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IoT-based drinking water quality measurement: systematic literature review

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ABSTRACT

Sustainable development throughout the world depends on several factors such as the economy, quality education, agriculture, industry, among others, but the environment is one of the most important. Industrialization and new land use plans have caused the proliferation of pollutants in water resources, which poses a serious public challenge. As outlined in the sustainable development goals (SDGs), innovative water quality monitoring methods are needed to ensure access to water, sustainable management and sanitation. In this sense, technologies are sought that contribute to the development and implementation of groundwater and surface water quality monitoring systems in real time, so that their parameters can be evaluated through descriptive analysis, in rural populations and areas of difficult access. Nowadays, the internet of things (IoT) and the development of modern sensors are more used, so this research reviews the latest technologies to monitor and evaluate water quality using the potential and possibilities of the IoT. The main contribution of this article is to present an overview of the state of the art of IoT applications and instrumentation for water quality monitoring, focusing on the latest innovations, in order to identify interesting and challenging areas that can be explored in future research.

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1. INTRODUCTION

The World Economic Forum considers the drinking water crisis as one of the global risks, because every day, about 200 children die from this situation. The consumption of non-potable water has caused, by itself, 3.4 million deaths in one year [1]. People's satisfaction with water may be one of the main variables related to welfare control, but the lack of factors that guarantee the quality and quantity of water leads to diseases that surround families and animals. Currently, international organizations such as the United Nations (UN), the World Health Organization (WHO), the World Bank (IBRD), the World Food Council (WFC), the Food and Agriculture Organization of the United Nations (FAO), among others, they have highlighted the need to guarantee a sufficient quantity and quality of water for sanitation and other basic purposes [2]. A clear example of the importance of water is how it has become a basic requirement of the COVID-19 virus infection, but unfortunately in Colombia many people still do not have access to water in informal settlements or marginal urban and rural areas [3]. UN experts say that without access to clean water for people living in vulnerable areas, COVID-19 will not go away [4], therefore, being able to monitor and guarantee their access contributes to the development of populations. According to data from the World Health Organization (WHO), one third of the people in the world do not have access to drinking water services, and two fifths of homes need basic infrastructure to wash their hands [5].

Monitoring water quality is a priority today due to global warming, shrinking water resources, and population growth, among other reasons. In the process of analysis and control of water quality, conventional monitoring measures are no longer a sufficient strategy to ensure its quality, since data collection requires different processes, equipment and trained personnel. The measurement of all the parameters to guarantee the ability to have safe water for human consumption is a complex task in rural and/or hard-to-reach areas, because it requires access to specialized laboratory equipment in areas such as microbiology, chemistry and radiology [6]. Therefore, it is necessary to develop better methods to monitor water quality parameters in real time.

The design and implementation of an intelligent system that enables the measurement of water quality parameters in remote places requires that important operating conditions be considered, such as: precision, environmental conditions (temperature/humidity limits), range (measurement limits), calibration (indispensable for most cases), decision-making capacity (largest increase detected by the meter), cost, and repeatability (changing readings are measured repeatedly in the same environment). The main contributions of this work are the following: a review of the techniques used to estimate parameters and water quality, and future methods of technology in this field. The document begins by briefly describing water quality assessment, following a review of work related to water quality measurement, a discussion of the findings, conclusions, and reference materials.

2. MATERIALS AND METHODS

The methodology for the systematic review of the literature (SRL) was used, which divides the process into four stages [7]: i) identifying the need for the review, ii) defining a review protocol, iii) conducting the review, and iv) developing an analysis of the review. In step i), the objective is to determine why a new SRL is needed in the domain. In stage ii) the data collection process is configured. To do this, the questions and search strategies that guide the investigation are specified; the criteria for the inclusion or exclusion of documents, the evaluation of the relevance and quality of the documents; and finally, queries are made from academic data sources. In step iii), each document is reviewed in detail to determine if it answers the research questions. Documents that do not meet the expected characteristics are discarded. In the final stage iv), a global analysis is performed for each research question.

2.1. Identification of the need for review

The selection of original articles from the last five years in English is included as a criterion, from the categories that the search string contains: "Monitoring water", "water quality", "IoT", "sensors" and "real time". In the bibliographic databases Scopus, ScienceDirect, PubMed Central, IEEE Explore and Springer. Topics corresponding to: estimation of pollution indices, distribution and consumption of water, prediction of flows and different uses of water for human consumption were not considered.

2.2. Definition of a review protocol

The review protocol for the aforementioned search string was developed based on guidelines for the SRL [8]. Where the works found in the bibliographic databases were imported to the Mendeley reference manager and duplicates were eliminated, giving as a product 4,170 articles selected in this investigation. As can be seen in Figures 1 and 2, there are various investigations that seek to comprehensively protect the environment, water quality monitoring methods are implemented for various applications such as aquaculture, drinking water for human consumption, monitoring of water quality of rivers and lakes, wastewater monitoring, environmental monitoring, among others.

2.3. Developing a review analysis

To identify and visualize the thematic groups taken from Scopus, ScienceDirect, PubMed Central, IEEE Explore and Springer, the frequency of occurrences and co-occurrences of the search string used is calculated. It is found that this exploration produced a considerable number of results, many of which were repeated or insufficiently useful for the review, but provided a global perspective of the breadth of the topic (see Figures 1 and 2). The steps taken to purge and make a suitable selection of the research articles of this SRL are shown in Figure 3. Existing studies based on new technologies focused on monitoring the quality of drinking water are considered, written studies are not taken into account. other than the English language, nor studies aimed at improving the quality of drinking water that do not include or specify monitoring and control factors, nor are articles that are not publications research results included. Figure 4 shows the bibliometric map of the selected final articles.

