Review

Advances in Technological Research for Online and In Situ Water Quality Monitoring—A Review

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Abstract: Monitoring water quality is an essential tool for the control of pollutants and pathogens that can cause damage to the environment and human health. However, water quality analysis is usually performed in laboratory environments, often with the use of high-cost equipment and qualified professionals. With the progress of nanotechnology and the advance in engineering materials, several studies have shown, in recent years, the development of technologies aimed at monitoring water quality, with the ability to reduce the costs of analysis and accelerate the achievement of results for management and decision-making. In this work, a review was carried out on several low-cost developed technologies and applied in situ for water quality monitoring. Thus, new alternative technologies for the main physical (color, temperature, and turbidity), chemical (chlorine, fluorine, phosphorus, metals, nitrogen, dissolved oxygen, pH, and oxidation–reduction potential), and biological (total coliforms, *Escherichia coli*, algae, and cyanobacteria) water quality parameters were described. It was observed that there has been an increase in the number of publications related to the topic in recent years, mainly since 2012, with 641 studies being published in 2021. The main new technologies developed are based on optical or electrochemical sensors, however, due to the recent development of these technologies, more robust analyses and evaluations in real conditions are essential to guarantee the precision and repeatability of the methods, especially when it is desirable to compare the values with government regulatory standards.

Keywords: water quality; in situ; sensors; green technology; water monitoring

1. Introduction

Water is an important natural resource for life on earth and for human activities and, therefore, it is necessary to have abundant clean water to quench thirst, irrigate fields, and sustain all forms of life in the environment [1]. Several sources contribute negatively to changing water quality, mainly caused by human action, such as population growth, industrialization, urbanization, agriculture, domestic sewage, and poor management [2,3]. To improve water quality, the 2030 Agenda for Sustainable Development established, as a goal for 2030, the availability and sustainable management of water and basic sanitation for all human beings, with the improvement of water quality, the reduction in pollution, and the elimination of dangerous pollutants [4].

Water quality monitoring allows the identification and quantification of polluting substances that can be compared to acceptable standards for each location, being a strategic management tool for decision-making and the improvement of water quality [5,6]. Tamm, Nõges, and Jävet [7], for example, monitored the load supply of dissolved organic

carbon (DOC) to Lake Võrtsjärv (Estonia) between 1990 and 2002 by ground and surface flow—parameters affected by hydrological factors—highlighting the importance of assessing the parameter both currently and under changing climatic conditions. Unfortunately, there is still a large gap in water quality data, especially in remote locations and in developing countries [8], raising concerns about the sustainability of water resources and risks to human health. Furthermore, the main conventional techniques for monitoring water are often expensive, requiring qualified professionals and complex equipment, and which, in many circumstances, do not allow direct analysis in the field with immediate results.

However, several studies have tried to fill the gap and overcome the lack of data provision, such as the incorporation of citizen science [9,10], for example, or the development of low-cost and in situ technologies, as will be described throughout this work. The development of low-cost, accessible, and easy-to-handle devices and sensors for water quality analysis can be a viable alternative for obtaining data, improving water quality, and, consequently, the security of the water [11,12]. Furthermore, in situ measurement contributes to cost minimization, as it eliminates the need for sampling, sample preservation, transport, and laboratory water analysis [13].

The combination of technologies and water quality sensors with components of microsystems, associated with a software architecture and cloud computing (online), allows the development of a system in the conception of Smart Water Quality Monitoring Systems (SWQMS), from the point of view of the Internet of Things (IoT) [14–16]. In addition, integration with the Big Data system can improve the modeling of the water system, reducing model uncertainties and ensuring more information in the management of risk analysis [17,18]. Pehme et al. [19], for example, highlighted the necessity of an advanced understanding of landfill hydrological regime, by modeling tools and evaluating the risks to environmental and human health related to landfill geomorphology and hydrological balance.

According to Webb et al. [11] and Hoolohan et al. [20], digital technologies are seen as resilient, innovative, and efficient devices that can enhance the relationship between water and society, being a progression toward solving challenges in water systems and helping to mitigate social and environmental problems. An approach to water quality improvement, for example, is also the association of Real-Time Control systems (RTC) and Nature-Based Solutions (NBS) in urban drainage infrastructures, as described by Brasil et al. [21].

Thus, this work aims at a literary review that brings together technologies and portable sensors aimed at monitoring the quality of water in situ (regarding physical, chemical, and biological water quality parameters), at low cost, which allows a prescreening of the condition of the water as a monitoring tool for decision-making and good water management.

2. Water Monitoring Parameters

Although there are several parameters for monitoring water quality, only a few are used as key parameters in the monitoring, which can vary according to the location or the purpose of water use [22]. Regarding water use, according to Boyd [22] and Alley [23], when intended for human consumption, such as drinking, for example, the water must not have high concentrations of minerals, taste, or odor, and must be free of toxins or pathogenic organisms; for recreation, despite being unsuitable for consumption, the water must not present risks of contagion or diseases through direct contact; for the environment, the water must not contain pollutants that cause adverse effects on flora and fauna. Alam et al. [24], Rahman and Bakri [25], Mohamed et al. [26], and Rahmanian et al. [27], for example, present water quality monitoring studies whose monitoring parameters were established according to the needs of each location.

For monitoring water quality, Boyd [22], Alley [23], the World Health Organization [28], Spellman [29], Cotruvo [30], and Omer [31] present a variety of physical, chemical, and biological parameters for drinking water, superficial water (fresh and saltwater) and groundwater, the sources of pollutants, types of speciation, and the main analysis techniques. In this work, the following were considered as physical parameters: (i) color,

(ii) temperature, and (iii) turbidity; and as chemicals: (iv) chlorine, (v) fluorine, (vi) phosphorus, (vii) metals, (viii) nitrogen, (ix) dissolved oxygen, (x) pH, and (xi) redox potential or ORP (Oxidation–Reduction Potential).

In biological monitoring, although it is possible to identify numerous pathogenic species in water, the methods of isolation and the enumeration of such microorganisms make this a complex and time-consuming task, making it impractical to monitor all microorganisms that may be present in water [32]. To solve this problem, the monitoring of biological contamination is conventionally carried out by the analysis of key microorganisms present in human and warm-blooded animal feces, (xii) total coliforms and *Escherichia coli* being the most-used parameters to assess the microbiological safety of drinking and surface water supplies [33,34].

The monitoring of (xiii) algae and cyanobacteria is also important, since in many aquatic ecosystems, including drinking water supplies, there is a proliferation of these microorganisms called Harmful Algal Blooms (HAB) [35]. As emerging contaminants, the occurrence of HAB depends on several environmental conditions, such as the presence of nutrients and water temperature, and it is responsible for producing a variety of toxins released into water, which are dangerous for public health [36–38].

Many of the parameters mentioned above make up the Water Quality Index (WQI), such as dissolved oxygen, total coliforms, pH, temperature, nitrogen, phosphorus, and turbidity [39]. The WQI appeared in 1960 (Horton Index), being a simple and concise tool that allows the expression of the quality of water bodies and their derivations, such as for recreation, irrigation, and public supply, for example [40,41]. Nowadays, there are different numbers of models developed by different international organizations and used for WQI calculation, such as the National Sanitation Foundation Water Quality Index (NSFWQI) and the Weighted Arithmetic Water Quality Index (WAWQI), for example [42].

3. Development of Technologies for Water Quality Monitoring

The main technologies under development are based on colorimetric techniques or electrochemical sensors to analyze drinking water, rivers, lakes, and salt water [16,43,44]. However, as will be presented later, there are also technologies and methodologies capable of simplifying and improving existing water monitoring techniques, reducing costs, integrating them with the IoT, and accelerating data acquisition, such as the use of automatic samplers and autonomous analyzers.

According to Alberti et al. [43], with the progress of nanotechnology and materials science, various sensors and biosensors based on nanomaterials, such as nanoparticles (NPs), quantum dots (QDs), carbon nanotubes and nanofibers (CNTs/CNFs), nanowires, and graphene, for example, were developed for monitoring the environment. Figure 1 shows the evolution of the number of publications per year in research related to the topic, considering the terms water quality, low-cost, in situ, real-time, online, and portable. It is possible to identify a significant growth in this topic since 2012, with about 641 works published in 2021.

