Smart Sensors in Environmental/Water Quality Monitoring Using IoT and Cloud services

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ABSTRACT

The growing social awareness and consequent concern for the environment has driven environmental analytical chemistry to a position of great prominence. In recent times, this position has translated into taking advantage of the great benefits provided by cloud computing and the Internet of Things (IoT), which are especially appropriate when devices such as chemical sensors are used. The use of such sensors is very common when in situ monitoring of environmental parameters is performed, but until recently, it was limited to the deployment of a small number of sensors. Currently, this approach has given way to genuine smart sensing systems (for instance, fully consolidated wireless sensor networks) that are able to provide a substantial amount of information. This type of sensor (the so-called smart sensor) is fundamentally characterized by (a) low consumption, versatility, and autonomy, (b) ease of integration with cloud solutions, (c) durability and reliability of IoT platforms and sensors, and (d) easy installation and deployment of sensor nodes. For all these reasons, and given the increasing importance and use of this type of device, a revision of the recent literature relating the development of smart sensors with environmental issues has been conducted, with major contributions being discussed, most notably those addressing the continuous in-line monitoring of water quality.

Keywords: Environmental Analytical Chemistry; Smart sensors; Water quality monitoring; Advanced sensing systems; IoT; Cloud services

1.- INTRODUCTION

For many years now there is a considerable need for continuous monitoring of environmental and water quality [1][2], paying special attention to wastewater and drinking water [3]. To do this, (physico)chemical parameters such as temperature, pH, salinity, oxygen balance, and concentrations of nutrient species, such as NO_3^- and NO_2^-, PO_4^{3-}, HCO_3^-, NH_4^+, and SO_4^{2-}, must be controlled to ensure that they are within the legally established limits and thus confirm high water quality [4]. Typically, water samples are collected in situ and transported to quality control laboratories [5-9]. In this way, many samples can be analyzed with high accuracy and precision, and low limits of detection (LODs) and quantification (LOQs) can be achieved, for example, using automatic methods of analysis. However, as these methods are not usually portable, the stability of the samples can be altered before they are analyzed; in addition, from an economic perspective, the cost per analysis can be high. Fortunately, continuous technological advances have permitted the emergence of inexpensive, easy-to-use portable kits permitting online analysis, even though they sometimes do not fully meet the needs of users [10]. As an alternative, new water quality analysis probes have recently been commercialized. These devices are straightforward, have high accuracy and often integrate fully consolidated wireless sensor networks (WSNs), where the obtained data can be collected and delivered over the Internet [11].

This technology is evolving in such a way that the latest trends point toward the development of "smart", easily deployable sensors not only in rivers and lakes but also in water supply systems and even connected to different kinds of wastewater treatment plants. These sensors have the important advantage that the information obtained can be made available to citizens via the Internet [12].

Furthermore, work is being done on the development of autonomous devices with all the steps required for the analysis (avoiding the use of conventional components). This approach is the so-called Micro Total Analysis System (μTAS) [13], which is able to convert the technology of an entire laboratory into a chip format; thus, this type of system based on electrochemical sensors and lab-on-a-chip (LOC) technology can be a satisfactory replacement for classical methods [3].

Notably, the design of new sensors with a high degree of technological advancement is leading to enhanced results in comparison to "traditional" sensors. Thus, in our view, these

new types of sensors will be of enormous utility in environmental analysis systems and are undoubtedly the spearhead of the research in this field.
For all these reasons, we present the state of the art of the use of smart sensors in the continuous monitoring of environmental parameters, most notably water quality, given its importance. First, there is a description of intelligent sensors and their main difference with respect to conventional sensors. Next, the role played by new IoT technologies and cloud services in the operation of smart sensors is discussed. Finally, we describe the main contributions made recently in the application of such sensors to environmental analysis, with special emphasis on the monitoring of water quality, along with their advantages and disadvantages.

2.– SMART SENSORS

Sensors, in general, are utilized in the specific real-time determination of species at very low concentrations. Nevertheless, and despite great technological advances, the major requirements of sensors, namely, (a) high sensitivity, (b) high specificity (that is, almost free of interference), (c) low LOQ, (d) autonomy from the energy perspective, and (e) affordable cost, remain major challenges for both scientists and manufacturers.