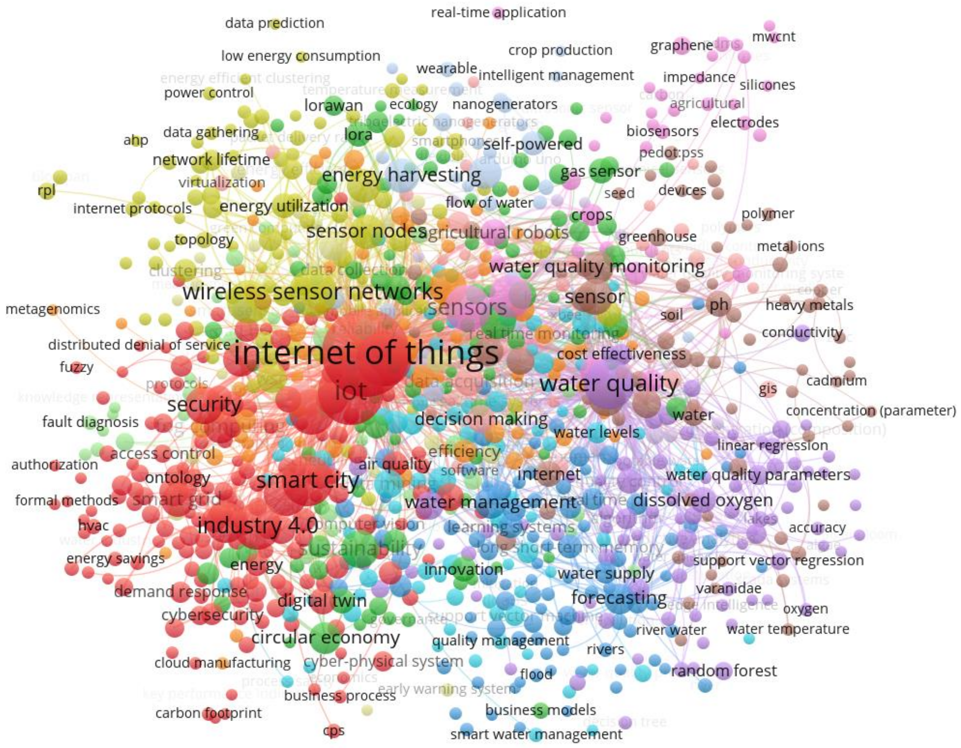

Figure 1. Bibliometric map needs for revision

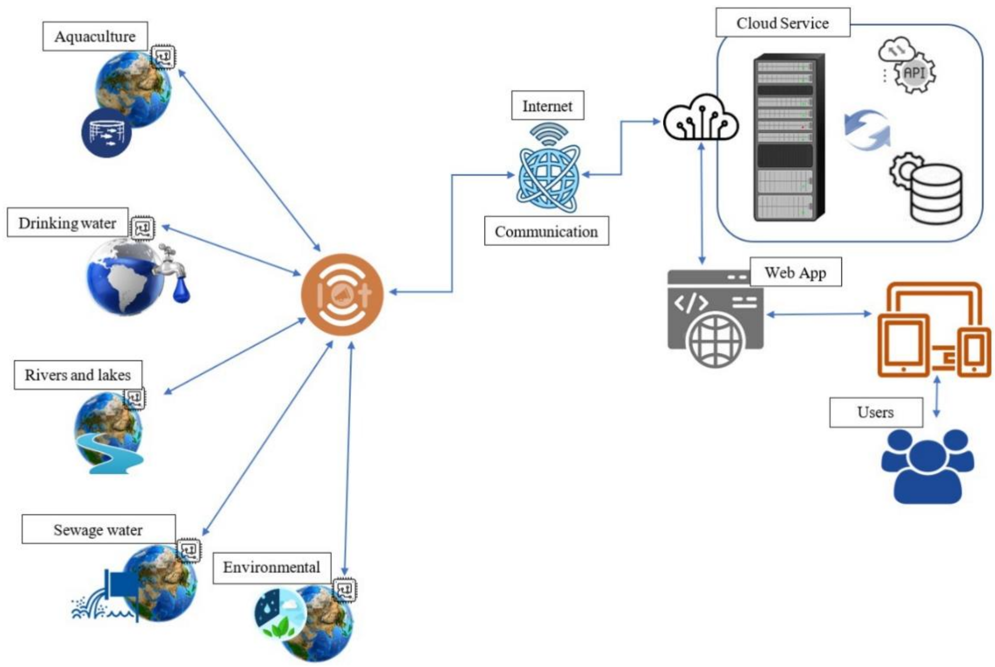

Figure 2. Different implementations of internet of things (IoT)-based water pollution monitoring systems