3.1. Technologies for Physical Monitoring of Water Quality

3.1.1. Color

The color of water refers to the reflection of light in tiny particles of organic or mineral origin, being an old indicator of water quality, even before technological development and the emergence of environmental sensors. However, when technology became part of our society's configuration, there was research directed toward water color measurements, such as Edwards [45], for example, who developed a sensor to measure the color and turbidity of natural waters using a four-beam intensity compensation technique for robust measurement. This prototype was operated in a water treatment plant, and at the time, it was considered very visionary research. The development of new technologies for color measurement will be described below, as well as presented in Table 1.
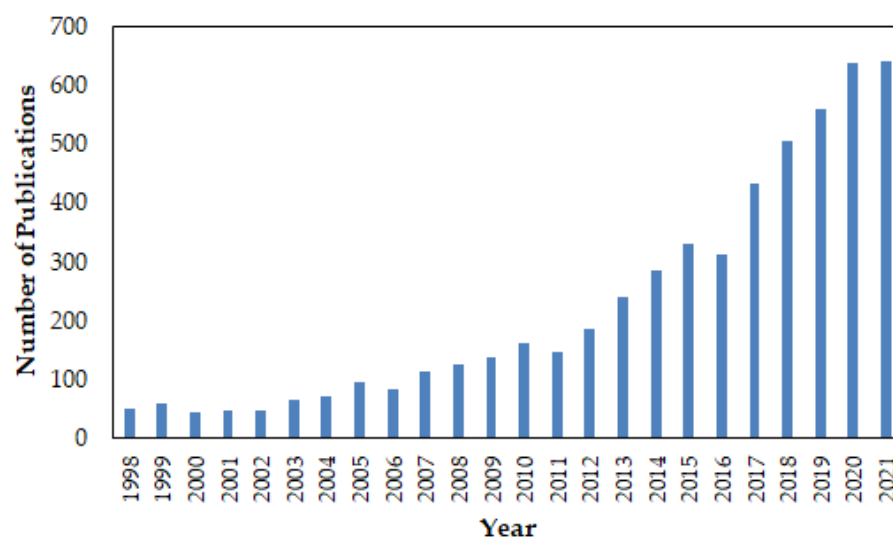
Figure 1. Evolution of the number of studies published per year related to the topic.

With the evolution of optical physics, studies such as Murphy et al. [46] reported a low-cost optical sensor for water monitoring, in which the sensor is based on a multi-wavelength light source with two photodiode detectors capable of measuring the transmission and lateral scattering of light at the detector head, estimating the parameters of color and turbidity. The tests were carried out in the laboratory, but the researchers' intention is to test the sensor in the future as a real-time water pollution monitoring system.

Given the importance of understanding the variation of color with other water quality parameters, Yang [47] developed a multisensory system for measuring water quality parameters (temperature, dissolved oxygen content, pH value, ammonia nitrogen, and color) for fish farming through algorithmically optimized sensors, in which the measurement of color parameters in the water is sent in real-time via the *ZigBee* communication standard [48]. Further, Saravanan et al. [49] also described a real-time IoT-based water quality monitoring system, which includes color as one of the parameters to be monitored in situ. In India, the real-time monitoring of water quality was integrated through an innovative alternative, as reported by George et al. [50], who described the initiative as a network of citizen scientists to monitor the color of water through Mini Secchi Disks, with Forel–Ule color scale stickers. This technique utilized a mobile app called "TurbAqua" to facilitate near real-time data transmission.

Table 1. Summary of studies that present new alternative technologies for monitoring the color parameter in water.

Author(s)	Type	Description	Research Findings
Murphy et al. [46]	Optical	Developed a low-cost Optical Colorimetric Sensor (OCS), equipped with telecommunication to assess the transmission of light in water.	The results show strong linear correlations between the signal response and the studied parameters.
Yang [47]		Introduced a multi-sensory system to monitor water quality parameters in fish ponds, with Zigbee wireless interface communication.	The system was able to collect water quality parameters and transmit them to the central station host computer, being a tool for fishing pond production management.

Table 1. *Cont.*

Author(s)	Type	Description	Research Findings
Saravanan et al. [49]		Proposed a low-cost system, called Supervisory Control and Data Acquisition (SCADA), to monitor various water quality parameters with remote communication (using a GSM module).	The device was able to measure the selected parameters in drinking water (including color) in real-time and with good accuracy.
George et al. [50]		Developed Mini Secchi Disks, with Forel–Ule color scale stickers used to measure water color and clarity, and a mobile app, called TurbAqua, was developed to facilitate near real-time data transmission.	The study presents a low-cost method for monitoring water quality on a voluntary basis, where the data can be used to validate satellite water quality products and be a tool for decision-makers to improve water issues.

3.1.2. Temperature

As with pH sensors, temperature sensors are present in most multi-parametric sensors. This is due, on the one hand, to the importance of temperature in relation to water quality; since several processes of other parameters occur as a function of temperature (e.g., biological activity, pH, dissolved oxygen, and conductivity), and, on the other hand, its easy monitoring, since there is a close linear relationship between temperature and resistivity, or electromotive force [51–53].

The measurement of water temperature can be performed by different methods, such as the thermal expansion of a material, thermoelectric processes, electrical resistance, semiconductors, optical fiber, and capacitance [54]. However, the most common low-cost temperature measurement process is the use of thermoelectric devices and/or resistive sensors. These techniques are mainly used for their accuracy, low cost for the operating temperature range required for water monitoring, robustness, and simplicity [55]. As most sensors and technologies presented in this review show the temperature measurement combined with some technique, only a few articles reported in the literature will be described in order to present the different techniques applied in the delimitation of this article (real-time, in situ, and low cost), as described in Table 2 also.

The most-used method for measuring temperature is the resistive method. This is not only due to the ease of development of the sensors but also because thermoelectric sensors (specifically, thermocouples) often use resistive sensors to determine the standard temperature required for this technique [54]. Alam, Clyne, and Deen [56] used sensors based on the Wheatstone bridge configuration to obtain a high sensitivity temperature measurement with low variability between 0 and 50 °C. Two of the four bridge terminals were produced with P-type Silicon Wafers, with a high Temperature Coefficient Resistance (TCR)—the calculation of a relative change of resistance per degree of temperature change—and the other two were produced with polystyrene sulfonate (PEDOT:PSS), with negative TCR values. Alam et al. [57] developed a sensor using the same principles (Wheatstone bridges); however, it used two separate layers of a glass substrate using a bulk silicon wafer, poly(3,4-ethylenedioxythiophene), and PEDOT:PSS. The authors also integrated the sensor into an Arduino platform with an Android systems interface application.

Still related to resistive sensors, Wu et al. [55] developed a sensor for temperature measurement using a platinum (Pt) layer, since this material is a good conductor and has good characteristics for temperature measurement. Finally, another option for resistive temperature sensor measurement was presented by Simic et al. [58], using a low-cost and commercially available sensor (LM35). They performed a calibration of the device in the laboratory and obtained an accuracy of ±0.25 °C. Srivastava, Vaddadi, and Sadistap [59], aiming at a quick response of the temperature sensor and a low cost, used a K-type thermocouple. A K-type thermocouple is a thermocouple (a device that converts thermal

energy into electrical energy) that uses a non-magnetic positive terminal (usually Chromel) and a magnetic negative terminal (usually Alumel) and performs the measurement based on the output voltage.

Finally, Huang [60] and Huang et al. [61] used optical fiber to measure the temperature. Despite being a method with a high cost, this technique is usually applied to temperature when the optical fiber is also used to measure other parameters. As the parameters monitored by the authors have high temperature sensitivity, two insulated fiber optic terminals were used. Thus, through the variation of the different central wavelengths, it was possible to find a linear relationship with the temperature, therefore calibrating the device.

Table 2. Summary of studies that present new alternative technologies for monitoring the temperature parameter in water.

