IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Instrumentation Mesure Métrologie
Vol. 23, No. 4, August, 2024, pp. 253-263
Journal homepage: http://iieta.org/journals/i2m

Selecting IoT-Enabled Water Quality Index Parameters for Smart Environmental Management

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https://doi.org/10.18280/i2m.230401

Received: 25 June 2024
Revised: 1 August 2024
Accepted: 12 August 2024
Available online: 23 August 2024

Keywords:
water quality, Water Quality Index, Internet of Things, physico-chemical sensors, real-time monitoring

ABSTRACT

The monitoring of water quality is crucial for safeguarding ecosystem health and ensuring the safety of water resources. The Water Quality Index (WQI) has been developed as a tool to condense complex water quality data into a single, easily interpretable value. Standard WQI calculations typically incorporate parameters such as pH, temperature, dissolved oxygen (DO), turbidity, and total dissolved solids (TDS). This study provides a comprehensive review of existing literature, focusing on the application of physico-chemical and biological sensors in water quality monitoring. The findings indicate that biological sensors, particularly those used for detecting contaminants such as Escherichia coli (E. coli), are often unsuitable for real-time monitoring due to inherent technical limitations. In contrast, the integration of Internet of Things (IoT) technologies significantly enhances the capability for real-time monitoring, enabling the prompt detection of variations in water quality. The study suggests that future research should prioritize the development of a WQI that incorporates the selected parameters identified in this research, ensuring that IoT-based water quality monitoring systems operate with greater efficiency and reliability. Such advancements are essential for supporting the sustainable management of water resources and enhancing environmental protection efforts.

1. INTRODUCTION

Monitoring water quality is essential as water is a vital resource for human life, ecosystems, and the economy [1]. Poor water quality can lead to various health issues, threaten the sustainability of aquatic ecosystems, and negatively impact the agricultural and industrial sectors [2]. Regular monitoring allows for the early detection of pollution and changes in water quality, enabling prompt preventive and corrective actions [3]. Modern technology, such as IoT, facilitates more efficient and real-time monitoring, providing accurate data that can be used for better environmental management, ensuring the sustainability of water resources and the protection of public health [4].

The IoT technology plays a crucial role in environmental management by providing efficient and accurate real-time monitoring solutions [5]. IoT sensors distributed across various environmental points are capable of continuously collecting data on air, water, and soil quality, as well as other environmental parameters [6]. This data is transmitted directly to analytical platforms, enabling early detection of issues such as pollution, climate change, or ecosystem damage [7]. With IoT, natural resource management becomes more responsive and proactive, allowing for better data-driven decision-making to maintain ecosystem balance and support conservation and sustainability efforts [8].

The main challenge in IoT-based water quality management is the absence of a WQI specifically designed to optimally utilize IoT data. Existing indices often fail to leverage the real-time monitoring and data analytics capabilities offered by IoT [9]. The first step in creating a WQI is to determine relevant and significant parameters. These parameters must cover key aspects of water quality, such as pH, temperature, DO, conductivity, and turbidity, and be tailored to the specific needs of the IoT system [10]. Selecting the appropriate parameters is crucial to ensure that the developed index can provide an accurate real-time picture of water quality conditions [11], enabling rapid response to changes or pollution, and supporting more efficient and effective environmental management [12].

The primary objective of this study is parameter selection, which is the initial step in developing the WQI integrated with IoT technology as the initial filtering mechanism in water quality management. This implementation focuses on rapidly assessing water quality to quickly identify anomalies. By leveraging IoT technology, the system aims to provide real-time monitoring and immediate evaluation of water conditions. If anomalies are detected, the water samples can then be directed to laboratory testing for further analysis. This approach enhances the efficiency and responsiveness of water quality management, ensuring timely detection and intervention.

2. LITERATURE REVIEW

2.1 WQI

The WQI is a tool used to convert raw water quality data into a single value that can reflect the status of water quality [13]. The WQI helps simplify the interpretation of complex water quality data and provides guidance on the levels of pollution or purity of the water [14]. Table 1 presents various water quality indices used by different countries and organizations. Each index uses a set of parameters to assess water quality.