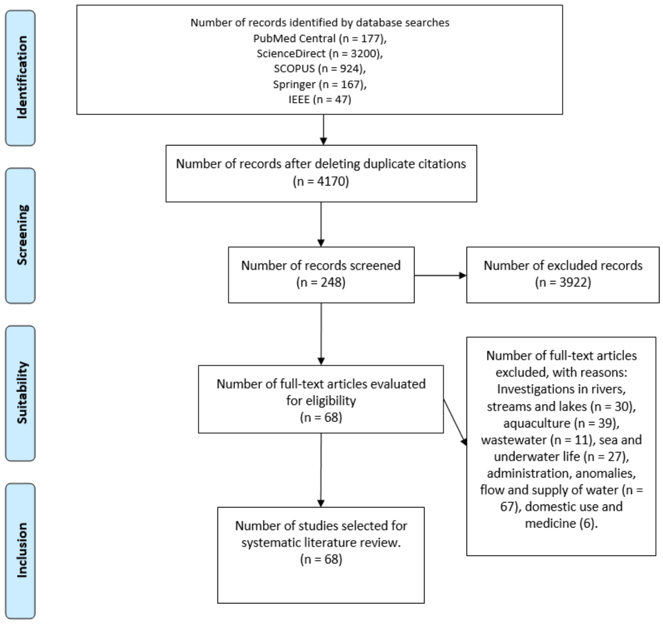

Figure 3. PRISMA flow diagram at four levels

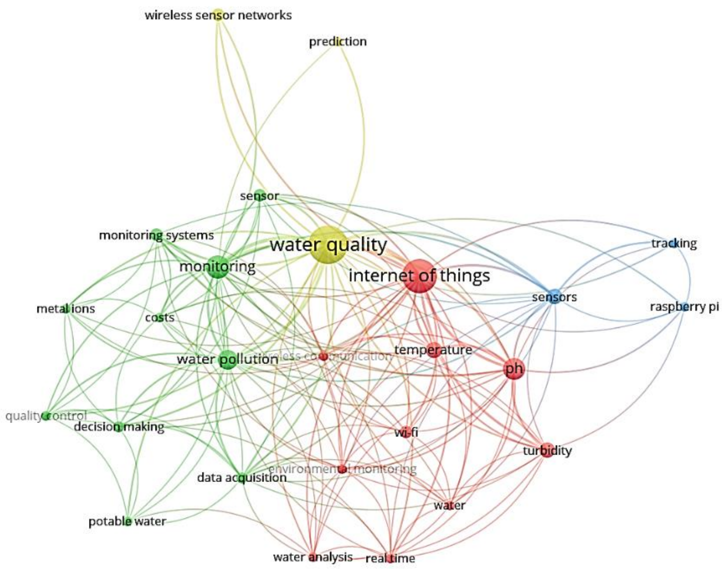

Figure 4. PRISMA selection bibliometric map

3. RESULTS AND DISCUSSION

A total of 68 documents were retrieved corresponding to the period 2016-2021, of which a total of 26 keywords were acquired with a frequency ≥ 3 (see Table 1). After applying the clustering algorithm, with a resolution parameter equal to 3, 4 thematic groups or clusters were created, showing the degree of similarity of the keywords (see Table 2). The thematic groupings obtained are visualized through a density bibliometric map as shown in Figure 5.

Figure 6 shows the evolution of the number of publications and citations of the 68 documents from 2016 to 2021. The number of citations has increased significantly, reaching a figure of 420 in 2021. It is also possible to see that the number of citations is higher than the number of publications per year (excluding the year 2021, which reflects a greater number of publications than citations). Of the 68 documents found, 28 (41.2%) have no citations and 25 (36.8%) have between one and five citations. Tables 3 and 4 list the 15

(22%) articles with the most citations (with more than 10 citations in Table 3, and with more than 5 citations in Table 4. The criteria of the 68 documents are those with more of 5 citations).

Table 1. Sample of the 26 keywords with the highest number of frequencies

Keyword	Absolute frequency	Relative frequency	Percentage
Costs	3	0.0141	1.41%
Data acquisition	4	0.0188	1.88%
Decision making	4	0.0188	1.88%
Environmental monitoring	3	0.0141	1.41%
Internet of things	36	0.1690	16.90%
Metal ions	3	0.0141	1.41%
Monitoring	17	0.0798	7.98%
Monitoring systems	5	0.0235	2.35%
pH	15	0.0704	7.04%
Portable water	3	0.0141	1.41%
Prediction	5	0.0235	2.35%
Quality control	3	0.0141	1.41%
Raspberry Pi	3	0.0141	1.41%
Real Time	3	0.0141	1.41%
Sensor	5	0.0235	2.35%
Sensors	7	0.0329	3.29%
Temperature	8	0.0376	3.76%
Tracking	3	0.0141	1.41%
Turbidity	7	0.0329	3.29%
Water	3	0.0141	1.41%
Water analysis	3	0.0141	1.41%
Water pollution	12	0.0563	5.63%
Water quality	45	0.2113	21.13%
Wi-Fi	5	0.0235	2.35%
Wireless communication	3	0.0141	1.41%
Wireless sensor networks	5	0.0235	2.35%

Table 2. Clusters and keywords with the highest weight of similarity

Cluster No.	No. Items	Keywords with greater weight or similarity index
Cluster 1	10	Environmental monitoring, internet of things, pH, real time, temperature, turbidity, water, water analysis, Wi-Fi and Wireless communication
Cluster 2	10	Costs, data acquisition, decision making, metal ions, monitoring, monitoring systems, potable water, quality control, sensor and water pollution
Cluster 3	3	Raspberry Pi, sensors and tracking
Cluster 4	3	Prediction, water quality and Wireless sensor networks

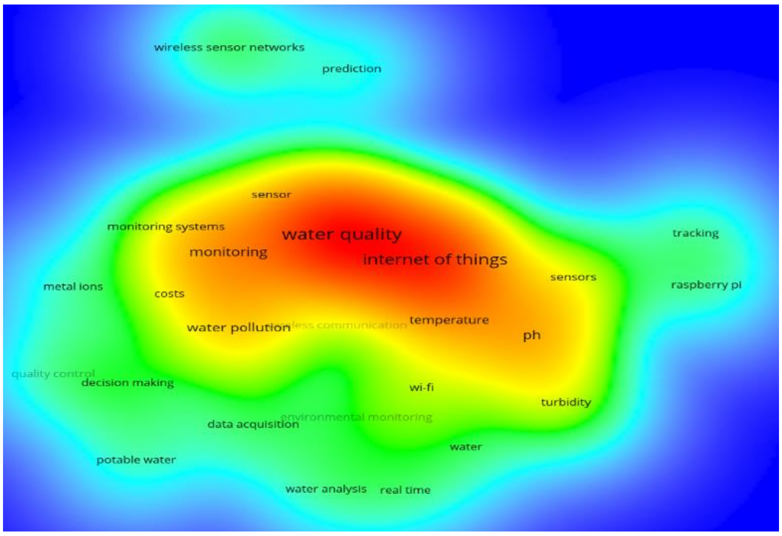

Figure 5. Bibliometric density map representing 26 analyzed keywords (colors closest to red indicate areas with the highest co-occurrence of keywords, colors close to yellow and green indicate areas with the lowest co-occurrences of words key)