Author(s)	Type	Description	Research Findings
Alam, Clyne and Deen [56]	Electrical	Developed a temperature sensor fabricated with p-type Si and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) film in a Wheatstone bridge configuration.	The results show that the sensor was able to measure temperature between 0 and 50 °C with high sensitivity and low variability.
Alam et al. [57]		Presented a sensor-based using poly(3,4-ethylenedioxythiophene) and PEDOT:PSS to measure temperature in water.	The experiments present an accuracy above 85% for temperature sensor measurement.
Wu et al. [55]		Developed a platinum (Pt)-based sensor for temperature measurement integrated into a micro-electro-mechanical system (MEMS).	The Pt thermistor with a three-wire orthogonal structure has a temperature response of 5.95 $\Omega/°C$.
Simic et al. [58]		Used a commercial sensor (LM35) to measure temperature in water.	The results show an accuracy of ± 0.25 °C.
Srivastava, Vaddadi and Sadistap [59]		Presented a K-type thermocouple sensor as a low-cost way to measure temperature integrated with a smartphone.	The system presents itself as a low-cost tool for monitoring water quality parameters in several urban locations.
Huang [60] Huang et al. [61]	Optical	A temperature sensor was developed using long-period fiber grating (LPFG).	The sensor can effectively monitor the temperature with a maximum difference of ± 1 mm for water level, ± 0.005 for refractive index, and 1 °C for temperature.

3.1.3. Turbidity

The turbidity of water is a parameter that indicates the degree of interference that a light beam encounters when crossing it, mainly because of the presence of suspended solids such as inorganic particles and organic debris, which can give a murky appearance to that water [62]. Because of this, turbidity is a fundamental parameter to assess water quality, being able to identify whether the water is fit for consumption and, consequently, prevent waterborne diseases [63].

Given the importance of turbidity, there are several turbidity sensors, commercially available, that can be integrated into water quality monitoring systems, as used and described in much research, to develop IoT-based online monitoring combined with other water quality parameters. Some examples of these studies are presented by Geetha and Gouthami [16], Lambrou et al. [64], Samijayani et al. [65], and Chowdury et al. [66]. In addition, the following works present the development of new technologies applied to the monitoring of water turbidity, as shown in Table 3 also.

With the intention of optimizing, and reducing the costs associated with detecting turbidity, some recent research, such as Azman et al. [63], has developed low-cost technology based on a nephelometric turbidity sensor for the continuous monitoring of water quality. According to the authors, the electronic sensor's operation is based on the intensity

of scattered light in relation to light scattering in solids and liquids, using LED (Light Emitting Diode) as a transmitter, LDR (Light Dependent Resistor) as a receiver, and an *RS232* module for communication between sensor and computer. Arifin et al. [67] researched the development of a sensor for water turbidity measurement using an infrared LED, a polymer optical fiber, and a photodetector as main materials, in which the experiments showed promising sensitivity results with 0.046 μW/NTU and 0.022 NTU resolution.

Wang et al. [68] also worked on a low-cost turbidity sensor and online water quality monitoring project, using an 850 nm infrared LED, dual orthogonal photodetectors, and, for communication, a custom IoT platform. The research showed that the device was able to measure the turbidity parameter with accuracy and robustness comparable to commercial sensors. Rahman et al. [69] also evaluated the performance of an LED-based sensor for water turbidity measurement, observing the response to different colors of light sources used for water turbidity measurement and determining the best photodetector according to the voltage variation during the ON/OFF condition. The authors showed that the white LED gives the best performance with less than 10% systematic error in most measurements and followed by the UV LED, but both lights were suitable for water turbidity measurements ranging from 0 to 1000 NTU. Finally, Schima et al. [70] developed an open-source optical sensor system for real-time and in situ turbidity monitoring, using detectors in the infrared range of the electromagnetic spectrum, which presented high accuracy when compared to standards methods in the laboratory. In addition, a Python script used on the Raspberry Pi was responsible for communication with the sensor, with which it was possible to show, even in the laboratory phase, that open-source technology can be a key to resilient and promising systems.

Table 3. Summary of studies that present new alternative technologies for monitoring the turbidity parameter in water.

Author(s)	Type	Description	Research Findings
Azman et al. [63]		Presented a low-cost nephelometric turbidity sensor for the continuous monitoring of water quality and communication using the RS232 module.	The results show that the developed low-cost sensor presented results as a commercial turbidity sensor.
Arifin et al. [67]		Developed a polymer optical fiber sensor for measuring turbidity in water.	The experiments provided promising results, with 0.046 μW/NTU and 0.022 NTU resolution for the sensor.
Wang et al. [68]	Optical	Presented a low-cost and online monitoring sensor for turbidity using an infrared LED and photodetectors.	The device was able to measure turbidity with high accuracy as a commercial device.
Rahman et al. [69]		Evaluated the performance of an LED-based sensor for measuring turbidity in water.	The use of visible and UV LED was able to measure turbidity between 0 and 1000 NTU.
Schima et al. [70]		Developed an open-source optical system for real-time and turbidity monitoring using detectors in the infrared range of the electromagnetic spectrum.	The developed in situ sensor system showed a very high agreement with the results obtained using a laboratory photometer but with less methodological effort.

3.2. Technologies for Chemical Monitoring of Water Quality

3.2.1. Chlorine

Chlorine is one of the main disinfectants in public water supplies since its oxidizing characteristic can eliminate pathogenic microorganisms present in the water [71]. Therefore, detecting the concentration of free chlorine in the water is essential for monitoring and detecting the presence of contaminants. The consolidation of free chlorine sensors in water has taken place gradually, so that, even after many years have passed since the first

attempts, many sensors are still under development and improvement. The development of new technologies for chlorine measurement will be described below, as well as presented in Table 4.

Table 4. Summary of studies that present new alternative technologies for monitoring the chlorine parameter in water.

Author(s)	Type	Description	Research Findings
Cassidy et al. [72]	Optical	Developed a spectrophotometric device for chlorine detection in real-time using a xenon light source and a flow sample chamber.	Device performed well, but improvements are needed for field application.
Hall et al. [73]	Optical and Electrical	Assessed electrical and optical sensors for chlorine detection in water.	The sensors were able to determine chlorine with good accuracy, but more analysis is needed to improve the devices.
Gimenez-Gomez et al. [74]	Electrical	Presented a low-cost, compact portable multisensory electronic system to measure parameters of water quality.	The device presented good performance compared to commercial equipment, including free chlorine analysis.
Cui et al. [75]		Described the development of a microcontroller system, with wireless communication, to measure water quality parameters.	The device allowed online communication and the commercial residual chlorine sensor used (free chlorine and monochloramine) showed good results.
Yen et al. [76]		Developed a low-cost chemo-resistive sensor based on nanohybrid paper to measure free chlorine ions.	The developed sensor showed a linear range of 0.1−500 ppm, and the limit of detection was 0.18 ppm.
Alam et al. [77]		Proposed a reusable, reagent-free sensor based on a thin gold film for chlorine measurement.	The sensor showed high-sensitivity accuracy, like commercial sensors.

Cassidy et al. [72], for example, studied a low-cost spectrophotometric sensor for chlorine detection with real-time data collection capability, aimed at increasing the acquisition time and improving the mechanical stability of chlorine sensors. The main components of this optical system were a xenon light source and a flow sample chamber. For communication, a DSP (Digital Signal Processor, EVM56303, produced by Motorola, Austin, TX, USA) board was used, which provides control signals and interacts with external devices. Overall, the device performed positively in the laboratory, but improvements are still pending for field applications and real-world scenarios.

Hall et al. [73] focused on the detection of parameters online to indicate contamination in the distribution system, using commercial sensors, including free chlorine sensors. Altogether, three sensors with different chlorine detection principles (colorimetric, polarographic, and voltammetric) were tested with costs ranging from US$3000 to US$10,000. The free chlorine was the best parameter, among the analyzed parameters, which responded to the presence of contaminants, but the authors point out that the technologies used were still in the consolidation phase and needed future improvements.

The quest to improve and reduce the costs of chlorine measurement was also presented by Gimenez-Gomez et al. [74], who proposed a compact portable device to simultaneously measure five water quality parameters, including amperometric parameters, using micro-

electronic technology with low power consumption. The electronic system was tested, and the analytical signals were compared with commercial equipment. In addition, the authors claim that the communication between the computer and the portable device can be carried out using a wireless protocol, such as a Wi-Fi or a low-power ZigBee interface.

To facilitate and modernize the detection of contaminants, Cui et al. [75] designed a Water Quality Monitoring System based on the *STM32F103* microcontroller integrated system and the *nRF24L01* wireless communication module. Various types of sensors were used to detect harmful components in the water, including the commercial residual chlorine sensor *CLE3-DMT* to detect free chlorine and monochloramine. The system's proposal was to allow users to use their smartphones to carry out the real-time and online monitoring of various parameters in water quality. As the system has been successful in experiments, the authors believe that the device can be widely used with further research.