Smart (intelligent) sensors represent a new technology and a new concept for considering the conditioning and acquisition of analog signals. These devices have an advantage over traditional sensors in that they integrate, apart from the sensor, signal conditioning, which can be performed via some electrical network for converting the sensor's analog signal into a time, frequency or digital signal, as well as some processing element such as a counter or a microcontroller. In this way, an intelligent sensor can be coupled to a digital or quasi-digital bus, enabling a better and faster transfer of information. It also allows several sensors to be connected to a network and to allocate a central element in charge of identifying the respective sensor.

In general terms, the main features of a smart sensors when used in environmental analysis include the following:

• a detection/transduction system to transform the analytical signal obtained into a measurable electrical quantity;
• a suitable measurement and signal processing interface to shape the electrical signal;
• data processing together with a calibration system to ensure that the measurement is reliable;
• an autonomous power source to guarantee the nonstop operation of the whole process.

The term smart sensor then refers to a device that combines data acquisition and its internal processing, along with new characteristics. These instruments integrate an embedded microcontroller to carry out calculations and internal processing, with a two-way communication ability, *i.e.*, external instructions are received, whereas measurements and status information are transmitted. They usually consist of one or more sensor arrays to measure concentrations and some embedded algorithms for analysis of the results obtained, thus providing decision support. In short, and by way of summary, it can be said that a smart sensor consists of a traditional sensor equipped with built-in computing capacity and (wireless) data transfer ability.

Taking advantage of the recent advances in data collection, storage, and processing, combinations of multivariate data analysis and machine learning methods are integrated with chemical sensor arrays (for example, so-called e-tongues and e-noses [14][15]) to achieve (a) an even better identification of analytes and (b) higher values of selectivity in environmental analysis. The aforementioned procedures are widely used, and highly satisfactory results have been obtained in this field.
There are various types of smart sensors that, connected to IoT technology, help control, maintain and improve the quality of environmental factors. Generally, they are intended for the detection of chemical, gaseous or liquid species and/or determination of their concentrations. For example, the various functions that smart sensors can have in water quality control include the following:
• Drinking water monitoring to control the quality of drinking water in population centers.
• Detection of chemical spills in lakes or rivers, as well as leaks and toxic discharge from nearby factories. The same can be applied to the sea.

3.- THE USE OF IoT AND CLOUD SERVICES IN ENVIRONMENTAL ANALYSIS

As mentioned above, in the field of environmental chemical analysis, IoT is the cornerstone of a system based on a very large number of connected smart sensors that measure environmental parameters and, together with cloud computing, are able to yield information in a range that can oscillate between the microscopic and the global.

Delving into the latter, the last stage of in-line analysis is followed by a new model based on cloud services that is in charge of collecting and storing all the data related to the obtained values. An appropriate communication network is then used.

The next step is the incorporation of these smart sensors into an IoT [16] platform, where sensor networks, as well as embedded systems, are integrated into the cloud to offer new services [17].

What might have appeared to be a utopia until recently is now perfectly feasible, thanks to the availability of very powerful and very small microprocessors. The possibilities of communication are now enormous, with almost the entire territory being able to be covered in developed countries. Finally, it must be remarked that communications and electronics are both inexpensive, which allows for (a) the acquisition of many devices, (b) covering large areas with high spatial resolution, and (c) implementing fault-tolerance mechanisms usually based on redundancy. In summary, these smart sensors continuously interact with the real world, thus offering constant and reliable information about the environment. Additionally, code can be incorporated into particular applications [18-20].

Intelligent and distributed sensing systems can then be considered of paramount importance within the IoT [21] and are applicable to wearable sensors for environmental monitoring. However, the use of smart wireless sensors in real implementations currently faces important challenges such as energy consumption, economic cost and, of course, the guarantee of an adequate useful life.

Figure 1 summarizes the different elements forming a cloud-based IoT platform. Information is exchanged among components through communication infrastructure. Each device has two strands: the strand specific to the device and the other strand, which is in charge of ICT issues (processing, communications, ….). The environment to be monitored is shown in the lower part of the figure, along with a series of sensors. Finally, in the upper part of the figure is the cloud, where services are offered to complement the information provided by the sensor nodes. Several applications running in the Cloud make use of this information that has been conveniently stored in different databases. Notably, the data support offered by the Cloud also includes its processing [22], for instance, the search for statistical information; nevertheless, in the case of a large data volume, there is no other option but to resort to big data techniques [23].

