methods effectively target organic matter, nutrients, and pathogens. Saravanan et al. [54] conducted a study that highlights the effectiveness of wastewater treatment systems in mitigating pollution levels released into water bodies. In addition, the implementation of best management practices (BMPs) in agriculture is crucial for reducing nutrient runoff, sedimentation, and pesticide contamination in waterways. Practices such as conservation tillage, cover cropping, and nutrient management planning are important in improving soil health and minimizing the impact of agriculture on water quality. Scientific evidence, such as studies conducted by [55], provides support for the effectiveness of BMPs in reducing agricultural pollution. In addition, it is important to note that stormwater management strategies are essential in preventing urban runoff from polluting surface waters. Guo et al. [56] conducted research that emphasizes the importance of implementing pollution prevention strategies to effectively mitigate industrial pollution. Policy recommendations based on scientific findings provide essential guidance for enhancing water quality and promoting ecosystem health. First and foremost, it is crucial to establish and enforce rigorous water quality standards. These standards are based on extensive scientific research on pollutant thresholds and ecological impacts. They offer a well-defined framework for regulating pollutant discharges and safeguarding aquatic ecosystems. Research conducted by Hering et al. [57] highlights the significance of using evidence-based standards to preserve the health of waterways.

Ultimately, a thorough examination of strategies to manage and reduce water pollution emphasizes the significance of adopting holistic and coordinated approaches that encompass regulatory measures, wastewater treatment, agricultural practices, stormwater management, and pollution prevention in industries. Stakeholders can strive to safeguard and rehabilitate the integrity of freshwater ecosystems for both current and future generations by implementing a variety of strategies. Water quality management is an essential component of environmental governance on a global scale, influenced by various regulatory frameworks that shape policies and practices. In this section, we will explore the evolution, effectiveness, and challenges of regulatory approaches to water quality management. We will consider both global perspectives and the specific context of India.

Changing scientific knowledge and socio-political factors have influenced the historical development of water quality regulations globally [58]. In India, there have been important regulatory milestones in the evolution of initiatives like the Water (Prevention and Control of Pollution) Act, 1974 [59]. International agreements, such as the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention), provide a framework for promoting transboundary cooperation [60]. In India, the Water Act, along with subsequent amendments, serves as the foundation of national legislation for water quality management (Government of India, 1974). Regulatory agencies play a crucial role in upholding water quality standards and closely monitoring compliance. The Central Pollution Control Board (CPCB), similar to the United States Environmental Protection Agency (EPA) and other global agencies, oversees regulatory enforcement in India [61]. Establishing water quality standards and implementing efficient monitoring systems are crucial elements of regulatory frameworks. International bodies like the European Commission have established standards, and India's Bureau of Indian Standards (BIS) has specifically designed standards for local conditions. Effective stakeholder engagement is essential for achieving success in water quality management. The National Water Mission in India highlights the importance of involving the public, aligning with the worldwide movement towards participatory governance. After analysing regulatory frameworks from a global and Indian perspective, it becomes evident that water quality management is a complex and diverse issue. Regardless of the specific circumstances, it is clear that there are shared challenges and opportunities that underscore the need for collaboration, innovation, and adaptive governance in protecting water resources for future generations.

6. Future Directions and Research Needs

Future advancements will probably centre around the creation of sophisticated sensor technologies capable of continuously monitoring and identifying various pollutants in real-time. The deployment of these sensors in different water systems allows for the collection of continuous data streams, enabling the early detection of pollution events and facilitating prompt response. The utilization of artificial intelligence (AI) and machine learning algorithms has the potential to greatly improve water quality monitoring and management. By analyzing large volumes of data, these technologies can effectively identify patterns, trends, and anomalies. The incorporation of artificial intelligence into monitoring systems has the potential to facilitate predictive modeling, enhance resource allocation, and optimize decision-making processes. Remote sensing and satellite technology provide potential methods for monitoring water quality across extensive geographical regions. Potential advancements could entail the creation of satellite-based sensors that have the ability to identify and measure various water quality factors, including turbidity, chlorophyll levels, and harmful algal blooms, with exceptional accuracy and frequency. Autonomous monitoring platforms, such as unmanned aerial vehicles (UAVs) and underwater drones, offer flexible and cost-effective options for gathering water quality data in remote or dangerous settings. Various sensors and cameras can equip these platforms to effectively monitor water bodies. Devices within the Internet of Things (IoT) and wireless sensor networks present promising prospects for the development of interconnected systems that enable real-time monitoring and management of water quality. These networks facilitate the transmission of data, enable remote control capabilities, and allow for automated responses to fluctuations in water conditions.

The use of block chain technology has the potential to improve the integrity and transparency of water quality data by implementing a decentralized and tamper-proof system for recording and disseminating information. Potential advancements may entail incorporating block chain technology into water quality monitoring systems in order to ensure data authenticity and traceability. Encouraging individuals to participate in water quality monitoring through citizen science initiatives and crowd sourcing platforms has the potential to greatly enhance monitoring efforts and promote community engagement. Potential advancements could entail the creation of easy-to-use mobile applications and the production of affordable sensor kits, allowing individuals to actively participate in monitoring initiatives. Potential advancements in water quality management could include the adoption of ecosystem-based methodologies that prioritize the restoration and enhancement of natural ecosystems as a means to improve water quality. We can employ various methodologies, such as wetland restoration, green infrastructure development, and sustainable land management practices, to mitigate pollution and enhance water filtration. Ultimately, upcoming advancements in water quality monitoring and management will center on the creation and incorporation of cutting-edge technologies, data-focused strategies, and cooperative endeavors aimed at improving the efficiency, efficacy, and sustainability of water resource management practices.

Conclusion

The ecotoxicological parameters of water analysis are essential for protecting aquatic ecosystems. By assessing chemical, physical, and biological indicators, these parameters provide a complete understanding of water quality and the potential impacts of pollutants on various organisms. Pollution has a profound effect on aquatic life, disrupting physiological functions, reproductive cycles, and biodiversity, thereby altering ecosystem dynamics. Heavy metals, pesticides, and organic contaminants pose significant threats, leading to bioaccumulation, toxicity, and long-term ecological imbalances. The insights gained from water analysis are crucial for identifying pollution sources, evaluating contamination levels, and devising effective mitigation strategies. This forms the basis for regulatory frameworks and conservation efforts aimed at protecting water resources. To ensure the sustainability of aquatic environments, stringent pollution control measures, sustainable practices and public awareness campaigns are essential. Continuous monitoring and research are critical for addressing emerging pollutants and adapting to evolving environmental challenges, ultimately securing the health and vitality of aquatic ecosystems for future generations.

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