With the objective of facilitating portability, Yen et al. [76] also broke new ground in chlorine monitoring and presented a chemo-resistive sensor based on a nanohybrid paper that can be used with smartphones to detect free chlorine ions. The sensor was manufactured using a simple, standardized coating process on graphene paper and PEDOT:PSS, whose results presented a linear range of 0.1–500 ppm for free chlorine measurement, with a detection limit of 0.18 ppm. The sensor was integrated into an electrical reading system, using *Arduino Uno Rev3 SM* (Arduino, Genoa, Italy), designed for miniaturization and wireless transmission to a smartphone by a Bluetooth module. The authors emphasize that the system is advantageous for its portability, low cost, and allowing real-time readings on a smartphone.

Furthermore, the innovation of chlorine sensors is ongoing, as shown by Alam et al. [77], who developed a reusable, reagent-free sensor based on a thin gold film. The sensor presented high sensitivity, which is often a challenge for other commercial sensors, and due to simple fabrication and good detection performance, the proposed device enables mass production and future application in distant regions with low investment.

3.2.2. Dissolved Oxygen (OD)

Dissolved oxygen (DO) is an important parameter in water quality and essential for aquatic life. According to Hou et al. [78], when the DO concentration is less than 3 mg/L, there is an impact on the health of the fish, which can even lead to death by asphyxia. Furthermore, according to Hsu et al. [79], a low concentration of DO can negatively affect a water system by facilitating the excessive growth of anaerobic bacteria. The DO concentration can also indicate various contaminants in water bodies, making DO one of the most important parameters for monitoring.

There are two types of DO sensors: electrochemical and optical. Electrochemical DO sensors are based on the electrical current produced to measure the concentration of dissolved oxygen in water and can be polarographic or galvanic [80]. Optical DO sensors, also called luminescent DO sensors (LDO), measure the concentration of dissolved oxygen in water according to the extinction of luminescence in the presence of oxygen, being able to measure the intensity or lifetime of luminescence, since oxygen affects both [81].

Research to optimize DO measurement technologies is directed towards both electrochemical and optical sensors, however, DO electrochemical sensors are currently seen as more promising and are more widely used, mainly because they perform online in situ measurements [80]. The following works present the advances in technologies for DO measurement in water, as summarized in Table 5 also. Thus, in situ and online monitoring systems for aquaculture and other water uses have been using commercial dissolved oxygen sensors with electrochemical detection, as described by Liu [82], Luo et al. [83], Vijayakumar and Ramya [84], and He [85]. Liu [82] and He [85] were able to monitor OD and other water quality parameters (turbidity, pH, temperature, and electrical conductivity) for fishery management based on the IoT concept. From the same approach, Vijayakumar and Ramya [84] also were able to measure DO in water for aquaculture management using a Raspberry PI B+ core controller and an IoT module (USR WIFI 232). Finally, Luo et al. [83]

used a commercial YCS-2000 dissolved oxygen sensor and Zigbee and GPRS modules to monitor water quality parameters in real-time at a low cost, including DO.

Table 5. Summary of studies that present new alternative technologies for monitoring the dissolved oxygen parameter in water.

Author(s)	Type	Description	Research Findings
Liu [82]	Electrical	Designed an IoT system for monitoring the water quality environment for fishing in real-time.	The system was able to acquire DO, turbidity, pH, temperature, and electrical conductivity parameters in real-time, storing them in a database.
Luo et al. [83]		Developed a real-time monitoring system to measure DO in water using a YCS-2000 sensor.	The system could fulfill the real-time remote monitoring of aquaculture water quality and had great practical significance in the reduction in labor intensity.
Vijayakumar and Ramya [84]		Present a low-cost system for real-time water quality monitoring (including DO) using a Raspberry PI B+ model.	The device was presented as a low-cost and real-time monitoring system, being capable of processing, analyzing, sending, and viewing the data in the cloud.
He [85]		Designed and developed an embedded aquaculture intelligent water quality monitoring system based on STM32F103VET6.	The system could provide technical support for the design and development of an aquaculture monitoring system.
Lee et al. [86]		Designed a DO sensor for in situ water quality analysis using a needle-like microelectrode arrangement (MEA).	The DO MEA exhibited a rapid 15 s linear response in the 0–9 mg/L (0–21% O_2) range.
Penso et al. [87]	Optical	Used a PDMS membrane coated with a platinum octaethylporphyrin (PtOEP) film to measure DO in water.	In a liquid medium, the sensor was able to measure DO in a range of 0–5.5 mg/L.
Mahoney et al. [88]		Optimized a multilayer optical-fluidic sensor for DO in situ measurement.	The results showed a comparable sensitivity and sensing range (0–20 ppm) compared to previously developed miniaturized DO sensors.

The development of new technologies for DO sensors is ongoing, as presented, for example, by Lee et al. [86], who studied a new DO sensor for in situ water analysis with a needle-like microelectrode arrangement, obtained by microfabrication technologies, which aims to integrate sensors with IC (Integrated Circuit) chips for online data acquisition. Thus, the authors obtain a rapid 15 s linear response in the 0–9 mg/L (0–21% O_2) range. Penso et al. [87] described the development, fabrication, and characterization of a low-cost, high-sensitivity optical sensor for DO detection with the potential for in situ measurement in a marine environment (between 0 and 5.5 mg/L) based on a PDMS membrane coated with a platinum octaethylporphyrin (PtOEP) film. Mahoney et al. [88] also innovated the optimization of a multilayer optical-fluidic sensor device based on the measurement of fluorescence suppression in a ruthenium-based oxygen-sensitive dye to obtain increased sensitivity in the in situ detection of DO in water between 0 and 20 ppm.

3.2.3. Fluorine

Fluoride analysis is essential for human health, especially concerning dental health [89,90]. For this reason, there are several techniques for the analysis of fluorine in water, such as

the potentiometric and colorimetric methods, with the zirconium dye complex (SPADNS) method being the most used [91]. According to WHO [28], fluoride is usually determined by means of an ion-selective electrode, which makes it possible to measure the total amount of free and complex-bound fluoride dissolved in water. The description of new technologies for measuring fluoride in water will be described below, as well as presented in Table 6.

Table 6. Summary of studies that present new alternative technologies for monitoring the fluorine parameter in water.

Author(s)	Type	Description	Research Findings
Jadhav et al. [92]	Optical	Used a fiber optic sensor based on Fiber Bragg Grating (FBG) to detect fluorine in water.	The sensor allowed fluorine detection with a good accuracy between 0.05 and 8 ppm.
Moradi et al. [90]		A simple method for fluoride detection is presented. The sensor comprises a 35 nm aluminum coating on the distal end of a length of single-mode optical fiber.	The fabricated sensor measures fluoride concentration within the range of 0–5 mg/L.
Levin et al. [93]		Determined fluorine in water using an optical device connected to a smartphone camera.	It was possible to measure fluorine in water by assessing RGB color, although the presence of other substances may interfere with the results.
Mukherjee et al. [94]		Used external bicomponent sensing material, powered and operated by a smartphone, for fluorine analysis.	The results were similar to the laboratory methods and showed good selectivity for fluorine.

In the field of in situ and low-cost technologies development, Jadhav et al. [92], using a fiber optic sensor based on Fiber Bragg Grating (FBG), were able to detect low concentrations of fluoride in water by observing the linear relationship between light transmitted by the fiber and the increase in fluoride concentration. In addition, the research observed a resolution of 0.03 nm for the spectrum light, which allows an accuracy of ± 20 ppm for fluoride analysis in the range of 0.05–8 ppm. Additionally, Moradi et al. [90] presented a technique that consists of coating a fiber optic terminal with aluminum by Direct Current Sputtering to reduce the sensor costs, making it possible to evaluate samples down to 5 ppm. As described by the authors, when the sensor is in contact with the fluorine in solution, a reaction occurs between the fluorine and the aluminum, removing the aluminum coating and causing a change in the light intensity proportional to the fluoride concentration.