In any case, these platforms encourage innovation in the intelligence applied to the data obtained by the sensors. When these reach a large number, advanced processing techniques must be used—for example, data science techniques—to make it possible to extract the relevant information [24]. In this sense, new artificial intelligence techniques, such as deep learning, have been developed.

However, these new technologies also present some important problems, namely, (a) security (inappropriate access or use), (b) integrity (data can be incorrectly or fraudulently manipulated), and (c) privacy [25,26] (since not all data are freely accessible). In addition, these new technologies often suffer from a lack of standardization, which makes their application difficult.

Overall, the concept of the IoT and its development is certainly an unstoppable process, and society is adapting to this revolutionary technology, especially because of the great benefits it offers. Undoubtedly, environmental analysis can and should take full advantage of this, especially the design and development of new smart sensors.

4.- SMART SENSORS IN IN-LINE WATER MONITORING

In this section, the most recent and relevant contributions (summarized in Table 1) of intelligent (smart) sensors that have been developed and perfected in the field of environmental analysis are described and commented on, with special emphasis on those of greatest interest for the monitoring and control of water quality in rivers, lakes, etc. They have been distributed in three subsections, namely: Water, environment (in general), and aquaculture systems (more specific, but interesting due to the need for constant control of the water in fish farms).

The most interesting starting point is perhaps a recent monograph [27] that summarizes the efforts to obtain state-of-the-art smart chemical sensors, with contributions from leading experts. The devices developed and the problems discussed in this book will allow the reader to delve deeper into this field. It begins by explaining some fundamentals and metrological features of different types of sensors. These basic principles are the cornerstone for understanding the different technologies and the problems that arise in the development and use of intelligent sensors.

Of great interest is also the compilation [28] of articles regarding the feasibility of making sensors (for example, those used in environmental analysis) that should be ubiquitous and adaptable to any environment since this will also permit them to become part of the IoT, which requires system mobility and self-powered capability to meet the requirements of most environmental chemical analysis processes.

4.1.- Water

Kazemi et al. [29] proposed a system for eliminating interference in microwave sensors with loss compensation to characterize the composition of water using an artificial neural network. Ambient temperature negatively affects the resonant frequency, causing data scrambling. This problem is solved by means of an artificial neural network with two hidden layers. Different concentrations of methanol in water were determined at temperatures from 22 to 30°C. This smart sensing system had the capability to discriminate correct data in spite of erroneous interference factors by up to 92 %.

A common procedure to measure water quality in real time is based on using WSNs in the IoT environment for the detection and measurement of relevant chemical parameters and the subsequent sharing of the corresponding data through the Internet. For this purpose, some authors have designed and developed several selective sensors based on interdigitated microelectrode array (IDA) electrodes, which have been applied to the detection of hypochlorite ions [30]. These sensors are more sensitive than traditional detection methods, with greater linearity and stability of the analytical signal. In addition, they have high selectivity for other ions usually present in water, such as chlorides, sulfates, or carbonates. Finally, they are small in size, fast in response, low in power consumption and low in cost, characteristics that are particularly suitable for IoT. Perhaps it is only missing to offer more information on the reliability of their use.

One type of wireless chemical sensor that is becoming increasingly important in environmental analysis is that based on fluorescence. A good example is the device developed by Kassal et al. [31], a small portable wireless fluorimeter. The device is programmed and its communication with tablets or PCs is achieved using radio frequency identification. Such sensors can be easily adapted for use with different analytes and fluorescent chemical species and can be a breakthrough in the field of environmental analysis, although they cannot yet be considered an IoT application.

Another relevant contribution is the development of smart sensors using IoT and cloud computing, especially for their interest in environmental analytical chemistry. Following the IoT philosophy, these new intelligent sensors are able to integrate the resulting data on existing IoT platforms such that information may be used whenever required. Moreover, the use of these technologies results in sensors with notably improved characteristics utilizing the information available in the cloud. From this perspective, a HCO_3^- IoT-based smart sensor has been developed with the aim of employing it in water monitoring [32]. A traditional, commercially available CO_2 ISE uses pH data from the cloud and then returns a [HCO_3^-] value obtained indirectly, the latter being offered to the cloud. The experimental results achieved correlate well with those provided by three other classical ISEs. Furthermore, this procedure is of great utility (as an IoT application) in the in-line monitoring of bicarbonate in lakes or rivers since the proposed sensor is inexpensive and has low energy consumption.