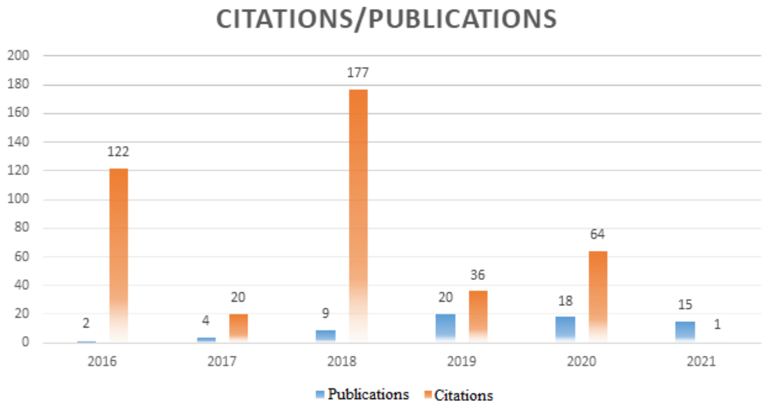

Figure 6. Total publications and citations per year

Table 3. List of papers with more than 10 citations

Year	Publication	Citations	Monitored parameters
2016	Internet of things enabled real time water quality monitoring system [9].	64	Turbidity, electrical conductivity, water level, pH.
2016	Real-time environmental sensor data: An application to water quality using web services [10].	58	Temperature, electrical conductivity, pressure transducer.
2018	Nanosensors for water quality monitoring [11].	56	Nanosensors in laboratory.
2018	Real-time water quality monitoring using internet of things in SCADA [12].	50	Temperature, flow, turbidity, pH, water level.
2018	Imprinted polymer coated impedimetric nitrate sensor for real- time water quality monitoring [13].	28	Nitrate-nitrogen.
2018	A compact ultrawideband antenna based on hexagonal split-ring resonator for pH sensor application [14].	16	pH.
2020	A self-powered wireless water quality sensing network enabling smart monitoring of biological and chemical stability in supply systems [15].	12	Temperature, electrical conductivity, pH, water pressure, water level and the thickness of the sludge that is deposited on the inside surface of the pipe.
2020	Smart water quality monitoring system with cost-effective using IoT [16].	11	pH, turbidity, temperature and humidity.

Table 4. List of papers with more than 5 citations

Year	Publication	Citations	Monitored parameters
2018	An Unpowered Sensor Node for Real-Time Water Quality Assessment (Humic Acid Detection) [17].	9	Humic acid (organic matter)
2018	Online measurement of water quality and reporting system using prominent rule controller based on aqua care-IOT [18].	9	Temperature, pH, turbidity, electrical conductivity
2020	A water quality prediction method based on the multi-time scale bidirectional long short-term memory network [19].	8	pH, dissolved oxygen, chemical oxygen demand (CODMn), ammonia nitrogen (NH3-N), temperature, atmospheric pressure, humidity
2017	Development of the MOOSY4 eNose IoT for Sulphur-Based VOC Water Pollution Detection [20].	8	Metal oxide gas sensors
2018	Internet of Things (Iot) Based smart water quality monitoring system [21].	8	pH, CO2, water level and temperature
2019	Evaluating IoT based passive water catchment monitoring system data acquisition and analysis [22].	6	Temperature, light intensity sensor, pH, GPS, and Inertial Motion Unit (IMU)
2020	Intelligent wide-area water quality monitoring and analysis system exploiting unmanned surface vehicles and ensemble learning [23].	6	pH, turbidity and total dissolved solids (TDS)

Tables 3 and 4 present related works that use the meters available on the market [24] to measure parameters in the IoT ecosystem and specifically for water quality, the following can be listed: ultrasonic sensor, temperature sensor, conductivity, turbidity, dissolved oxygen, oxidation reduction potential and power of hydrogen (pH) sensor. Currently, there are a variety of technologies that can be used in the design and development of IoT systems. On the one hand, there are many open source platforms for IoT development, such as Particle.io, Raspberry Pi, ESP8266, and Beagle Bone [25], [26]. These platforms support short-range communication technologies (such as Bluetooth and wireless fidelity (Wi-Fi)) and also support remote control (such as general packet radio service (GPRS), universal mobile telecommunications service (UMTS), 3G/4G/5G, and long range (LoRa)), which is an effective method. The communication and processing architecture, on which the investigations presented in Tables 3 and 4 are based, can be divided into three elements: microcontrollers, meters and communications as presented in Figure 7.

The development of smart solutions for monitoring water quality using the latest technologies that provide access to data in real time (see Figure 7), requires a portable, modular, extensible and easy-to-use architecture design. For the IoT environment to work, the different devices must be able to communicate. To do this, the following aspects can be considered in terms of IoT connectivity: bandwidth capacity (speed), coverage range and energy consumption. It can be difficult to find an option that prioritizes these three factors [27]. Next, Table 5 presents the main means for connecting IoT devices used, referring to their pros and cons to understand what are the requirements to take into account in specific solutions using IoT.

Regarding the microcontrollers, which have the important task of reading and processing the data obtained by the meters, there are several alternatives [28], Table 6 shows devices that have at least: analog inputs, digital inputs, Wi-Fi connection or the possibility of expansion through shields, it is also possible to find boards such as the Raspberry Pi that do not have analog inputs, which would require use external ADCs (analog-to-digital converters).