Using other techniques to detect fluoride, Levin et al. [93] and Mukherjee et al. [94] also tested the development of a smartphone camera technique to measure fluoride in real-time, in situ, and at low cost. In the study by Levin et al. [93], an optical device was connected to the smartphone camera by a suitable case to measure the fluoride concentration in water samples. In this way, using the smartphone camera, it was possible to assess the relationship between the red, green, and blue (RGB) colors of the water samples to estimate the fluoride concentration. The authors obtained consistent results in the laboratory, although it is important to highlight that the turbidity and chlorine may interfere with the results of the analysis. Mukherjee et al. [94] used an external bicomponent sensing material, powered and operated by a smartphone, for fluorine analysis. The sensor used a mixture of near-cubic ceria−zirconia NC and XO dye that rapidly changes color from yellow to red based on interaction with fluorine. The authors also evaluated the device's accuracy against other laboratory equipment such as XPS and NMR spectroscopy, as well as testing the system for high concentrations of other anions also present in water. Thus, the results were similar to the laboratory methods and showed that the device has a good selectivity for fluorine, showing no influence of other anions in the analysis.

3.2.4. Metals

The pollution of the aquatic environment by heavy metals is a growing problem worldwide. There are several sources of heavy metals, many of them originating from human action, mostly domestic sewage, hospital waste, and industrial and mining activities, among others [95,96]. Since heavy metals cannot be biodegraded, they are continuously deposited, accumulated, and incorporated into water, sediment, and aquatic organisms [97]. Within organisms, some heavy metals can exert a toxic and harmful effect and alter the functioning of the kidneys, liver, and nervous system, for example [98,99]. However, it should be noted that many metals, such as iron, copper, zinc, and magnesium, are essential for living beings in low concentrations, but exert a toxic effect in high concentrations [100].

According to Sibal and Espino [96], the mainly lab-based techniques to measure metal in water are atomic absorption spectrometry (AAS), mass spectrometry (MS), inductively coupled plasma MS (ICP-MS), atomic emission spectrometry (AES), X-ray fluorescence (XRF), and optical techniques. For Garciá-Miranda Ferrari et al. [101], such techniques are characterized as being sophisticated and expensive and may require the use of pre-concentration and separation techniques for high-analysis performance. On the other hand, when it comes to in situ analysis, methods with electrochemical sensors can be considered more appropriate, mainly due to the small size of the equipment, easy installation, low cost, and simple handling [101]. Gumpu et al. [102], for example, present techniques for measuring metallic ions, based on electrochemical biosensors for measuring arsenic (As), cadmium (Cd), mercury (Hg), lead (Ld), chromium (Cr), silver (Ag), zinc (Zn), and copper (Cu). The development of new technologies for measuring metals in water are presented below, as well as shown in Table 7.

Table 7. Summary of studies that present new alternative technologies for monitoring the metals parameter in water.

Author(s)	Type	Description	Research Findings
Oliveira et al. [103]	Optical	Developed spectrophotometry using a DVD as a diffraction medium to measure iron in water.	The system was able to measure iron between 0.5 and 15.0 mg/L.
Zhou et al. [104]		Used portable X-ray fluorescence (pXRF) equipment to estimate lead and copper in a lake.	The equipment was capable of determining the concentrations of heavy metals in polluted water, especially for heavily polluted water with relatively high concentrations.
Srivastava and Sharma [105]		Developed ultra-compact portable spectrophotometry, integrated with a cloud database, to measure iron and copper in drinking water.	The spectrophotometer system provides an innovative chemo-electronic cost-effective system to measure heavy metal contamination present in water samples in real-time.
Wu et al. [55]	Electrical	Used a sensor manufactured by MEMS (Micro-Electro-Mechanical System) technology to measure copper in water.	The sensor was able to detect copper between 0.0 and 0.6 mg/L, with an accuracy of 0.04 mg/L.
Wang et al. [106]			The sensor suffers no interference from other metals and was able to measure copper between 0.0 and 400 mg/L.
Alam et al. [57]		Developed a multi-walled carbon nanotubes and β-cyclodextrin (MWCNT-βCD) sensor to measure lead in water.	The sensor was able to detect lead in water between 5 and 100 mg/L.

Table 7. *Cont.*

Author(s)	Type	Description	Research Findings
Yen and Lai [107]		Designed a metal-oxide-semiconductor microelectromechanical system (CMOS-MEMS) sensor to detect lead in water.	The sensor was able to detect lead in water between 0.01 and 100 mg/L.
Li et al. [108]		Used a Disposable Electrode-Printed (DEP) chip, integrated with a plastic pipette, to measure Pb, Hg, Cu, and Zn.	The device was able to measure the metals at different concentrations, which demonstrated that there existed a linear relationship between the peak current and the concentration.

In the development of portable optical systems for the determination of metals in water, Oliveira et al. [103], Zhou et al. [104], and Srivastava and Sharma [105] presented simple, low-cost solutions for measuring lead, copper, hexavalent chromium, and iron. The portable spectrophotometry system developed by Oliveira et al. [103], in Medium Density Fiberboard (MDF) material, using a DVD as a diffraction medium, and a smartphone device camera, was able to measure Fe^{2+} in a range of 0.5–15 mg/L, with a LOD of 0.02 and LOQ of 0.07 mg/L. Srivastava and Sharma [105] also developed an ultra-compact and portable spectrophotometry system, which integrates with a smartphone device and a cloud database (IoT), for measuring iron and copper in drinking water. Zhou et al. [104], using portable X-ray fluorescence (pXRF) equipment, were able to estimate the concentration of Pb and Cu directly in a lake, yielding results of 28 and 21 mg/L for Pb and Cu, respectively.

In the development of electrochemical sensors for metal determination, Wu et al. [55], Alam et al. [57], Wang et al. [106], Yen and Lai [107], and Li et al. [108] were able to measure copper, lead, mercury, and zinc in an aqueous medium, with portable, low-cost electrochemical sensors that could be integrated with other electronic devices for in situ and real-time responses. Alam et al. [57], from sensors made of multi-walled carbon nanotubes and β-cyclodextrin (MWCNT-βCD), were able to determine a concentration of Pb^{+2} in water between 5 and 100 mg/L, even in the presence of other metals, such as Cd^{2+}, Zn^{2+}, Cu^{2+}, Hg^{2+}, and Ni^{2+}. Wu et al. (2020) [55] and Wang et al. [106] used a sensor manufactured by MEMS (Micro-Electro-Mechanical System) technique to measure Cu^{+2} between 0.0 and 0.6 mg/L and 0.0–400 mg/L, respectively. Wu et al. [55] observed an accuracy of 0.04 mg/L for the equipment, while Wang et al. [106] observed that the sensor suffered no interference by the presence of other metals (such as Pb^{2+}, Zn^{2+}, and Mg^{2+} ions). Yen and Lai [107], by the technology based on a metal-oxide-semiconductor microelectromechanical system (CMOS-MEMS), which can be operated in real-time and in situ, were able to detect Pb^{2+} between 0.01 and 100 mg/L with a detection limit of 0.005 mg/L. Finally, Li et al. [108] developed a portable device, costing less than U\$160.00, based on plastic pipetting equipment using a Disposable Electrode-Printed (DEP) chip, for the determination of Pb, Hg, Cu, and Zn at different concentrations. Furthermore, the experimental results demonstrated that the limits of detection for Pb, Hg, Cu, and Zn were 2.2 ng/mL, 2.5 ng/mL, 15.5 ng/mL, and 10 ng/mL, respectively, and the limits of quantification for them were 10 ng/mL, 25 ng/mL, 25 ng/mL, and 14 ng/mL, respectively.

3.2.5. Nitrogen

Nitrogen can be found in different sources, such as decomposed plants, human waste, animals, and chemical fertilizers [64]. For nitrogen monitoring, several techniques can be applied, such as chromatography, electrochemistry, and spectroscopy methods [109]. Chromatography is the most suitable method when there is organic matter in the samples, since this method does not suffer interference from other compounds; however, it is the most complex and expensive method of application, as it uses different techniques and

specialized materials in the process [110]. Spectroscopy can also suffer interference, but it is easier to apply than the other two methods, in addition to the advantage of obtaining results faster [111]. Monitoring through electrochemistry has great potential for low-cost applications, but it can be influenced by ions and organic matter present in the samples [112]. The development of new technologies for nitrogen measurement will be described below, as well as presented in Table 8 also.

