Assessing Global Water Quality: A Review of Monitoring Techniques and Emerging Contaminants

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Dr. Ashay Devidas Shende[1]

[1]*Assistant Professor, Department of Civil Engineering, K.D.K College of Engineering, Nagpur, Maharashtra*

Abstract

A diverse array of unregulated pollutants that are becoming more prevalent in the environment are known as emerging contaminants (ECs). In the present day, water contamination has emerged as a global concern that impacts the majority of countries worldwide. Monitoring water quality can let authorities take prompt action by warning them of water contamination. The many studies on water quality monitoring methods and new water pollutants are reviewed in this article. It concluded that the global presence of emerging contaminants in water highlights the urgent need for advanced monitoring techniques. IoT-based systems, combined with CPS technologies, offer real-time, efficient, and cost-effective solutions for detecting and managing water quality. While traditional methods provide essential physicochemical data, integrating modern approaches enables early detection, remote access, and deeper insights into pollutant sources. These innovations are crucial for sustainable water resource management and environmental protection worldwide.

Keywords; Emerging contaminants (ECs), Pollutants, Global Water Quality, Monitoring Techniques, IoT-based systems, etc.

INTRODUCTION

At the regional and global levels, freshwater supplies are essential for maintaining ecosystems, promoting human activity, and propelling economic growth. Diverse animal and plant species inhabit freshwater ecosystems. Each of these ecosystems—which include lakes, rivers, streams, and wetlands—has its own distinct wildlife and plants [1]. The preservation of biodiversity is greatly aided by freshwater bodies, which provide appropriate habitats. Additionally, by "filtering and recycling organic waste", freshwater ecosystems aid in the cycling of nutrients, which is essential for maintaining life in aquatic environments [2]. Industries that depend on freshwater resources produce export income for several nations. Export revenue is mostly derived from agricultural goods like crops and animals. Furthermore, industries like as mining, forestry, horticulture, viticulture (grape farming), and fishing rely on freshwater inputs and generate export income from the selling of their goods abroad. Additionally, freshwater bodies boost general economic development by sustaining secondary industries like tourism, leisure, and power production [3].

Even though freshwater resources are important, human activity, population increase, climate change, and other anthropogenic stresses are causing them to face increasing water quality problems [4]. For instance, the use of fertilisers to increase agricultural productivity is negatively affecting water quality, which has an adverse effect on aquatic and marine ecosystems. Similar to this, growing industrial water use is causing worries about maintaining water quality and lowering water-related health problems, especially in developing countries with lax rules for industrial wastewater treatment and water reclamation [5]. To overcome these obstacles, comprehensive water management plans must be put into place, sustainable practices must be adopted, and coordinated efforts must be made to lessen and adjust to environmental effects.

When it comes to protecting freshwater resources, ecosystems, and human communities, water systems must be robust and healthy. Effective management and protection are essential to ensuring the long-term survival of freshwater ecosystems and fostering prosperity for future generations [6], [7].

Although they are existing in the environment, “emerging contaminants (ECs)” are a class of pollutants that are not yet extensively controlled or monitored. Chemicals used in industry, personal care items, medicines, and nanomaterials are all included in this category [8]. Usually, these are substances whose effects have just recently been acknowledged or that have only recently been found in the environment. The lack of extensive regulatory frameworks is mostly due to inadequate evidence addressing the health and environmental effects of these pollutants [9]. The fact that many of these contaminants persist in environmental environments and "bioaccumulate in the food chain" is significant since it may eventually jeopardise ecological systems and human health. Leaching, air deposition, and wastewater discharge are some of the ways that these pollutants may reach the environment. Their origins range from industrial emissions and home trash to agricultural runoff [10].

Emerging contaminant in water

It is possible for groundwater to include a variety of substances, both naturally occurring and man-made, some of which may be hazardous to human health or the environment. Certain factors have restrictions established by regulations. An unregulated material that may pose a risk to human health or the environment is referred to as an "emerging contaminant." "Substances of emerging concern" is one synonym. These substances may often evade water treatment even though they are usually found in trace amounts [11].

The following categories of newly discovered pollutants have been discovered in groundwater globally:

- “caffeine and nicotine and their metabolites
- flame/fire retardants and surfactants
- industrial additives and byproducts
- nanomaterials (very small particles)
- personal care products and fragrances
- pesticides and their metabolites or breakdown products
- pharmaceuticals and hormones, including veterinary medicines
- water treatment byproducts”

Water quality monitoring

A body of water's many features are regularly assessed and tested as part of the water quality monitoring process. The water's physical attributes, chemical makeup, and biological makeup are some of these features. Monitoring water quality attempts to guarantee that bodies of water fulfil certain criteria and demands in order to satisfy ecological and human demands. Water quality is often evaluated by field testing or laboratory analysis once water samples are collected. Monitoring water quality is crucial for preserving the environment, supporting ecosystem balance, ensuring safe drinking water, and advancing sustainable development [12].