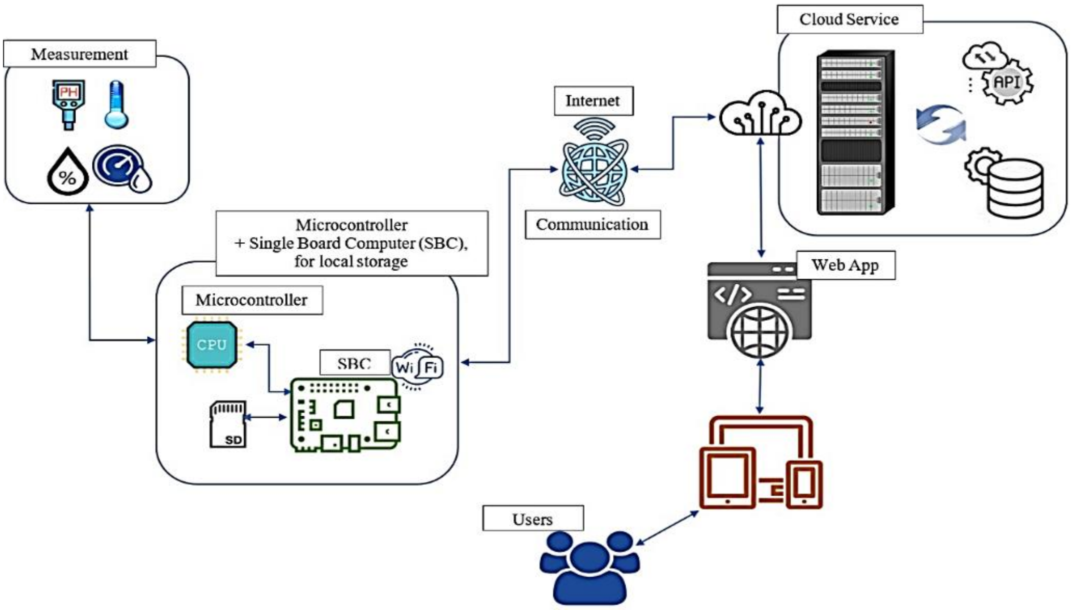

Figure 7. Configuration of IoT measurement devices, communication and data storage

Table 5. Types of IoT connectivity

Characteristic	Wi-Fi	4G	Bluetooth	Ethernet	NB-IoT	LoRa
Bandwidth	High	High	Half	Very high	Low	Very low
Performance	54 Mbps-1.3 Gbps	> 1Mbps	125 Kbps-2 Mbps	10 Mbps-10 Gbps	> 200 Kbps	10-50 Kbps
Network reach	Local area	Extended area	Personal area	Local area	Extended area	Extended area
Connection type	Wireless	Wireless	Wireless	Wired	Wireless	Wireless
Infrastructure	Need Wi-Fi access point	Need 4G networks	Bluetooth network	Wired network	Requires low-power wide-area networking (LPWAN)	Requires low-power wide-area networking (LPWAN)
Scalability	High	Half	High	Low	Very high	High
Flexibility and mobility	Half	High	Half	Low	Very high	High
Maturity/Compatibility	High Very high	High Half	High Half	High Half	High Half	High Half

Table 6. Comparison of microcontrollers

Characteristic	Arduino Uno	ESP32	Raspberry Pi B+	Particle.io Argon	Teensy 4.1	Beaglebone
Processor	ATmega328P (32 bit)	Xtensa LX6 (32 bit)	Cortex-A72 (64 bit)	ARM Cortex-M4F (32 bit)	ARM Cortex M7 (64 bit)	ARM Cortex-A8 (32 bit)
Memory	32KB Flash + 2KB SRAM	520 KB SRAM	1 GB, 2 GB, 4 GB or 8 GB (shared with the GPU)	1MB flash and 256KB RAM	1 MB	512Mb or 1 GB RAM + 4GB eMMC + MicroSD
A/D inputs	6 analogical/14 digital (6 PWM)	12 analogical/24 digital (16 PWM)	14 analogical/26 digital (15 PWM)	6 analogical/14 digital (8 PWM)	18 analogical/32 digital (35 PWM)	7 analogical/65 digital (8 PWM)
Interfaces	UART, I2C, SPI	UART, I2C, SPI, I2S	UART, I2C, SPI	UART, I2C, SPI	UART, I2C, SPI	UART, GPMC, SPI, I2C
Connectivity	No. (Wi-Fi via shield)	Wi-Fi	Wi-Fi + Ethernet	Wi-Fi	No. (Wi-Fi via shield)	Ethernet

For the most part, the different proposals for microcontrollers are quite similar, they are based on the same hardware, however, there are two alternatives that stand out from the rest, either because of the power of their processor, because they can work with operating systems based on Linux, they have Wi-Fi connectivity, which allows the use of wireless sensor networks (WSN) solutions and in other cases they require an additional module. It is really interesting that these boards include the integrated Wi-Fi module, it is an advance for automation engineers who would not implement radio frequency (RF), it simplifies the design of IoT devices for data capture and they would not have to certify the wireless receiver.

The 68 selected documents show that in several countries (India, the Netherlands, the United Kingdom, China, the United States, among others) studies related to IoT-based water quality monitoring have been carried out and published. The Sankey diagram of Figures 8 and 9 shows that the topics that represent the greatest interest are: IoT, water quality and monitoring (according to the data obtained in Tables 1 and 2) in the production of documents focused on these topics, especially in IoT, Figure 10 shows the relationship between the country of origin of the research and the country of publication. In this sense, India is one of the countries with the greatest interest, the excess of arsenic, fluorides and heavy metals contaminate groundwater in this country that depends on this source for 80% of its domestic water supply [29]. Climate change is making things worse. Unusual weather conditions and drought mean that groundwater in agriculture and domestic use is not always replenished. Rising sea levels have polluted fresh water with salt water, making it undrinkable [30]. An example of this is how about 1.700 kilometers from Barswa, the residents of Mangamari Peta in the Bay of Bengal saw the Indian Ocean rise around them and infiltrate the groundwater [31]. The bottled water market increased by 184% between 2012 and 2017 [32]. The Indian government has committed to ensuring that every household in the country has access to clean drinking water by 2022 [33], but it is a problem that is currently becoming more acute with the appearance of COVID-19 and its high impact in India [34].