As it is an important parameter from a monitoring point of view, the development of low-cost sensors for the real-time and in situ detection of nitrogen has gained attention in the literature. Akhter et al. [113], for example, developed an electrochemical sensor using Polydimethylsiloxane as a flexible substrate with multi-walled carbon nanotubes as a conductive material. Although graphene has better electrical properties, the mass production of this material is complex, which can change the repeatability of the developed sensor. In addition, the authors developed an IoT platform based on LoRa (Long Range) [114] to send the collected data in real-time, finding a relationship between temperature and resistivity for different concentrations of nitrate. When evaluating repeatability, the authors observed that the Relative Standard Deviation (RSD) was below 2% when comparing three different readings from the same sensor, and an RSD below 5% when compared to the other five sensors of the same manufacture. Finally, the values obtained by the developed sensor were compared with those obtained by the UV-vis spectrometry method to validate the results, obtaining a higher maximum concentration with a difference of 4.91% in relation to the standard method.

Obrovski et al. [111] used a chemical fiber optic probe based on the HSV (Hue, Saturation, and Value) color model. The sensor is based on the principle that when water is exposed to light, certain wavelengths are transmitted while others are absorbed depending on the color of the evaluated sample. Then, the device uses three RGB LEDs and a *TLS250* photodetector to detect the transmitted light. The device was compared to the UV-vis spectrometer, and it was found that nitrate was the only parameter with which it was possible to obtain a correlation with the concentration variation, the detection limit of this sensor being between 0 and 0.7 mg/L. In addition, the authors performed only laboratory evaluation; therefore, it is not possible to verify the performance of the device in real applications, nor evaluate the repeatability and durability of this sensor in field conditions.

Finally, Ingles, Louw, and Booysen [115] developed a sensor that can be used with smartphones based on a laboratory photometer spectrum, however, with fewer components, more portability, and less expense. The device has four parts: the light source, the wavelength filter, a cuvette, and a scintillator. For the light source, the only one commercially available and capable of emitting light at the indicated wavelength was the *CompactFiberlight D2*. The wavelength filter was developed with quartz, which is a material that has a negligible absorbance at a wavelength of 205 nm: the ideal wavelength for nitrogen evaluation [116,117]. The cuvette was 3D printed in plastic with a 1 cm opening to isolate external light while allowing instrument light to pass through. With this device, the authors obtained a maximum deviation of 27% compared to the analysis performed by the photometer spectrum, with the sensor operating range between 1 and 10 mg/L for nitrate.

3.2.6. pH

As pH is an essential parameter to ensure good water quality, this parameter is widely monitored and found in practically all multiparameter equipment. Different techniques can be applied to measure the pH in a water sample, namely visual analysis, photometric and potentiometric methods [118,119]. While the visual method uses color change as a pH indicator using specific materials (litmus paper), this method does not have good accuracy and only provides approximate pH values. The potentiometric method is based on the Nernst equation, which measures the change in hydrogen ion concentration due to chemical reactions. The photometric method is based on spectrophotometry, which provides information about the change in wavelength absorption based on the pH change

of the samples. The following research presents the development of alternative technologies for measuring pH in water, as described in Table 9 also.

Table 8. Summary of studies that present new alternative technologies for monitoring the nitrogen parameter in water.

Author(s)	Type	Description	Research Findings
Akhter et al. [113]	Electrical	Developed an electrochemical sensor using Polydimethylsiloxane as a flexible substrate with multi-walled carbon nanotubes nitrate in water.	The sensor had a difference of 4.91% in relation to the standard method for measuring nitrate.
Obrovski et al. [111]	Optical	Used a chemical fiber optic probe based on the HSV model to detect nitrate in water.	The detection limit of this sensor was between 0 and 0.7 mg/L.
Ingles, Louw and Booysen [115]		Presented a low-cost, portable sensor that can be used with a smartphone to measure nitrate in water.	The sensor operating range was between 1 and 10 mg/L for nitrate, with a 27% deviation compared to commercial equipment.

Table 9. Summary of studies that present new alternative technologies for monitoring the pH parameter in water.

Author(s)	Type	Description	Research Findings
Alam, Clyne and Deen [56]	Electrical	Used a special ink made of palladium (Pd) with a silver/silver-chloride electrode (Ag/AgCl) to measure pH in water.	The sensor was able to measure pH in real-time with high accuracy.
Wu et al. [55]		Used the Ruthenium (Ru) redox to measure pH in water.	The sensor has a sensitivity of -57.34 mV/pH in pH detection and was able to measure pH in a 4.01–10.87 range.
Simic et al. [58]		Used Titanium Dioxide (TiO_2) as the main film in the pH sensor.	The design ensured reliable in situ measurement.
Hossain et al. [120]	Optical	A Photo-Induced Electron Transfer (PET) method was used with 4-aminonapthlimide (integrated into a smartphone) to measure the pH parameter in water.	The application of a novel smartphone-based pH meter showed a rapid assessment and mapping of the quality of drinking water.
Dutta, Sarma amd Nath [119]		Used a simple laboratory optical components and the camera of a smartphone as a low-cost, portable device to measure pH in water.	The sensor presented reliable data for pH measurement.
Silva et al. [118]		Developed a smartphone camera and a microfluidic paper-based device (IPAD) to measure pH.	The device was able to measure pH between 4.7 and 12.

Alam, Clyne, and Deen [56], Wu et al. [55], and Simic et al. [58] developed pH sensors using the potentiometric method in different ways. Alam, Clyne, and Deen [56] used a special ink made of palladium (Pd) with the silver/silver-chloride electrode (Ag/AgCl) as a reference in a polyimide substrate. Wu et al. [55] used the ruthenium (Ru) redox to measure pH; compared to Pd, Ru has low contamination potential, easy preparation, and good chemical resistance. The authors were able to measure pH between 4.01 and 10.87 with an accuracy of 1.02%. Finally, Simic et al. [58] used titanium dioxide (TiO_2) as the

main film in the pH sensor, which was connected to an integrated circuit (using an AD5933 module) for online communication.

In the study by Hossain et al. [120], the authors used a multi-parametric sensor to assess water quality. For pH, a Photo-Induced Electron Transfer (PET) method was used with 4-aminonapthlimide as a dye for analysis. Regarding further photometric methods, Dutta, Sarma, and Nath [119] sought to perform analyses in colorless liquids, that is, without the use of dyes for analysis. The sensor uses the capture of the image spectrum and, through an optical preparation and consequent conversion into intensity and wavelength distribution, performs the pH measurement. Finally, Silva et al. [118] used a device based on the measurement of colorimetry using a smartphone camera and a microfluidic paper-based device (IPAD) to measure the pH of the samples. For the method, 3D printer supports were developed to ensure the stability of the device, in which the device was able to determine pH in the 4.7–12 range.

3.2.7. Phosphorus

Phosphorus is an essential nutrient used by plants and microorganisms, mainly for growth and energy transport, and it is a limiting element for primary production in terrestrial and aquatic ecosystems [121,122]. In the aquatic environment, phosphorus usually occurs in dissolved forms, such as orthophosphates, and organic phosphorus [123]. However, high concentrations of phosphorus in rivers and lakes can favor the proliferation of plankton and algae, accelerating eutrophication [124].

The determination of phosphorus in water depends on the type to be analyzed, such as dissolved, precipitated, associated, organic, or inorganic [125], with the main methodologies used being based on electrochemical sensors, such as potentiometry, voltammetry, and amperometry techniques [126], and in optical sensors [127]. Although the spectrophotometry technique is one of the most widely used for the detection of phosphorus [128], according to Berchmans, Issa, and Singh [126], the use of potentiometric systems offers a simple and low-cost instrumentation for monitoring phosphorus in the environment, clinical analysis, and remote sensing. However, electrochemical sensors can be influenced by several factors, such as temperature fluctuation and the presence of other substances (such as metals), hindering the results [129]. The following research presents the development of new technologies for measuring phosphorus in water, as summarized in Table 10.

Table 10. Summary of studies that present new alternative technologies for monitoring the phosphorus parameter in water.

Author(s)	Type	Description	Research Findings
Lin et al. [130]	Optical	Developed an automatic collector of water samples, called "Fish-Bite" to measure phosphorus in water.	The device was able to detect phosphorus up to 1.00 mg/L, with a lower detection limit of 0.01 mg/L.
Akhter et al. [131]	Electrical	Used multi-walled carbon nanotubes (MWCNTs) and Polydimethylsiloxane (PDMS) to detect phosphorus in water for agricultural use.	The sensor was able to measure phosphorus between 0.01 and 40 mg/L, with 95% accuracy.