Importance of Water Monitoring Quality

Future and present water quality management choices may benefit from the objective data supplied by monitoring. The purpose of water quality monitoring is to safeguard other water-related activities, detect new, persistent, or developing issues, and determine the extent to which drinking water requirements are being met [13].

In order to better safeguard the health of people and the environment, lawmakers and water managers use evaluations according to monitoring data to assess the effectiveness of water laws, determine if water quality is rising or declining, and create new rules. Since climate trends are altering and will continue to change, it is crucial because rising water temperatures will lead to "eutrophication and excessive algal growth", which will lower the quality of drinking water [14].

Several Different Methods of Water Monitoring

1. CDOM/FDOM Monitoring

Watercourses inherently contain chromophoric or coloured dissolved organic materials (CDOM). After absorbing UV light, this organic molecule decomposes and releases tannin, an organic pollutant that causes murky water. Additionally, tannin depletes oxygen and lowers "the pH (acidity) of water".

2. Chlorophyll Fluorescence Analysis

Wet-chemical chlorophyll and active chlorophyll ratios in water samples are measured using algae toximeters. This is a useful technique to monitor water quality and spot excessive algal growth.

3. Conductivity, Salinity, and TDS Monitoring

The quality of a lake or river may be accurately determined by measuring its conductivity. Water's oxygen content is influenced by its conductivity, which in turn affects its "salinity and total dissolved solids (TDS) concentration".

4. pH and KH Monitoring

Colour-coded water test kits, which provide a variety of pH values, may be used to determine pH. These are the best kits for determining the water's pH range. Conversely, automated pH sensors provide data measured to the nearest two digits, allowing for very accurate pH readings. The amount of carbonate and bicarbonate in the water is measured by "KH, or carbonate hardness", which also has a major effect on the pH of the water.

LITERATURE REVIEW

(Essamlali et al., 2024) [15] With a particular emphasis on the utilisation of IoT wireless technologies and ML techniques, the aim of this paper is to offer a thorough examination of the present state of the art in water quality monitoring. The research investigates the usage of several “Internet of Things” wireless technologies, such as "Bluetooth, cellular networks, Wi-Fi, Zigbee, Radio Frequency Identification (RFID), and Low-Power Wide Area Networks (LpWAN)", in the context of water quality monitoring. Additionally, the manuscript investigates the utilisation of unsupervised as well as supervised machine learning algorithms to analyse and interpret the data that has been gathered. This review discusses the present state of the art and discusses the difficulties and unanswered problems associated with combining machine learning (ML) with IoT wireless technologies for "water quality monitoring (WQM)".

(Forhad et al., 2024) [16] This investigation discusses the development and execution of a "real-time water quality monitoring system" that is specifically designed for water treatment plants (WTPs) and is based on the Internet of Things (IoT). The system incorporates state-of-the-art sensor technology to continuously monitor "temperature, total dissolved solids (TDS)", dissolved oxygen (DO), and pH, among other important water quality factors. The study emphasises how the system's real-time warnings, historical data recording, and remote monitoring capabilities support proactive maintenance, improved operational efficiency, and well-informed decision-making. This creative method of managing water quality not only increases WTP operations' efficacy but also guarantees public health and environmental sustainability. The research emphasises how IoT technologies have the potential to completely transform methods for monitoring water quality.

(Li et al., 2024) [10] The sources, varieties, and chemical characteristics of ECs are the focus of this comprehensive review. As well as identifying deficiencies and suggesting potential improvements, the review evaluates the current regulations and policies. The review makes suggestions for future research to address these important challenges, highlighting areas that need further study to fully understand the effects of these toxins. Additionally, it suggests the following: the creation of standardised procedures, "the adoption of precautionary rules", the development of sophisticated detecting technologies, the inclusion of scientific research in policy-making, and more financing and support for research. Enhanced public awareness and education are also recommended. By putting these ideas into practice, we can decrease the hazards to the environment and public health by strengthening our capacity to identify, track, and manage ECs.

(Kumar et al., 2022) [17] "Pesticides, plasticisers, surfactants, fire retardants, nanomaterials, and pharmaceuticals and personal care products (PPCPs)" are some of the most well-known categories of ECs. The detrimental effects of certain ECs on endocrine systems have led to their classification as endocrine disrupting chemicals (EDCs). To lessen the negative effects of ECs, a number of methods have been investigated for their degradation and elimination. MBR and treatment methods like "reverse osmosis, ultrafiltration, or nanofiltration" may efficiently eradicate it by up to 99% at concentrations as low as 5 g/liter. Membrane technology is capable of eliminating colloidal particles and particles as tiny as 10 µm. The information presented in this paper provides an overview of emerging contaminants, their origins, and their removal through the implementation of a variety of treatments that are based on recent research.