The continuous advances in the IoT and wireless communication technologies have enabled novel, interesting applications in environmental analytical chemistry. In the work of Salunke et al. [33], a new smart sensor interface for water quality monitoring in an IoT environment was proposed. Different sensors are used to monitor water quality based on the analysis of chemical and physicochemical parameters, such as dissolved O_2, pH, temperature, and turbidity. In this sense, the IoT provides an interface to remotely monitor these parameters from anywhere and at any time. The Intel Galileo Gen 2 board is utilized as the interface device in the aforementioned system, whose performance has been successfully checked in aquatic environments.

A comprehensive overview has also been published covering the period between 2013 and 2018 [34], with a critical discussion of chemical sensor concepts and technologies used in the IoT environment or considered ready to be used. These smart devices have been chosen by the authors because they can be located remotely and easily adapted to the characteristics of the environment. Furthermore, their implementation in networks is of paramount importance for the continuous monitoring of environmental parameters. This publication also includes an overview of current and future challenges in this field.

A major chemical parameter to be determined in rivers and lakes is ammonium, mainly for obtaining global knowledge of the environmental impact of human actions and pollutants. ISEs have been commonly utilized for this purpose, but potentially interfering ions (Na^+ and K^+), as well as random failures, may affect the measurement quality. A smart NH_4^+ sensor with improved characteristics was designed to overcome these drawbacks [35], and its performance was verified in water samples. Its success is due mainly to the implementation of a knowledge-based system that is in charge of supervising a group of ISEs with a double goal: (a) avoid random malfunctions and (b) interference rejection. Clearly, this contribution may also be appropriate for in-line water monitoring through the implementation of WSNs. The latter are increasingly being used for water monitoring, but the feeling persists that the advantages of new IoT environments are not being fully exploited. To mitigate this limitation, an IoT-based generic architecture for chemical species monitoring systems was recently developed by Campelo et al. [36] and embodied in the design of a smart potassium sensor. The proposed system is straightforward, with fast and simple deployment, high reliability, and interference rejection. Thus, the authors integrated it into an IoT environment for use in water quality monitoring, and satisfactory correlation with the results provided by reference methods was achieved.

The determination of nitrates in water is also very common in environmental analysis, often requiring the simultaneous measurement of the concentration at many different points. To perform this task, sensor networks, which in many cases are ion-selective electrodes, are typically employed. The problem is that their measurements are affected by the presence of other interfering ions. As a solution to this issue, Capella et al. [37] proposed a new methodology to address the main sources of interference (chloride and bicarbonate in the case of the determination of nitrates) in such a way that the results obtained in the measurements of the nitrate content with an ISE can be considered virtually free of errors caused by these interfering species. To achieve this task, a new sensor node that consists of three ISEs (nitrates, chlorides, and bicarbonates) coupled to a low-power, low-cost microcontroller, which receives and processes all the signals coming from the electrodes, has been developed. This information (described in detail in the article) is properly treated to provide an accurate estimate of the real nitrate concentration. The application of this methodology results in a smart nitrate sensor (interference-tolerant) capable of being used in a wireless sensor network to perform continuous monitoring of the concentration of nitrates in rivers, lakes, and aquifers.

López-Leal et al. [38] described the state of the art in the development of intelligent sensors based on microelectromechanical systems (MEMS), explaining their evolution from the beginning to the most recent generation of smart sensors. They also discuss future prospects for new designs that could meet current and future market demands, thus making it possible to turn a passive sensor into an intelligent sensor. These authors also describe the most important characteristics that these smart sensors must have to be used in environmental analysis, mainly in water. A microcontroller-based platform with an algorithm to estimate the real-time reliability of MEMS sensors is also proposed.

4.2.- Environment

Lagraini et al. [39] highlighted the benefits of wireless sensors, focusing on computer protocols to reduce consumption and thus extend the useful life of sensors before having to be replaced or recharged. For this purpose, the LEACH protocol was shown to maintain energy consumption at a minimum. To measure the performance of the modified algorithm, a simulation was utilized to compare consumption. The results show that the algorithm increases the useful life of the network and decreases the energy required, which is necessary to increase the useful life of environmental sensors.