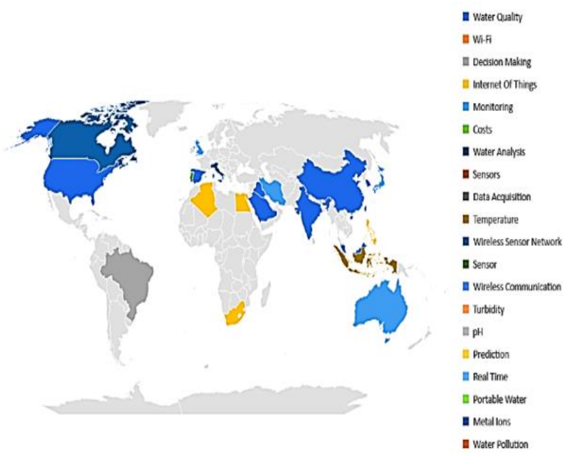

Figure 8. Keywords by country of origin of publication

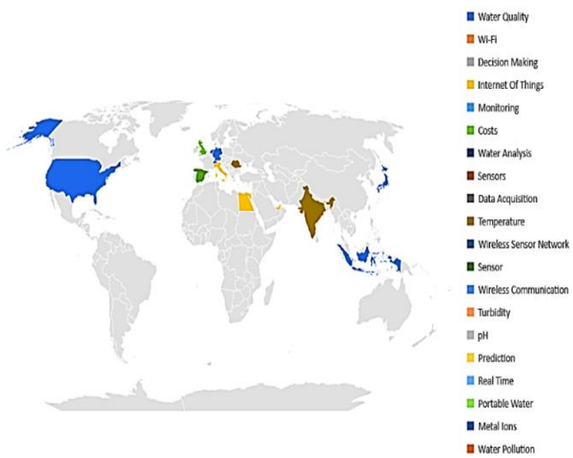

Figure 9. Keywords by country of publication

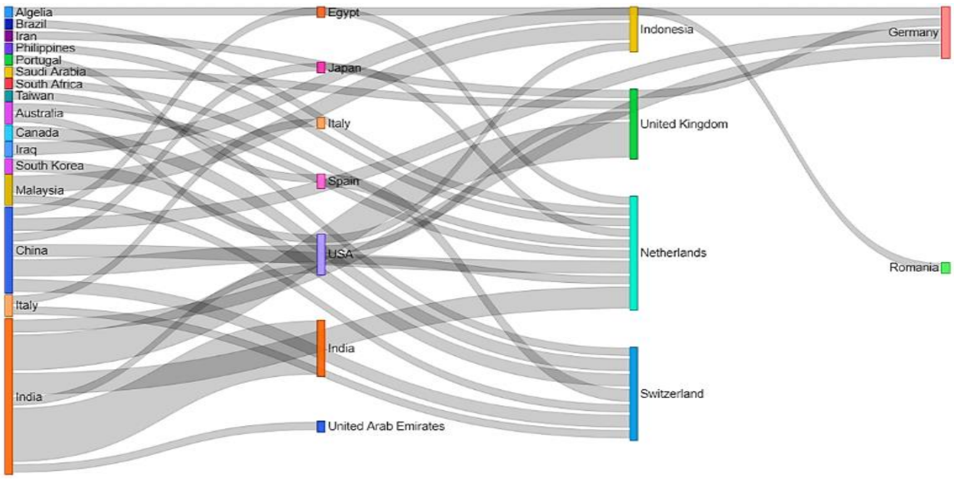

Figure 10. Country of origin by country publication

In the case of China, it is not a country rich in water resources. The country's per capita water supply is actually very low [35]. Existing water resources are unevenly distributed across China's vast territory. Similarly, there are sufficient treatment facilities to reduce the severity of agricultural and industrial pollution [36]. China's main river system is an indicator of the seriousness of the problem, in addition to the untreated sewage that is discharged into these waterways [37], high-growth industries like textiles, paper manufacturing, chemical manufacturing, and pharmaceuticals are also major causes of such pollution. The works found in this SRL result in real-time monitoring and evaluation investigations of water quality that can be evaluated for the human population in various places [23], which shows the high interest in China to attend to the solution of the aforementioned problems with drinking water. These recent investigations use machine learning techniques, including deep learning methods, which have been widely used in big data analysis of water quality, demonstrating extensive work done in China to improve prediction of changes in water quality. parameters of water quality, these types of models can complement the ICT decision-making process and the various challenges related to water quality.

In the case of the United Kingdom, the Netherlands and the United States, the documents describe the importance of generating a set of approaches for real-time monitoring and control of drinking water networks based on advanced information and communication technologies, which represent an important progress against climate change, combined with the growth of the population of these countries, considered as alternatives to face their sustainable development and strategies to mitigate water scarcity [38].

In Colombia, more than 11.6 million people live in rural areas [39]; however, a third of this population does not have access to drinking water or to appropriate basic sanitation solutions. According to these data, the country failed to achieve the goals agreed in 2015 of the Millennium Development Goals (MDG) for the rural water and sanitation sector in Colombia [40]. If this trend continues, the country is not expected to meet the new 2030 goal agreed in the SDGs [41]. Taking into account the above, the development of this type of research is relevant where international trends developed for the monitoring of water quality are presented that can contribute to the generation of technologies that, supported by IoT, allow access to drinking water with monitoring of its quality parameters in real time and remotely.