In the late 20th century, many organizations began using WQI to assess water quality [15]. In the 1960s, WQI was first introduced to evaluate river water quality [16]. Horton [17] developed a rating system, using ten variables such as sewage treatment, DO, pH, coliforms, electrical conductivity (EC), carbon chloroform extract (CCE), alkalinity, chloride, temperature, and visible pollution, assigning scale values and weighting factors for each variable [17, 18].

Later, Brown et al. [19] introduced a new WQI with nine variables using an arithmetic mean. The Scottish Research Development Department (SRDD) developed the SRDD-WQI based on Brown's model to assess river water quality [20]. The Bascaron Index (1979) [21], House Index (1986) [22], and Dalmatian Index [23] are derivatives of the SRDD-WQI.

Table 1. Water Quality Index

No.	NSF WQI [35]	INA WQI [36]	CCME [37]	NWQS Malaysia [30]	WQI Vietnam [38]	DOE WQI [39]	CWQI [40]	UWQI [41]	RWQI [42]	NZQWI [43]
1	pH	pH	pH	pH	pH	pH	pH		pH	pH
2	Temperature									
3	DO	DO		DO	DO	DO				
4	Turbidity				Turbidity			Turbidity	Turbidity	
5	TDS	TDS	TDS				TDS			
6							EC	EC		
7										
8	TSS	TSS		TSS	TSS	TSS				
9	BOD	BOD		BOD	BOD	BOD				BOD
10					Ammonia			Ammonia		
11	Nitrate	Nitrate	Nitrate				Nitrate	Nitrate	Nitrate	
12										
13	Total phosphorus	Total phosphorus	Phospate		Phosphate				Phosphate	phosphorus
14	Fecal coliform	Fecal coliform			Fecal Coliform				Fecal coliform	
15		COD		COD	COD	COD			COD	
16										
17									Detergent	
18										
19										
20									Total Coliform	
21							Hardness	Hardness		
22										
23										
24			Sulphate				Sulphate	Sulphate		
25										
26								Fluorides		
27			Chlorides				Chlorides	Chlorides		
28										
29										
30			Calcium				Calcium	Clacium		
31			Iron							
32				Amonical Nitrogen		Amonical Nitrogen				Nitrogen
33							Magnesium	Magnesium		
34							Sodium			
35								Chlorophyll a		
36								Pondus		
37								Hydrogenium		
38									Esherihia Coli	Esherihia Coli
39										Munsell Colour
40										Visibillity
41									Enterococci	
Sum	10	9	8	6	9	6	10	13	10	7

In 1973, they recommended geometric aggregation as a better method, supported by the National Sanitation Foundation (NSF) [24]. Steinhart et al. [25] created an environmental quality index (EQI) for the Great Lakes using nine variables covering biological, physical, chemical, and toxic aspects. Dinius [26] introduced WQI with multiplicative aggregation. In the mid-90s, British Columbia introduced a WQI, later adopted by the Canadian Council of Ministers of the Environment (CCME) in 2001 [27]. In 1996, the Watershed Enhancement Program (WEPWQI) in Dayton, Ohio, added variables related to pesticides and polycyclic aromatic hydrocarbons (PAHs) [28].

Liou et al. [29] developed a WQI in Taiwan with 13 variables, reduced to nine based on environmental and health significance. Said et al. [28] used logarithmic aggregation for five variables in Florida, USA. The Malaysian WQI (MWQI) in 2007 included six variables with weights determined by an expert panel [30]. The Iraqian WQI (IWQI), developed in 2011, addresses Iraq's water challenges using various physico-chemical parameters [31]. The West Java WQI (WJWQI) from 2017 refines 13 water variables to nine for better accuracy in Indonesia [11, 32]. The 2019 Godavari River WQI (WAWQI) in India rapidly assesses water health using pH, DO, and more [33]. The African WQI (AWQI) of 2021 addresses diverse African water issues [34].