Kassal and collaborators [40] developed and characterized an ultralow-power radio frequency identification (RFID) wireless sensor tag with potentiometric input for utilization with pH electrodes and ion-selective electrodes (ISEs). The potential measured by the tag is conveniently stored in its internal memory, and the data are wirelessly transmitted via RFID to a nearby suitable device. This sensor tag is simple, with very low power consumption and self-contained data logging. These features make it appropriate for use in environmental chemical analysis, for example, in the continuous monitoring of determined species (pH electrodes or other ISEs are implemented as stand-alone chemical sensors or as part of larger networks that will support the IoT).

Corbellini and coworkers [41] proposed a global cloud-based infrastructure for environmental monitoring. Low-size, battery-powered sensors are wirelessly connected to tiny receivers that route data to the cloud. These data can then be accessed in real time across multiple devices and downloaded for further analysis. Each of these smart sensors can measure humidity and temperature nonstop for over twelve months. All data are transmitted to the receiver and stored in the sensor's memory in such a way that the system can properly work without power supply or access to the Internet. The architecture makes use of the μPanel environment, which can also work in the case of poor Internet connections (sensors are locally controlled). This architecture proposal is highly versatile, which means that it can be used for different types of environmental analysis.

Zhao and collaborators [42] developed a system based on a hydrophobic surface nanogenerator to harness the energy of the wind and sustainably power a temperature sensor, although it could be applicable to any other sensor that requires a similar current. After 14 hours at a wind speed of 12 m s^{-1}, the nanogenerator was able to continuously supply 3.3 V and a pulsed output current of 100 mA to achieve energy storage in a capacitor. An intelligent and wireless temperature sensor node powered by this nanogenerator can send data to a smartphone at a distance of 26 meters. The article is very interesting since if progress is made at this point, the batteries will not have to be replaced or recharged; however, the ability to transmit the data further would have to be improved, which would require higher-power nanogenerators to continue working continuously.

Another major aspect that should be taken into account in this field is the fact that, unfortunately, IoT devices are attacked with some frequency. In this sense, a compromise is always required between safety requirements and ease of assembly, employment and maintenance. A good example is the industrial implementation of the EZConnect™ security infrastructure developed by BECS Technology, Inc., a firm specializing in water monitoring from a chemical perspective [43].

Mois and coworkers [44] presented three different IoT-based wireless sensors for environmental monitoring; the difference is in the type of communication used, namely, (a) Wi-Fi and HTTP Protocol, (b) Wi-Fi based on user datagram protocol (UDP), and (c) Bluetooth Smart. All three approaches offer the possibility of recording data in remote locations and viewing them from any device with an Internet connection, which is very important since it enables monitoring of large geographical areas. The three proposed systems are described in detail and compared with each other. Moreover, all three are likely to be used satisfactorily in environmental analysis applications since they are remarkably easy to use, are energy autonomous, have good internet connectivity and are suitable for IoT-based solutions. The latter is the basis of the subsequent work of these same authors [45], who show that design and development in the IoT environment are highly influenced by the requirements of the sensors used. In this sense, factors such as energy efficiency, economic cost, miniaturization, and Bluetooth low energy (BLE) technology have been taken into account in this study. In general, the useful life of these wireless sensors ranges from a couple of months to 3 years, assuming they are powered by a single commercial battery. The final conclusion is that these types of systems are suitable for implementation in IoT scenarios and open many future possibilities due to their energy and measurement capabilities, all helped by the rapid evolution in the development of integrated circuits (ICs) and firmware optimization.

An interactive model based on the location of IoT and cloud integration (IoT-cloud) has also been developed for mobile cloud computing applications [46]. The main goal is to avoid power losses due to possible redundant transmissions carried out by the sensors when they must supply data periodically. Instead, this IoT-cloud model offers on-demand sensing services based on user requirements, which play a key role in the in-line monitoring of environmental parameters. In this sense, the cloud is in charge of controlling the detection schedule of the sensors since it knows where and when the sensor data are required. Consequently, in the case of no-demand periods of time, the sensors are kept in standby mode, and energy is saved. The network lifetime is then prolonged using this location-based system.

