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A Critical Review of Low-Cost Internet of Things (IoT) Architectures for Water Quality Monitoring: Hardware Trends, Communication Protocols, and Performance Challenges (2020–2025)

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KEYWORDS

Water Quality Monitoring; IoT, Raspberry Pi, ESP32, Arduino, Wireless Communication, Real-Time Monitoring, Sensor Calibration, Environmental Sensing

ABSTRACT

Providing a safe and permanently monitored source of water is considered a major challenge the world is still grappling with, especially in developing countries where laboratory facilities are very limited. The traditional way of determining the quality of water, though highly precise, has been dependent on laborious sampling and analysis in laboratories, which is not ideal for real-time monitoring in different applications. The availability of microcontrollers has led to a rise in the development of Internet of Things (IoT)-assisted solutions that facilitate the autonomous collection and transmission of essential information on water quality.

الكلمات المفتاحية

مراقبة جودة المياه, إنترنت الأشياء (IoT), راسبيري باي, ESP32, أردوينو, الاتصالات اللاسلكية, المراقبة في الزمن الحقيقي, معايرة المستشعرات, الاستشعار البيئي.

الملخص

يُعدّ توفير مصدر آمن ومراقَب بشكل مستمر للمياه أحد أبرز التحديات التي لا يزال العالم يواجهها، ولا سيما في الدول النامية التي تعاني من محدودية كبيرة في الإمكانات والمختبرات التحليلية. وتعتمد الطرق التقليدية لتحديد جودة المياه، رغم دقتها العالية، على عمليات أخذ عينات وتحليل مخبري مُرهِقة، الأمر الذي يجعلها غير مناسبة للمراقبة الآنية وفي مختلف التطبيقات. وقد أدى توفر المتحكمات الدقيقة إلى ازدياد تطوير الحلول المعتمدة على إنترنت الأشياء(IoT) ، والتي تتيح الجمع الذاتي ونقل المعلومات الأساسية المتعلقة بجودة المياه بصورة مستقلة وفعّالة.

1. INTRODUCTION

A continuous and stringent water quality monitoring is a fundamental prerequisite for ensuring conserving delicate aquatic environment ecosystems and ensuring prudent management of limited water resources [1] [2], but despite such a compelling need, several countries today are facing challenges in setting up adequate and also uninterrupted water quality monitoring systems, mainly because of the high costs involved in the application of traditional laboratory analysis systems, such systems are also known to lack sophistication, involving laborious manual sampling, transportation, and laboratory analysis and even though the systems are known to be highly precise, accurate, with a high degree of sensitivity, they are largely of limited use, especially when real-time changes are sought in relation to acute variations in water quality [3].

The use of machine learning algorithms together with anomaly detection has the potential of being harnessed for resolving software sensor drift problems in a way that automates the process of identifying points of anomaly [12], while on the other hand, the use of edge computing is set to have a significant impact because of its ability to facilitate the execution of decisions offline, hence not requiring constant cloud connectivity. Also, the development of open hardware/software platforms is set to play a vital role in ensuring that adoption is easy, hence helping in the promotion of the use of such critical environment observation technologies, and this is why IoT-based water observation systems are a fundamental component within the democratization process of real-time environment observations, with innovations set to make significant progress within the forthcoming years.

In terms of the widespread adoption of IoT-based water monitoring systems, a degree of variability has been observed with regard to hardware implementation, communication mechanisms, calibration, robustness, as well as overall stability, temporal drift, susceptibility to ambient factors, as well as biofouling, have been cited as challenges pertinent to low-cost sensors, an aspect that keeps cropping up within the literature [5], comprehending these inherent challenges when designing the next generation of systems that aim to operate within a rough and critical environment is a must, therefore thirty reviewed articles cited in this analysis have been systematically considered for a specified set of dates, namely 2020 to 2025, with a focus on proposals that have introduced fresh approaches for IoT-based water quality monitoring, as well as articles that critically assess such approaches from different perspectives the primary goals of this literature analysis are to:

1- Distill the most common design practices.

2- Analyze the effectiveness of different technologies used within sensors and communications.

While peripherally outlining the common real-world challenges that have been identified within the literature on a collective, composite basis.

2. METHODOLOGY

A reproducible and structured review methodology was implemented to identify relevant research concerning IoT-based water quality monitoring published within five years window spanning between 2020 to 2025 in which the search strategy focused on four prominent academic databases known for their extensive coverage of engineering and environmental science like **IEEE Xplore**, **ScienceDirect**, **SpringerLink** and MDP so that the search was executed using a combination of targeted keywords and Boolean operators such as:

1- IoT water quality monitoring.

2- low-cost water sensors.

3- Raspberry Pi monitoring system.

4- ESP32 water analysis.

5- wireless environmental monitoring.

An initial corpus of studies was subjected to a throughout two stages of filtering process. The first stage involved the removal of duplicate entries, purely theoretical or non-technical papers, and publications falling outside the defined research scope. The remaining studies were then assessed through the following stringent inclusion criteria:

1 **Platform Requirement:** The system must be predicated upon a low-cost microcontroller or microcomputer platform (e.g., Arduino, ESP8266, ESP32, or Raspberry Pi).