Based on the colorimetry technique, Lin et al. [130] developed a sensor for the automatic monitoring of phosphate in situ, and at a low cost (US$200), through the use of an automatic collector of water samples, called "Fish-Bite", which contains multiple capsules of reagents for analysis. The equipment was developed to be used to monitor water intended for agriculture and is capable of measuring phosphate concentrations up to 1.00 mg/L, with a lower detection limit of 0.01 mg/L. Akhter et al. [131] were also able to determine phosphate in water for agricultural use, with concentrations between

0.01 and 40 mg/L and with 95% accuracy. The measurement technique is based on an electrochemical sensor, produced from multi-walled carbon nanotubes (MWCNTs) and Polydimethylsiloxane (PDMS), with the possibility of integration with smart devices (Internet of Things) for continuous monitoring.

3.2.8. Oxidation Reduction Potential (ORP)

The Oxidation Reduction Potential (ORP) is a measure of the molecular charge corresponding to the oxidation or reduction capacity of a substance and is an important indicator of water quality, capable of contributing to the understanding of variations in other parameters. For this reason, the ORP sensors are commonly coupled in multiparameter systems [132,133]. The development of new technologies to measure ORP in water are presented below, as well as in Table 11.

Table 11. Summary of studies that present new alternative technologies for monitoring the Oxidation Reduction Potential (ORP) parameter in water.

Author(s)	Type	Description	Research Findings
Qasem et al. [134]	Electrical	Built a remotely operated underwater vehicle with an ORP sensor.	The proposed hardware and software designs can monitor ORP in water.
Dejus et al. [135]		Used a commercial ORP sensor to monitor water quality.	Mahalanobis distance method with DW quality sensors has a good potential to be applied in warning systems (EWS).
Helmi, Hafiz and Rizam [136]		Developed a mobile buoy for water quality assessment, with the ORP parameter, operated remotely.	The device was able to measure the ORP parameter and transmit the water quality reading data in real-time.
Siyang and Kerdcharoen [137]		Described the development of a low-cost unmanned surface vehicle to monitor water quality.	The system has the capability to perform water quality assessment (including the ORP parameter) missions on inland water resources.
Khatri et al. [138]		Presented the development of a sustainable water quality monitoring system, with ORP as a parameter.	The developed system can be a suitable replacement for traditional water quality monitoring techniques, with which the ORP measure uncertainty was equal to 0.029.
Ilie et al. [139]		Developed a Smart Water kit connected to the internet for real-time water quality monitoring.	The developed system can be used in many environmental conditions, to give an idea about the state of the water in real-time.
Lee et al. [140]		Developed a microelectrode array for the in situ sensing of ORP.	The sensor developed exhibited a very fast response time and proved to be extraordinarily stable.
Jang et al. [141]			The sensor performance was equal to or more accurate than the commercial sensors.
Lin et al. [142]		Used micro-fabricated platinum electrodes to measure ORP in water.	The sensor was able to measure ORP from 150 to 800 mV.

In developing new techniques for monitoring ORP, Qasem et al. [134] built a remotely operated underwater vehicle containing ORP sensors, and sensors for three more parameters (electrical conductivity, dissolved oxygen, and temperature), to identify oil spills in ocean waters using Raspberry Pi 3 connected to the internet via Wi-Fi. Dejus et al. [135] also

used a system containing online ORP sensors and five more parameters to detect drinking water contamination events. For water quality control, Helmi, Hafiz, and Rizam [136] developed a surface water quality monitoring buoy with ORP, pH, and temperature sensors, also remotely controlled by an internet-connected computer that sends instructions to the Intel Atom N2600 board, which, in addition to the quality data, sends the physical location coordinates. Subsequently, Siyang and Kerdcharoen [137] innovated with a small, unmanned vehicle coupling an Arduino Uno with standard Wi-Fi, where ORP, Electrical Conductivity, Dissolved Oxygen, pH, and Temperature sensors were connected, whereupon the acquisition and transmission of data took place by XBee wireless communication directed to the control station and then to the database server on the internet. Similar system designs were studied by Khatri et al. [138] and Ilie et al. [139], who developed a low-cost drinking water quality monitoring station, with ORP as a parameter, for online and real-time monitoring using commercial sensors.

The systems described above refer to projects in the laboratory phase, not consolidated in the market, although the ORP sensors used are commercial probes for embedded systems. In contrast, due to the lack of low-cost, in situ devices for ORP measurement, Lee et al. [140] studied the fabrication of microelectrode sensor arrays (MEAs) for in situ ORP measurements using a chemical etching technique, where MEAs exhibited a substantially faster response time in the order of seconds rather than minutes, as compared to the commercial milli-electrodes. Jang et al. [141] also developed arrays of microelectrode sensors for ORP measurements, in an easier and more robust method, which presented readings equal to or more accurate than conventional ones. Finally, Lin et al. [142] were able to measure ORP, as well as pH, chloride, and conductivity, using microfabricated platinum electrodes deposited on a glass substrate as a sensor. The authors described that the sensor was able to measure ORP from 150 to 800 mV and, due to its simple fabrication, the sensor costs about US$0.10.

3.3. Technologies for Biological Monitoring of Water Quality

3.3.1. Algae and Cyanobacteria

The determination of algae and cyanobacteria in water can be conducted through numerous techniques, such as cell counting with the aid of an optical microscope or the analysis of indicator substances, such as chlorophylls [143]. Chlorophyll analysis is widespread because it is an active optical pigment capable of being determined by spectrophotometry, fluorimetry, and High-Performance Liquid Chromatography (HPLC) [35,144]. In addition, the analysis of such organisms can also be done remotely by observing different bands of satellite images [144] and by means of cytometry [145], which allows counting the number of cells. The following works present the development of new technologies for Algae and Cyanobacteria in water quality monitoring, as also summarized in Table 12.

Table 12. Summary of studies that present new alternative technologies for monitoring the algae and cyanobacteria parameters in water.

Author(s)	Type	Description	Research Findings
Lee et al. [146]	Electrical	Developed a portable, 3D-printed device with a smartphone and opto-electrowetting to measure algae in water.	The device offers a highly portable, user-friendly, low-cost tool that enables simple on-chip sample preparation and the detection of viable algae.
Saboe et al. [147]	Optical	Used a microbiological potentiometric sensor to measure algae in water by electrical signal patterns.	The very low NRMSE <3% for algal and chlorophyll concentrations demonstrated that these and similar biological parameters could be monitored in natural waters with extremely high precision.

Table 12. *Cont.*

Author(s)	Type	Description	Research Findings
Lee et al. [148]		Developed a device connected to a biological optical sensor for the diagnosis of algae growth in a water treatment plant.	The proposed system emulated a real-time water treatment plant for algae monitoring.
Izydorczyk et al. [149]		Presented an Algae Online Analyzer (AOA) system to monitor algae in water.	A positive correlation between cyanobacteria, as determined by conventional methods, was found ($p < 0.05$).
Zamydi et al. [150]		Used multi-parametric commercial probes to detect cyanobacteria using the fluorescence technique.	The analysis revealed significant correlations between the extracted Chl-a, extracted PC, and cyanobacterial biovolume and in vivo fluorescence parameters measured.
Beckler et al. [151]			The results demonstrated the potential for mapping unispecies of harmful algae using a Navocean autonomous sail vehicle (Nav2).
Naughton et al. [152]			The sensor allowed algae monitoring over 10 months, data from which can be used as a way to improve reservoir management.
Yamahara et al. [153]	Polymerase Chain Reaction	Designed an automatic sampler to detect harmful algae and fecal indicators in water using the qPCR technique.	The device showed good performance, with qPCR efficiencies ranging from 86% to 105%.

In algae analysis, several studies have sought to use new sensors and low-cost techniques to obtain in situ data with good accuracy. Lee et al. [146] developed a portable, 3D-printed device that uses a smartphone and utilizes opto-electrowetting (in the acronym OEW, being a method of manipulating liquid droplets used in microfluidic applications) for the determination of algae in freshwater (*C. reinhardtii* and *M. aeruginosa*) and seawater (*Amphiprora* sp. and *C. closterium*). Saboe et al. [147] studied the determination of algae using a microbiological potentiometric sensor, through the analysis of electrical signal patterns, as a means of diagnosing changes in water quality and the presence of algae in the aquatic environment. For this, the authors made use of machine learning to differentiate the sensor response under different conditions and in the presence of other contaminants, resulting in a linear relationship between the microbiological concentration of algae and the potentiometric signal of the sensor.