In general, of the 68 selected documents, in the case of the countries where the research originated, the USA stands out with 114 citations (27.2%) and India with 156 citations (37.2%) of the total of their works. In the case of the countries where the journals accepted the publications, the Netherlands obtained 172 citations in total (41%) for 10 documents (14%), Germany 80 citations (19%) with 5 documents (7.3%), United Kingdom 65 citations (15%) with 3 documents (4%), Switzerland 62 citations (14.7%) with 9 documents (13.2%) and among other countries a total of 41 citations (9.7%) for 13 documents (19%). These results show the lack of studies related to the measurement of the quality of drinking water based on IoT for Colombia in the academic databases selected in this study, which suggests that efforts should be concentrated on the implementation of this type of research that contributes within reach of the goals contemplated in the SDGs [41], as the generation of publications of the results of this type of research work in specialized academic databases. This study does not include queries in Google Scholar, because on the part of this search engine, there is no quality control of the processed sources, it contains calculated citations from a variety of sources, including Power Point presentations, Word documents, unknown or unconfirmed sources, among others, and assigns the same rank to other academic or scientific works [42]. However, via Google Scholar it is possible to find academic works carried out in Colombia and publications in non-indexed academic journals [43]–[45]. Figure 11 shows the Sankey diagram, which relates the countries of the journals where the 15 most cited documents have been published.

Parameters such as turbidity, electrical conductivity, dissolved oxygen, pH and water level are the most studied indicators, as shown in Tables 3 and 4. Having cheap portable meters to detect other parameters (such as heavy metals and/or ions, among others) will require advances in sensor technology. Future research in this area may be the study of alternative sensor technologies to determine a wide range of parameters that allow IoT to quickly describe the suitability and quality of water. In this sense, in Tables 3 and 4 only 5 works are evidenced [11], [13], [17], [19], [20].

The contribution of this work is to propose the design of an integrated model for monitoring water quality based on IoT, using data analysis and prediction techniques for the detection of anomalies based on the most important parameters according to the WHO that improve the Architecture of Hardware, Software and Communications presented in Figure 7 results of this SRL [46]–[49]. In this sense, Figure 12 presents a configuration where its innovation represents main trends in terms of real-time water quality sensors, with wireless connection and IoT, data management with a clear trend towards storage, processing in the cloud and machine learning algorithms. The process modeling of Figure 12 that is proposed as a contribution to this SRL is presented in Figure 13 using a business process model and notation (BPMN).