2.2 Water parameter classification

Surface water quality is assessed using 69 parameters classified into three categories: biological, physical, and chemical, as shown in Table 2 [44]. The biological category includes six parameters, such as Salmonella spp. and total coliform. The physical category consists of ten parameters, including temperature, pH, and turbidity. The chemical category encompasses 53 parameters such as TDS, COD, BOD, and various ions and heavy metals. Measuring these parameters allows for a comprehensive assessment of water quality. Physical and chemical parameters enable the rapid detection of changes in water quality [45], while biological parameters provide a deeper analysis of ecological conditions [46, 47]. This understanding is crucial for effective water management and responsiveness to pollution [44].

Table 2. Parameter classification

Category	Parameters	Total parameters
Biological	Salmonella spp., total coliform, fecal coliform, pseudomonas, algae, bacteria indicator	6
Physical	Temperature, pH, total solids, pressure, turbidity, odor and grease, EC	10
Chemical	TDS, oxidation-reduction potential (ORP), DO, ammonia (NH_3), dissolved organic matter, sulphide (S^{2-}), colored, chemical oxygen demand (COD), biochemical oxygen demand (BOD), chloride (Cl^-), nitrate (NO_3^-), salinity, tryptophan ($C_{11}H_{12}N_2O_2$), bicarbonate ($NaHCO_3$), alkalinity (HCO_3^-), total hardness as $CaCO_3$, arsenic (As), zinc (Zn), phosphate (PO_4^{3-}), chlorine (Cl), fluoride (F^-), aluminum (Al), chromium (Cr), copper (Cu), iron (Fe), nitrogen (N) total, potassium (K), organic matter by $KMnO_4$, barium (Ba), carbonate (HCO_3^-), chromium hexavalent (Cr(VI)), hydrocarbons (C_nH_{2n+2}), sulfate (SO_4^{2-}), hydrogen sulfide as H_2S, dissolved organic carbon (DOC), beryllium (Be), silver (Ag), boron (B), tin (Sn), manganese (Mn), nickel (Ni), selenium (Se), lead (Pb), carbon tetrachloride (CCl_4), 1,2-dichloroethylene ($C_2H_2Cl_2$),1,1-dichloroethylene ($C_2H_2Cl_2$).	53
	Sum	69

Table 3. Implementation of IoT in environmental monitoring

Researchers	Application	Results
Kumar et al. [51]	Water quality monitoring in the Ganga and Sangam Rivers	Early detection of pollution and improvement in water quality. The water quality of both rivers was found suitable for irrigation and fisheries but not for drinking, considering the average oxygen levels.
Shihab [52]	Air quality monitoring in Mosul City	Reduction in air pollution and protection of public health. The first model uses the highest sub-index according to USEPA pollutant standards. The second model includes the weights of all pollutants as an aggregate air quality index (AAQI), which is considered more comprehensive and applicable in environmental management.
Kusuma et al. [53]	Marine environment monitoring	The study demonstrated the feasibility of using IoT-based water level monitoring devices to accurately measure water levels and transmit data in real-time, providing valuable information for the improvement and further development of water level monitoring systems.
Anchal and Mittal [54]	Parking availability monitoring in urban areas	Predictor parameters were optimized using Bootstrap and bagging algorithms. The proposed method was tested on an IoT dataset containing several sensor recordings.
Potgantwar [55]	Soil moisture and temperature monitoring in agricultural land	The proposed method uses various sensors to detect different aspects of soil, such as temperature, humidity, and soil moisture, and automates irrigation by turning motors on and off based on soil moisture values.
Nandhakumar et al. [56]	Industrial waste monitoring in industrial zones	An approach to building cost-effective and standardized pollution monitoring devices using wireless (IoT) technology and cloud computing technology.
Ananthi et al. [57]	Forest fire monitoring in vulnerable areas	The proposed logic helps identify fire signals and notifies relevant parties to take appropriate actions to prevent forest fires.
Pérez-Padillo et al. [58]	Water pressure monitoring in water distribution systems	The pressure monitoring system was successfully implemented in a real water distribution network in Spain, capable of detecting faults and leaks in real-time.
Muslim et al. [59]	Disaster monitoring in Sumberbrantas Village	Placement of IoT sensors in Sumberbrantas Village, which is prone to floods, landslides, and strong winds. The installed sensors include wind behavior sensors, rainfall sensors, and temperature sensors. Monitoring data include temperature, humidity, wind direction, wind speed, barometric pressure, and rainfall.