Using optical sensors, Lee et al. [148] developed a device connected to a biological optical sensor and an *ARM Cortex-M3* processor, with a wireless connection, for the diagnosis of algae growth in a water treatment plant, whose control and monitoring could be performed remotely. Izydorczyk et al. [149], in turn, were able to monitor cyanobacteria in a water supply reservoir, through chlorophyll analysis using a system called Algae Online Analyzer (AOA). The AOA device is composed of five light-emitting diodes (450, 525, 570, 590, and 610 nm), which, through the fluorescence technique, allow the determination and differentiation of algae from the *Chlorophyceae*, *Bacillariophyceae*, *Cyanophyceae*, and *Cryptophyceae* classes.

In the use of multiparametric probes, Zamydi et al. [150] detected cyanobacteria (*Phycocyanin* and *Chlorophylla*) in the Yamaska River Reservoir and Lake Champlain Bay, Canada, using the fluorescence technique and the *YSI 6600 V2–4* probe. Beckler et al. [151] were also able to monitor and map the algae bloom on the coast in an automated way

using a fluorometer sensor (*Cyclops Integrator/C3*) coupled to a remotely operated boat (*Navocean Nav2 ASV*). Naughton et al. [152] monitored microalgae on an aquaculture farm for 10 months using the *AlgaeTorch®* probe, in the Republic of Ireland, as a tool for monitoring seasonal changes in cultivation and for decision-making by producers.

Finally, Yamahara et al. [153] presented the integration of an automatic sampler that, through molecular analytical techniques, allows the in situ detection of fecal indicators (fecal coliforms) and harmful algae in surface waters. The equipment, called an Environmental Sampling Processor (ESP), is capable of measuring and issuing reports with a certain frequency and uses the qPCR (real-time Polymerase Chain Reaction) technique in chemical-biological analysis.

3.3.2. Total Coliforms and *Escherichia coli*

According to the American Public Health Association [91], the main methods for rapid coliform detection in water are based on radiometric, glutamate decarboxylase, electrochemical, gas chromatographic, colorimetric, and potentiometric techniques. The Membrane Filter Coliform Test, for example, is a method for coliform analysis that can detect 50–200 CFU in water samples in 24 h with the aid of a microscope [23]. The analysis of total coliforms and *E. coli* can also be done by the commercial tests *Colitag^TM and Colilert®* [154] and by the Multiple Fermentation Technique [155] with high performance and results between 24 and 48 h. The following research presents the development of alternative technologies for monitoring total coliforms and E. coli in water quality, as also shown in Table 13.

Table 13. Summary of studies that present new alternative technologies for monitoring the total coliforms and *Escherichia coli* parameter in water.

Author(s)	Type	Description	Research Findings
Simões and Dong [156]	Optical	Used a fluorescent optical sensor to monitor *E. coli* and *Legionella* in drinking water.	The equipment had a good performance, with a detection limit equal to 1.4×10^3 CFU/mL.
Bedell et al. [157]		Used a Tryptophan-Like Fluorescent (TLF) technique to monitor *E. coli* in drinking water.	The results showed a close correlation between TLF and *E. coli* in model waters and proof of principle with a sensitivity of 4 CFU/mL for *E. coli*.
Gunda et al. [158]		Developed the Mobile Water Kit (MWK) to detect microorganisms in water based on the colorimetric method.	The device was able to detect the total coliform and *E. coli* bacteria in water samples within 30 min or less.
Patil et al. [159]		Presented a quick screening and alerting of coliform and *E. coli* contamination in water samples using a device attached to a smartphone.	The system was able to measure coliforms and *E. coli* contamination and issued an alert when contamination was detected.
Tok et al. [160]		Presented a cost-effective and automated device to monitor coliforms and *E. coli* in water based on fluorescent techniques.	The system can automatically detect the presence of both *E. coli* and total coliforms in drinking water within ~16 h, down to a level of one colony-forming unit (CFU) per 100 mL.

Table 13. *Cont.*

Author(s)	Type	Description	Research Findings
Hausot and Angelescu [161]		Described the development of an Autonomous Microbiological Alert Sensor (AMAS) for bacterial monitoring in water based on colorimetric and fluorimetric techniques.	The sensor is able to quantify initial concentrations of pathogens present in each sample and alert operators in the case of high bacterial contamination.
Grossi et al. [162]	Electrical	Presented a portable sensor implemented as an electronic embedded system for microbial concentration assessment.	The system provides a much faster response than standard techniques and can be used for in situ microbial tests rather than taking samples to a laboratory for analysis.
Zhang et al. [163]		Developed an automatic electrical bacterial growth sensor (EBGS) based on a multichannel, capacitively coupled, contactless conductivity detector (C4D).	The sensor was able to detect the bacteria as much as the conventional online monitoring methods.

In the development of new methodologies for the detection of pathogens in water, Simões and Dong [156] were able to perform the continuous and real-time monitoring of *E. coli* and *Legionella* in drinking water distribution networks using a fluorescent optical sensor fluid (*Hamamatsu H17023*), at a low cost, and whose equipment had a detection limit equal to 1.4×10^3 CFU/mL. Bedell et al. [157], in turn, used the *Tryptophan-Like Fluorescent* (TLF) technique, with deep-ultraviolet light-emitting diodes (UV-LEDs), sensitive semiconductor photodiodes, and photomultipliers to detect the presence of *E. coli* with a sensitivity of 4 CFU/mL.

Based on the use of smartphones, Gunda et al. [158] and Patil et al. [159] were able to detect the presence of total coliforms and *E. coli* in water. The device developed by Gunda et al. [158], called the Mobile Water Kit (MWK), was able to detect such microorganisms in 30 min, using chemical reagents such as colorimetric/fluorescent sensors and a smartphone, which captures and analyzes the images obtained. The system developed by Patil et al. [159] is operated by a smartphone that captures images of a water sample contained in a chamber and, through an algorithm, analyzes the images to identify the growth of bacteria through the increase in turbidity and/or changes in the color. The system can issue an alert when contamination is detected.

Tok et al. [160] and Huynh, Hausot, and Angelescu [161] discussed in situ devices for sampling and the automatic testing of total coliforms and *E. coli*, with a low cost and high efficiency. The device developed by Tok et al. [160] is operated by a *Raspberry Pi* microcontroller and a camera that measures water absorption and fluorescence, through a blue LED and UV light, in 100 mL samples each 24 h. Huynh, Hausot, and Angelescu [161] presented the Autonomous Microbiological Alert Sensor (AMAS), whose bacterial presence is monitored using multispectral measurements (colorimetry and fluorimetry), and the data are transmitted wirelessly to a remote server.

Finally, Grossi et al. [162] and Zhang et al. [163] were able to detect bacterial growth (which may indicate the presence of *E. coli* and total coliforms) using electrical sensors. The system developed by Grossi et al. [162] is composed of two electronic boards—one to measure the electrical parameters and the other to control the temperature of the sample. It can be used for in situ analysis on different types of samples, with results between 3 and 12 h. On the other hand, Zhang et al. [163] used a capacitively coupled multichannel contactless conductivity detector (C4D) to detect bacterial growth in an apparent normalized relationship between conductivity and incubation time.

4. Conclusions

Monitoring water quality is an important water management tool, acting to control pollution and minimize impacts on the environment and human health. However, due to the high cost of monitoring, through the sampling process, sample preservation, transport, qualified professionals, and the use of expensive laboratory equipment, unfortunately, there is a lack of water quality data for the correct management of this resource. With the development of new technologies and the progress of nanotechnology and material sciences, integrated with the Internet of Things, it is possible to accelerate and minimize the costs of obtaining water quality data. In this review, several studies were described that presented the development of low-cost technologies, with in situ applications, that can accelerate the collection of data for the monitoring of physical, chemical, and biological parameters of the waters. It was also possible to observe that there was an increase in the number of publications related to the topic, mainly from 2012, with a total of 641 studies being published in 2021 alone. However, although many technologies presented have the potential for monitoring water quality, it is important to highlight that more robust analyses are necessary to guarantee its efficiency, such as equipment useful for life and interference from the environment, being indispensable with the help of standard methodologies at first. Moreover, it should be noted that reporting values for governmental regulatory purposes require that methods undergo exhaustive scrutiny with regard to accuracy and repeatability before being authorized for use.

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