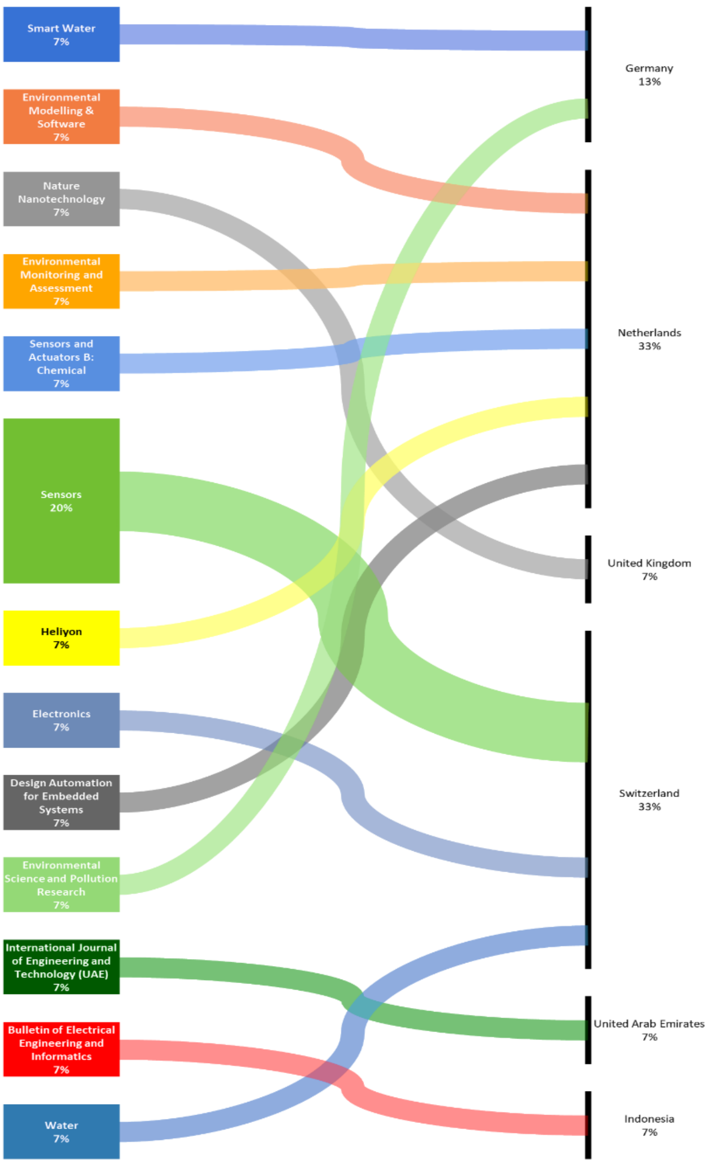

Figure 11. List of the journal's country for the most cited articles

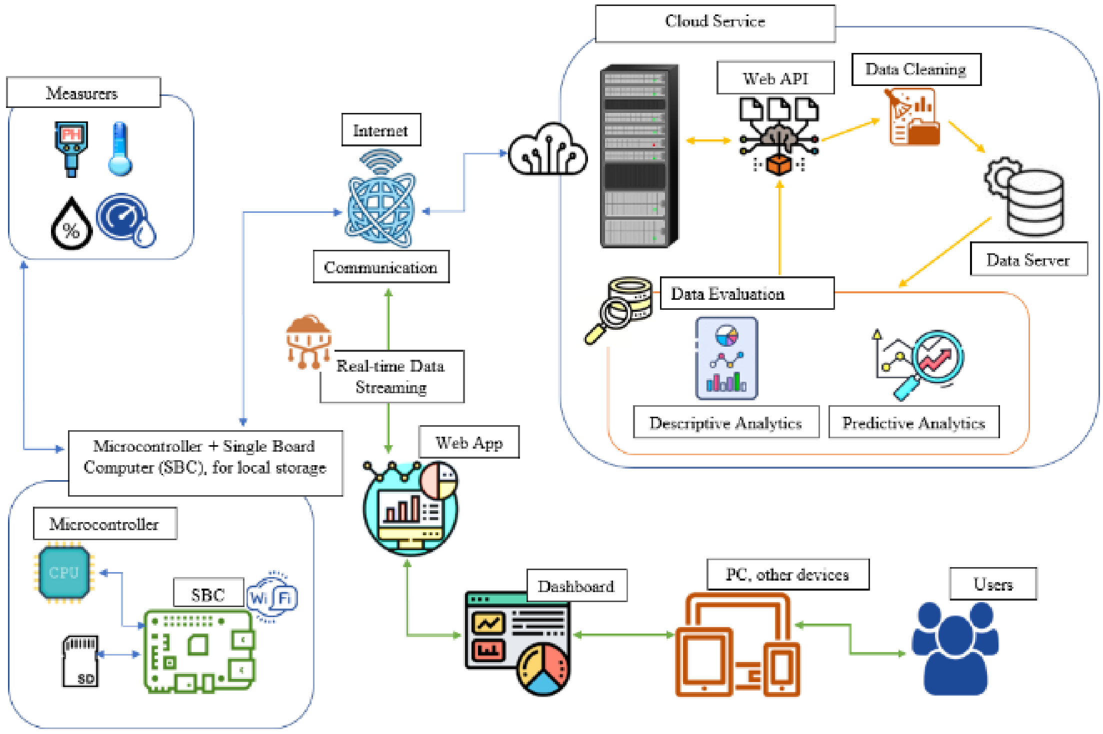

Figure 12. Software architecture, hardware of measurement devices and communication in real time implementing descriptive analytics and machine learning

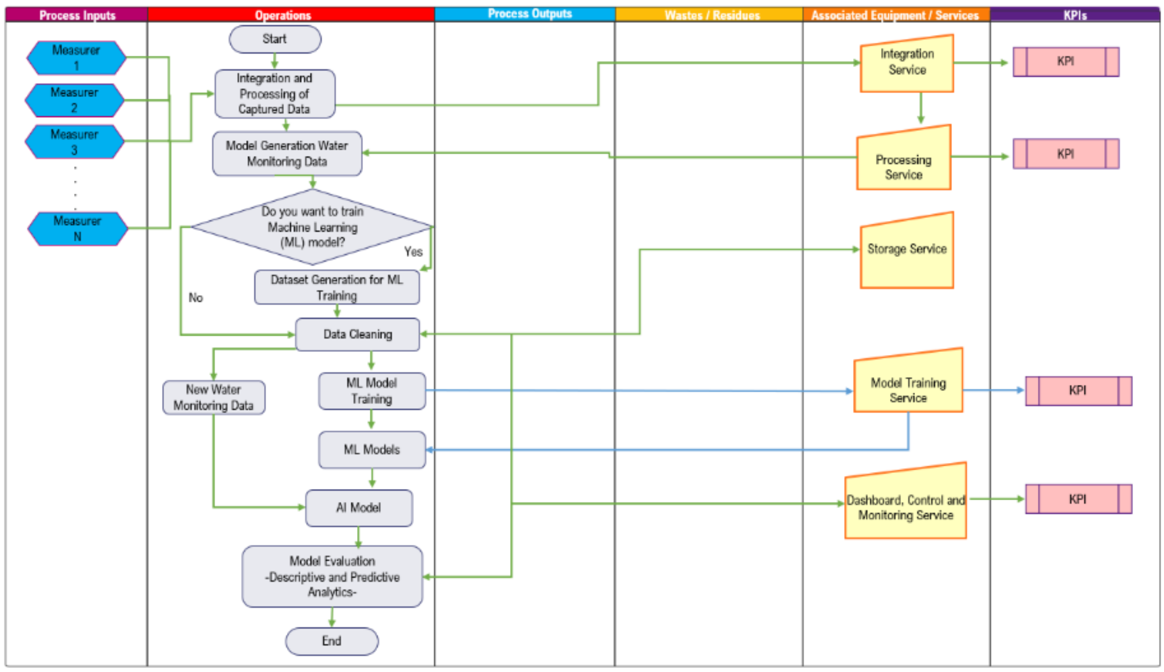

Figure 13. BPMN Integrated model for IoT-based water quality monitoring

4. CONCLUSION

The advance of industrialization and urbanization has become a challenge for water resources. Providing and accessing water, sanitation and personal hygiene services is essential. Through the SDGs, requirements are established that provide innovative methods for the management and mitigation of water quality, including to combat the effects of the current COVID-19 pandemic, helping to maintain the health of millions of people. The vast amount of data collected from field monitoring using sensor technology can be combined with advanced data analytics techniques, such as deep learning, that can be used to manage water quality more effectively. Unfortunately, however, many parts of water quality monitoring systems still rely on regular manual sample collection and monitoring. Therefore, it is necessary to develop and apply real-time in-situ monitoring systems using sensor technology and high-tech data analysis technologies, such as deep learning, to find better water quality management solutions that allow increase the accuracy and efficiency of smart water management systems.

This SRL examines the latest technologies that use the potential of emerging IoT technologies in monitoring and evaluating water quality parameters; These advantages are real-time monitoring, the automation of intelligent solutions, the possibility of a highly adaptable and responsive system, and the possibility of reducing the cost of monitoring water quality, which allows having data for analysis and projection. for decision making.

It is worth noting that, according to the studies obtained in this review. IoT-based water quality monitoring systems have not been applied in-situ to some more complex parameters such as metals and other ions (see Tables 3 and 4). The advances that may be presented in this regard are associated with the study of alternative sensor technologies to determine a wide range of parameters that can adequately describe water quality.

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