Table 4. Implementation of IoT for river monitoring

Researchers	Application	Parameters	Results
da Rocha Santos et al. [60]	Solimões River	Maximum range, maximum time, communication distance, communication time, packet delivery rate	78% package delivery rate at the maximum range of 1563 m. Results are satisfactory within the parameters configured and study conditions.
Nguyen et al. [61]	Mekong River	Daily water levels	Feasible results were achieved by SVR with a mean absolute error of 0.486 m, meeting the Mekong River Commission's requirements.
Jimale et al. [62]	Somalian River	Flood data	Early warning systems for floods enable preventative actions to mitigate natural disasters' effects.
Sahib [63]	Indian River	Environmental parameters	Continuous monitoring and rigorous analysis to trigger health alerts in case of anomalies, similar to smart health bands for humans.
Pantjawati et al. [64]	Citarum River	pH, turbidity, TDS	IoT system monitors real-time water quality. The values showed that water quality did not meet WHO standards before and after factory sewer locations.
Pujar et al. [65]	Krishna River	pH, conductivity, DO, temperature, BOD, TDS, conductivity	Real-time monitoring using IoT. Analysis of Variance (ANOVA) was effective for water quality analysis, helping in decision-making for water quality management.
Kumar et al. [51]	Ganga River and Yamuna River	pH, DO, temperature, conductivity, ORP	Water quality was suitable for irrigation and fisheries but not for drinking, considering average oxygen levels.
Abdulbaqi and Hashim [66]	Malaysian River	Water level	Continuous updates using ESP32 and Wi-Fi; real-time information for river conditions and actions depending on river conditions.
Soh et al. [67]	Singaporean River	River water level, riverbank level	Viable approach combining computer vision and IoT cloud; effective early flood monitoring and community alert system.
Pujar et al. [68]	Malaprabha River	Temperature, pH, DO, TDS, BOD, conductivity, nitrate	Real-time assessment of water quality; the IoT system monitors and assesses water quality parameters regularly to manage pollution from urban, industrial, and agricultural sources.
Dinesh et al. [69]	Bangladesh River	Various water quality parameters (unspecified)	Real-time data access through IoT; alerts sent via SMS for values exceeding thresholds; effective for raising awareness and reducing water pollution.
Alimkulov et al. [70]	Kazakhstan River	River flow, water level, water discharge	System accurately predicts flood events with high F1-scores; effective for managing water resources and mitigating flood risks.
Prakash et al. [71]	Indian River	Hydrological and meteorological data (water flow, water level, water discharge, temperature, humidity, wind speed)	Accurate flood prediction with the Long Short-Term Memory (LSTM) model; early warning system for evacuating people and protecting properties from floods.
Zain et al. [72]	Malaysian River	River water level, rainfall	Real-time monitoring with ESP32 and sensors; effective flood prediction and community notification system.
Taha et al. [73]	Malaysian River	pH, turbidity, TDS, DO, temperature	Real-time monitoring with the LoRa network; effective for urban environments with high capabilities for integration with IoT applications.

2.3 IoT in environmental monitoring

Environmental monitoring is a crucial aspect of efforts to maintain sustainability and ecosystem balance [48]. The IoT technology has revolutionized the way monitoring is conducted, enabling more efficient, real-time, and accurate data collection [49]. In the context of water quality monitoring, IoT offers numerous benefits, including the ability to detect environmental changes early and take prompt actions to prevent further damage [50]. Table 3 demonstrates that IoT technology is effectively applied in various environmental monitoring contexts, ranging from water and air quality to agricultural land management and disaster detection, resulting in increased efficiency, accuracy, and rapid response to environmental condition changes.

In more specific studies on water monitoring in Table 4, IoT technology in river water quality monitoring has demonstrated significant improvements in efficiency, accuracy, and the ability to respond quickly to changes in water conditions. Various studies show that the use of IoT sensors enables real-time monitoring of critical parameters such as pH, DO, temperature, and water turbidity, which is highly beneficial for the management and conservation of river ecosystems. This technology also enables effective flood prediction and risk mitigation, as seen in applications in the Mekong River and rivers in Somalia.