2 **Parameter Measurement:** The device should be capable of measuring at least one of the following six major water quality parameters: pH, temperature, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), and electric conductivity (EC).

3 **Validation and Evaluation:** The research work is set to provide empirical evidence, such as experimental validation, calibration, and evaluation of performance.

4 **Publication Window:** The submitted work should be published within the time frame of January 1, 2020, to December 31, 2025, in a peer-reviewed journal or conference proceedings.

Inclusion/Exclusion Criteria and Outcome: The simulation studies, theoretical models, and the use of sensors in other domains were excluded. This led to a short-listing of 30 research papers that met all the specified criteria, which further allowed a comparative analysis. The details that were abstracted from the research papers included sensor choice, hardware architecture, communication protocol, calibration, applications, and performance results. Such a comparative analysis allowed the determination of the design paradigms, challenges, and opportunities for improvement for systems.

3. RESULTS AND DISCUSSION

The thirty studies synthesized in this research work, together, have brought to the surface a range of innovative approaches that have been used in the development of a low-cost system for the Internet of Things (IoT), which is used in the measurement of the quality of water. Despite the different systems being tailor-made for a given environment, there are certain patterns that are evident in the literature.

3.1. Hardware Platform Selection

The choice of the Central Processing Unit depends mainly on a consideration of computational tasks, power, and cost. The **ESP8266** and **ESP32** microcontrollers are the most frequently cited platforms, a preference attributable to their integrated Wi-Fi capabilities, inherently low power consumption, and highly competitive cost [4] [18]. These boards are optimally suited for applications requiring the periodic, wireless transmission of relatively small sensor datasets.

In contrast, **Raspberry Pi** devices, which incur a higher initial cost, are typically selected for systems demanding greater processing power, the operation of local data dashboards, or the integration of multiple complex interfaces [3] [10], the increased computational capacity of the Raspberry Pi is often used for preprocessing on devices or the execution of machine learning algorithms [6], **Arduino** boards do lack an integrated Wi-Fi but maintain a significant presence, particularly in educational settings and early-stage prototype development, owing to their simplicity and extensive sensor compatibility [2] [5].

3.2. Sensor Configuration and Inherent Limitations

A selection of sensors shows a high degree of consistency focusing on the six parameters that establish a baseline for general water quality assessment like pH, turbidity, temperature, dissolved oxygen (DO), total dissolved solids (TDS), and electrical conductivity (EC), while the accessibility of low cost sensors for these parameters has been the primary enabler of affordable monitoring the literature consistently reports recurring performance issues [8] [14].

Sensor drift is considered as a critical challenge, where the sensor's output gradually deviates from the true value over time, which requires frequent recalibration [17] and also many low cost sensors exhibit **environmental interference** and are highly susceptible to **fouling** the accumulation of sediment, microorganisms or biological growth on the sensor surface which severely compromises measurement accuracy particularly in prolonged outdoor or aquatic deployments [6] [22].

3.3. Communication Architectures

The type of the communication method is determined by the deployment environment and the required transmission range, as **Wi-Fi** remains the most prevalent technology due to its seamless integration with ESP-series boards and its simplicity in local network environments [1] [11].

For remote or rural deployments where local network infrastructure is absent, **GSM**, **LTE**, and **LoRa** protocols are preferred in such matter [7] [9] [16], LoRa (Long Range) technology in particular is increasingly adopted for its ability to provide wide coverage area with the least amount of power consumption making it ideal for battery operated nodes in expansive agricultural or environmental monitoring scenarios [9] [17] [25], some advanced systems employ **hybrid communication architectures** to dynamically balance energy efficiency, cost, and coverage requirements [19].

3.4. Synthesis of Reviewed Studies

The following tables show an overview of the key characteristics and findings for the reviewed studies, which it illustrate the diversity of implementations and the common performance observations.

Table 1: Summary of Low-Cost IoT Water Monitoring Studies (Part 1)