(Morin-Crini et al., 2022) [18] "Industrial formulations and chemicals, pesticides, medicines, medications, cosmetics, personal care products, surfactants, cleaning products, food additives, food packaging, metalloids, rare earth elements, nanomaterials, microplastics, and pathogens" are just a few of the many new pollutants. In this section, we examine the most significant instances of contamination in Brazil, Colombia, Mexico, Portugal, and China. For instance, China's lake and ocean ecosystems contain persistent organic pollutants like "polychlorinated biphenyls, dibenzofurans, and polybrominated diphenyl ethers"; Portuguese rivers contain alkylphenols, natural and synthetic oestrogens, antibiotics, and antidepressants; and Mexican, Brazilian, and Colombian waters contain pharmaceuticals, hormones, cosmetics, personal care items, and pesticides. These contaminants have an impact on all continents. Therefore, to reduce environmental contamination, wastewater treatment facilities should be updated, for example, by adding tertiary treatment systems.

(Zainurin et al., 2022) [19] To determine the techniques' advantages and disadvantages, the review aims to examine a variety of traditional and contemporary approaches to water quality monitoring. Among the strategies are optical technologies, cyber-physical systems (CPS), virtual sensing, and "the Internet of Things (IoT)". In comparison to conventional methods, modern methods are evaluated in terms of reliability, complexity, and parameters. We found that CPS's combination of physical and computational methods makes it effective for monitoring water quality. It is possible to program its processors, actuators, and built-in sensors to detect and react to their environment. In addition, prior monitoring techniques had trouble measuring water quality indicators accurately in real time. Relatively few tools are available for detecting pollutants and producing insightful data on water quality. The study is therefore essential for the comparison of previous methods and the improvement of the accuracy and efficiency of modern water quality evaluations.

(Zolkefli et al., 2020) [20] In recent years, academics have been working to improve water pollution monitoring technologies, and this study aimed to clarify the general elements of their work. These major actors examined and grouped the most recent technologies used in wastewater and surface water mapping into three categories: molecular techniques in taxonomical and functional studies, biomonitoring, and physicochemical and compound characterisations. Overall, scientists are always working to improve the identification of the root cause of water pollution utilising either traditional or mostly cutting-edge methods that centre on technologies like flow cytometry, high-throughput sequencing, and spectrometry, among others. According to this research, every pollution evaluation technique has unique benefits, and it would be advantageous to integrate several elements of pollution assessments into a complimentary package for improved aquatic environmental management throughout time.

(Zulkifl et al., 2020) [21]Water treatment plants and water distribution systems are only two examples of the many water ecological applications that utilise water monitoring technology to identify pollutants. Water monitoring has become more advanced with the use of in-situ measurements and multiple detection analyses. One such technique is the successful development of handheld sensing devices, which increase portability in real-time and can detect contaminants such as "pesticides, microorganisms, heavy metal ions, and inorganic and organic components". This study is to investigate the developments in chemical and biological pollution detection systems for water quality in accordance with instrumental constraints. The primary objective of this investigation is to examine the most recent methodologies for conducting water contamination detection applications. In addition, some suggestions and viewpoints about the future of water quality assessments will be discussed.

(Ahmed et al., 2020) [22] The rapid deterioration of water quality and contamination as a result of industrial development and urbanisation has made its rapid, cost-effective, and precise detection imperative. Such as the manual analysis procedure conducted in a laboratory, conventional methods for measuring water quality are inefficient, costly, and protracted. This study examines the issue from a number of angles, including the conventional approaches to water quality assessment to obtain a better understanding of the issue and the examination of cutting-edge technologies, such as "the Internet of Things (IoT) and machine learning methods", to address water quality. This study examines existing solutions and suggests a low-cost, Internet of Things-based system that uses machine learning methods to track "water quality in real time", examine patterns in water quality, and identify unusual occurrences like deliberate water pollution.

CONCLUSION

To sum up, there is an immediate need for better water quality monitoring systems due to the widespread presence of hormones, pesticides, antibiotic-resistant bacteria, cosmetics, and medications in the world's waterbodies. Traditional wastewater treatments often fail to remove these emerging contaminants effectively, primarily due to their complexity and persistence. Modern monitoring methods—ranging from IoT-based systems and cyber-physical systems (CPS) to optical and virtual sensing techniques—offer a transformative shift in water quality assessment. The integration of IoT and CPS allows for real-time, remote, and continuous data collection, enabling timely interventions and enhancing the reliability of water quality management. These systems bridge the physical and digital worlds, making monitoring smarter and more efficient. While conventional methods focus on physicochemical parameters like pH, turbidity, and suspended solids, innovative approaches now incorporate bioindicator tracking and smart sensor networks to improve specificity and early detection.

Overall, the review underscores the necessity of adopting advanced, interconnected technologies to combat water pollution and protect environmental and public health globally.

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