2.4 Sensor technology

Sensor technology is a key component in applying the IoT to water quality monitoring [74]. These sensors are responsible for measuring various parameters that reflect water quality conditions [75]. The sensor technologies used in river water quality monitoring are categorized into two types: physico-chemical sensors and biological sensors.

2.4.1 Physical-chemical sensors

Physical-chemical sensors are essential components in water quality monitoring systems. They measure various parameters that reflect the physical and chemical conditions of water, which are crucial for assessing overall water quality. The sensors convert the chemical quantities of input into electrical signals that can be analyzed, as shown in Figure 1. This chemical information can come from chemical reactions with biomaterials, chemical compounds, or a combination of both, which adhere to the surface of a physical transducer.

The field of chemical sensors is a growing discipline derived from multidisciplinary studies, including chemistry, biology, electronics, optics, mechanics, acoustics, thermology, semiconductor technology, microelectronics technology, and membrane technology [76].

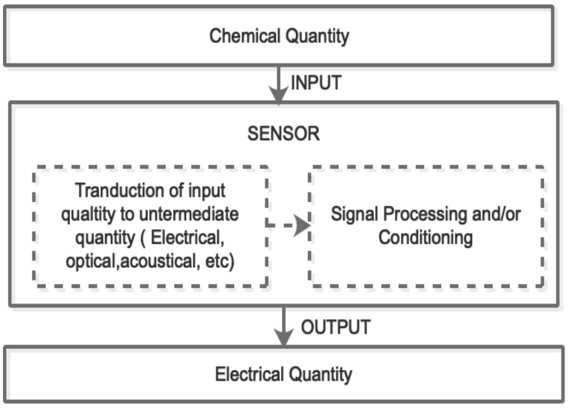

Figure 1. Sensor principle [76]

The following are some types of physical-chemical sensors used in water quality monitoring, including pH, TDS, temperature, turbidity, DO, EC, and the oxidation-reduction process. The use of physical-chemical sensors in real-time water quality monitoring allows for rapid response to changes in water conditions. For example, detecting an increase in turbidity or a decrease in DO levels can trigger immediate mitigation actions to prevent further negative impacts. The collected data can also be used for long-term analysis, aiding in water resource management and environmental policy planning.

2.4.2 Biological sensors

Biological sensors are used to detect the presence of microorganisms or other biological indicators that can affect water quality. Examples include E. coli sensors (Figure 2) developed by Afrineldi et al. [77] using optical fiber technology with several stages. The structure of this sensor involves an optical fiber with partially stripped cladding, which is then functionalized using Octadecyl Trichloro Silane (OTS). The evanescent wave formed on the surface of the optical fiber interacts with attached E. coli bacteria, causing a reduction in light intensity. This reduced light intensity is measured by a photodiode, and the output voltage from the photodiode is analyzed to determine the concentration of E. coli bacteria.

Aslan et al. [78] also employed a different approach with genetic design in their research. Genetic modifications were used on E. coli to alter the metabolic pathway so that cell growth depends on the presence of the target compound, glycerate. By deleting certain genes, it was ensured that E. coli could only grow if glycerate was available. Computational modeling, particularly flux balance analysis (FBA), was used to predict the effects of these gene deletions. After computational design, various modified strains were experimentally tested to see if they only grew in the presence of glycerate.