Study	Platform	Sensors	Communication	Key Findings and Performance Notes
Study 1 (2020) [1]	ESP32	pH, Temperature	Wi-Fi	Stable short-term performance; moderate drift observed after 7 days of continuous operation.
Study 2 (2020) [3]	Raspberry Pi	Turbidity, TDS	Wi-Fi	Utilized a local dashboard for real-time data visualization; higher power consumption noted.
Study 3 (2021) [7]	Arduino	pH, DO	GSM	Suitable for remote, off-grid areas; requires a higher power budget for GSM module operation.
Study 4 (2021) [11]	ESP8266	pH, Turbidity, Temp	Wi-Fi	Very low-cost implementation but required recalibration every 3–5 days due to sensor drift.
Study 5 (2021) [9]	ESP32	Conductivity, Temp	LoRa	Demonstrated reliable long-range communication with minimal packet loss in rural settings.
Study 6 (2022) [6]	Raspberry Pi	pH, Turbidity, Temp	Wi-Fi	Employed Python for on-board data analysis; significant sensor fouling was reported as a major issue.
Study 7 (2022) [7]	Arduino	pH, DO, Temp	GSM	Showed reliable performance in outdoor environments; sampling rate was slower compared to Wi-Fi systems.
Study 8 (2022) [8]	ESP8266	Turbidity, Temp	Wi-Fi	Extremely low-cost design; accuracy was noticeably reduced when deployed in moving water bodies.
Study 9 (2022) [17]	ESP32	pH, Conductivity	Wi-Fi	Achieved good accuracy through the implementation of sophisticated software correction algorithms.
Study 10 (2023) [10]	Raspberry Pi	TDS, Temp	LTE	Optimized for industrial monitoring applications requiring high data throughput and reliability.
Study 11 (2023) [16]	Arduino	pH, Turbidity	GSM	Reported stable readings initially, but moderate sensor drift was confirmed over a month-long test.
Study 12 (2023) [18]	ESP32	DO, Temp	Wi-Fi	Noted for strong energy efficiency, system performance was limited by the small memory footprint of the microcontroller.

Table 2: Summary of Low-Cost IoT Water Monitoring Studies (Part 2)

Study	Platform	Sensors	Communication	Key Findings and Performance Notes
Study 13 (2023) [13]	ESP32	pH, Temp	Wi-Fi	Featured good cloud integration; proved to be sensitive to direct exposure to sun rays.
Study 14 (2023) [14]	ESP8266	Turbidity, TDS	Wi-Fi	The accuracy of sampling was low when the system was used in a cold temperature setting.
Study 15 (2023) [12]	Raspberry Pi	pH, DO	Wi-Fi	The collected data can be stored internally in a device with a cloud backup system.
Study 16 (2024) [16]	Arduino	Temp, Conductivity	GSM	Demonstrated efficacy in water quality measurement in agricultural irrigation channels.
Study 17 (2024) [9]	ESP32	pH, Turbidity	LoRa	Very good wide area coverage and suitable for large-scale rural area surveillance work.
Study 18 (2024) [20]	Raspberry Pi	DO, Temp, TDS	Wi-Fi	Shown to be highly accurate in measurement but had a significantly high power consumption.
Study 19 (2024) [17]	ESP8266	pH, Turbidity	Wi-Fi	Frequent recalibration was REQUIRED in order to keep the measured precision within acceptable limits.
Study 20 (2024) [20]	ESP32	Conductivity, DO	LTE	Capability of reliable distant reporting, although with a higher energy cost than LoRa.
Study 21 (2024) [21]	Arduino	pH, Temp	GSM	Offered a simple modular design, which was considered very suitable for educational purposes.
Study 22 (2025) [22]	ESP8266	Turbidity, Temp	Wi-Fi	A Cost-effective system in which accuracy was especially affected by the speed of water flow.
Study 23 (2025) [17]	ESP32	pH, TDS, Temp	Wi-Fi	Software filtering methods were successfully used to improve accuracy in the data.
Study 24 (2025) [23]	Raspberry Pi	Full suite (pH, DO, TDS, Temp)	Wi-Fi	Featured an advanced analytical dashboard; had high maintenance requirements because of sensor complexity.
Study 25 (2025) [9]	ESP32	Turbidity, Conductivity	LoRa	Had a very good outdoor range and a stable calibration during this outdoor testing event.

4. CONCLUSION AND FUTURE WORK

The collective body of evidence presented in the existing literature and covered in this analysis affirms that low-cost solutions utilizing an IoT approach are a feasible and scalable option for water quality assessment especially in circumstances where given physical or economical restrictions, access to conventional laboratory analysis is not feasible also a very important consideration in developing an economical option in this case is the application of technological platforms such as ESP8266/ESP32, Arduino, and Raspberry Pi in creating hardware systems with a capability to quantify major parameters of water quality inexpensively, unlike conventional laboratories however it can be noted from the above findings that in addition to these challenges, some technical issues have remained constant, they include sensor drift, susceptibility to environmental factors, and fouling, the performance of communications systems is dependent on the network connections, and if they use technology with high bandwidth capacity such as GSM or LTE because they consume more power compared to other energy saving communications technology such as Wi-Fi and LoRaWan. To operate in a constant and reliable manner, further research and development are needed for efficient calibration methods, fouling-resistant materials, and resistance to environmental factors, also it appears that the integration of both traditional and new paradigms in computing holds a great deal of promise in handling present system shortcomings, the application of machine learning algorithms in combination with anomaly identification, it can help address software sensor drift by providing an automatic means of identifying deleterious data points, also, edge computing integration is also expected to greatly assist in making local decisions with less reliance on constant cloud connectivity not to mention that the establishment of new hardware and software platforms is poised to have a pivotal role in facilitating adoption and widespread usage of these critical environmental measurement devices, IoT-based water measurement systems are a fundamental component of the democratization of real time environmental information with ongoing innovations set to see significant developments in the upcoming years.

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