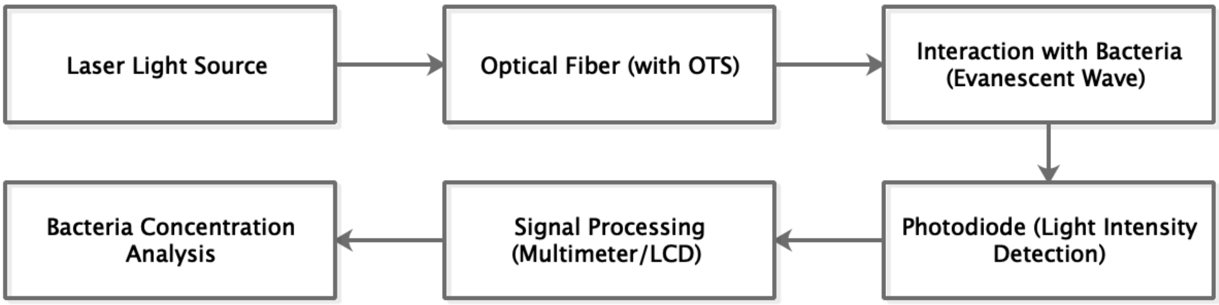

Figure 2. Flow diagram of the E. coli sensor [77]

Both optical fiber sensors and the genetic design approach for E. coli face significant challenges such as biofilm accumulation, particle interference, the need for regular calibration, and strict environmental control, making them less ideal for real-time water quality monitoring. Additionally, optical fiber sensors and genetically engineered sensors for detecting E. coli are generally not available as consumer products, affecting their availability.

3. METHODOLOGY

This study is at the parameter selection stage, which is the initial step in developing the WQI, as shown in Figure 3. At this stage, the primary focus is on identifying and selecting the most relevant and significant parameters to be included in the WQI. This stage is crucial to ensure that the chosen parameters can provide an accurate and representative picture of water quality so that the WQI framework and calculation model developed later can be more valid and effective.

3.1 WQI development

The proposed WQI integrates IoT technology and cloud computing to collect, process, store, and analyze water quality data in real-time. The comprehensive framework of this system has been previously detailed in prior research [79]. Figure 3 illustrates how data is obtained from rivers and water quality assessment is conducted.

3.2 Parameter selection

The first step in developing the WQI is the selection of relevant parameters, which include physico-chemical parameters. This process involves selecting parameters based on continuous IoT sensor data for initial water monitoring.

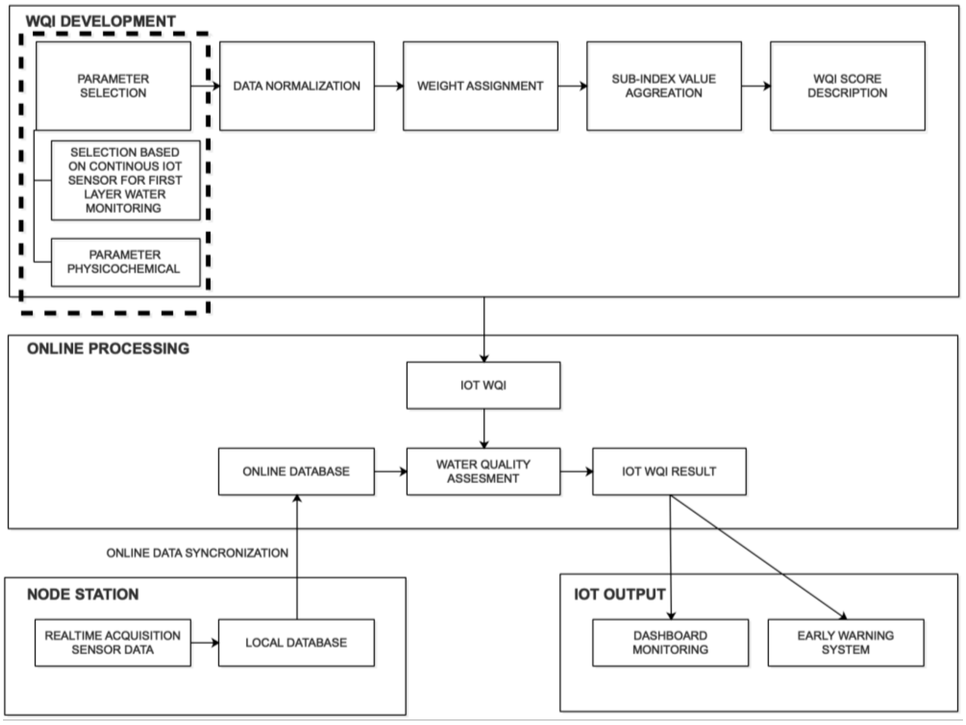

Figure 3. WQI development

4. DISCUSSION

The system utilizes commercially accessible sensors to measure water quality parameters. In previous research, data collection was facilitated by these sensors, with the data being transmitted in real-time via an IoT network to a cloud server. The raw data collected by the sensors is stored in the cloud, enabling quick access and further analysis without significant delay. Integration with cloud computing facilitates secure data storage and rapid access for analysis. The system transmits data every three seconds, demonstrating its capacity for continuous monitoring and frequent data updates, which is crucial for water quality monitoring applications in dynamic and rapidly changing environments [79].

The selection of parameters is the first and critical step in the development of the WQI. Parameters are selected based on the three main classes that determine water quality and are guided by management objectives and specific environmental characteristics. These classes include physical, chemical, and biological aspects [44]. In the development of an IoT-based WQI, research focuses on parameters with sensors that can be integrated with IoT devices, such as pH, turbidity, temperature, TDS, DO, EC, and ORP, as shown in Table 5. However, Table 1 shows that the ORP parameter is not used in previously developed WQI parameters. Additionally, the data indicate that no WQI uses all six parameters, i.e., pH, turbidity, temperature, TDS, DO, and EC, as index-determining parameters.

(a) pH sensors: pH sensors work by measuring the concentration of hydrogen ions in water and are often used in river water quality monitoring to detect changes that may be caused by pollution or industrial activities [90].

(b) Temperature sensors: Temperature sensors are used to monitor temperature changes that can affect aquatic life and ecosystem health [91].

(c) DO sensors: DO sensors are used to detect decreases in oxygen levels, a potential indicator of pollution [92, 93].

(d) Turbidity sensors: Turbidity sensors measure the amount of suspended particles in water, which can affect water clarity. High turbidity can be caused by soil erosion, agricultural runoff, or industrial activities [94, 95].

(e) TDS sensors: TDS, consisting of inorganic salts and organic matter, are pollutants to aquatic and water systems for human use [96].

(f) Conductivity sensors: Conductivity sensors measure the water's ability to conduct electricity, which is directly related to the number of dissolved ions in the water [97].

Table 5. Water monitoring systems and sensors used

No.	Researchers	pH	DO	Temp	TDS	Turbidity	EC	ORP
1	Sugiharto et al. [79]	√		√	√	√		
2	Daconte et al. [80]	√	√	√			√	
3	Jabbar et al. [81]			√	√	√		
4	Adeleke et al. [82]	√	√	√	√	√		√
5	Lakshmikantha et al. [83]; Pasika and Gandla [84]	√		√		√	√	
6	Vasudevan and Baskaran [85]	√		√		√		
7	Huan et al. [86]	√	√	√				
8	Jayaraman et al. [87]	√	√	√		√		
9	Chowdury et al. [88]	√		√	√	√	√	√
10	Islam [89]	√		√		√		

5. CONCLUSIONS

This study presents the initial phase of parameter selection for developing a WQI integrated with IoT technology. This stage focuses on identifying and selecting relevant parameters critical to water quality assessment. Therefore, detailed explanations of the WQI framework and calculation model are not provided at this point, as they will be developed based on the selected parameters in subsequent phases of the research.

Based on the literature review and analysis conducted, it is clear that the WQI plays a crucial role in simplifying complex water quality data into a single, easily understood value. Various countries and organizations use different parameters to develop WQI that suit their local needs and conditions, such as pH, temperature, DO, turbidity, and TDS.

Moreover, biological sensors, such as those used to detect E. coli, are often not utilized in real-time monitoring systems for several key reasons. For example, these sensors are susceptible to biofilm accumulation and particle interference, require routine calibration, and need strict environmental control. Limited commercial availability and the need for intensive maintenance also hinder their use in continuous water quality monitoring.

Future research will focus on developing a WQI based on selected parameters in subsequent phases of the research. The integration of IoT technology in water quality monitoring provides the capability for real-time measurements, enabling early detection of changes in water quality and rapid response to potential pollution. By addressing these challenges, IoT-based water quality monitoring systems can become highly effective tools for water resource management and environmental protection.

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