The development of wireless chemical sensors (WCSs) has taken advantage of simultaneous advances in chemical sensors and wireless communications. These hybrid devices allow for the determination, storage and wireless distribution of information related to chemical analysis processes, and these IoT sensors are very useful in environmental applications. A complete review [47] of the main chemical sensors and major radio technologies in this field has been conducted, including the most recent advances and trends regarding portable sensors. Particular emphasis is placed on radio-based WCSs, clearly demonstrating the improvement in chemical detection achieved using ubiquitous wireless technologies such as Bluetooth, ZigBee, RFID, and near field communication (NFC). However, this work does not mention modern and promising IoT protocols, such as Sigfox [48], Lora [49] or 5G [50], which should be used increasingly frequently to provide real IoT solutions regarding data access.

However, some authors think that the benefits of low-cost data collection by IoT sensors have not yet been fully realized. A recent work focused on various practical experiences in the use of intelligent sensors in environmental analysis [51]. In such cases, there is an additional benefit (lower computing costs) when cloud computing is integrated into the data collection process. In addition, there is a significant decrease in the overall cost of distributed IoT sensor networks.

On the other hand, applications involving the monitoring of chemical parameters in water require measurement devices (sensors) to be deployed in different geographical zones but be centrally controlled from a remote location. Therefore, sensors in such applications must have a small size, low energy consumption and the ability to cover a vast geographical area. Perera et al. [52] designed a generic reconfigurable and reprogrammable smart sensor node that uses ZigBee as a field programmable gate array (FPGA). The design includes transducer communication, processing, and control in a single core, with an enhanced processing speed achieved by using interprocess communication within the chip.

Alreshaid et al. [53] discussed the process of integrating chemical sensors into the IoT environment. Starting from new-generation sensors implemented on wireless platforms, they propose a microfluidic sensor for the detection of several types of liquids. Another important achievement in the application of IoT technology in environmental analysis is the optimization of data transmission processes, for which several compression techniques have been tested, among which "compressive sensing" (CS) stands out. This model offers many possibilities for the further development of IoT platforms. It is, in fact, a new theory of signal acquisition and compression leading to important IoT applications [54]. Some of the main emerging trends in future CS-based IoT research are highlighted in this last work.

4.3.- Aquaculture systems

Constant control of the water in fish farms reduces mortality due to the lack of control of the most important parameters (in this case, dissolved oxygen and pH), which are very important for the correct growth of fish, especially fingerlings, which are extremely sensitive to changes in any of these parameters. Managers of this type of facility need accurate information at all times about the status and performance of the system. Simbeye et al. [55] developed and deployed such a system through short-range and low-cost modules of a network of wireless sensors in the ZigBee standard to monitor and control the system in real time. The system consists of several smart sensors, a coordinator/gateway node and a computer. The sensors measure parameters such as pH, dissolved O_2, and water temperature and send the information to the sink node (Gateway), which transmits the commands to a PC to obtain a visualization interface. The constant monitoring of these parameters makes it possible to reduce the probability of fish mortality in aquaculture, with corresponding economic benefits.

Continuing with aquaculture, but now in a more specific field, *i.e.*, in oyster farms, oyster growth is highly dependent on the same parameters mentioned above. Thus, a cloud-based platform has been proposed to obtain the values affecting this growth process [56]. Hardware and software of the measurement system are reported in detail, as well as how the storage and processing of the data are performed, all accompanied by different experimental results. The outcome is a real cloud-based platform that utilizes the ThingSpeak platform [57], which is an IoT analysis service that permits the addition, visualization, and analysis of data flows in the cloud.

5.- CONCLUSIONS AND FUTURE TRENDS

As smart sensors are developed, we will undoubtedly be able to better understand our environment and the changes that occur therein. Sensor devices are rapidly improving to achieve more intelligent and autonomous modes of operation. The key to this efficiency of operation is the proper processing of sensory data. True information sometimes requires data to be brought together from multiple sources. Additionally, trend data are sometimes more valuable than spot measurements. To achieve this mode of operation, increased functional integration based on highly integrated components in the sensor electronics has already been discussed. Pattern detection, plus data acquisition and advanced algorithmic analysis, are essential to take sensor data to the next level. For this purpose, sensor devices are increasingly equipped with on-board analytics and can also connect to cloud platforms to deliver new insights. The sensing device is increasingly given capabilities such as self-monitoring, interference detection and diagnosis, self-calibration (self-tuning), and reconfiguration. The use of these capabilities to drive preventative maintenance has the potential to dramatically reduce operating costs in industrial and commercial settings. Another area where sensing devices are making progress is in their ease of use and implementation (for integrated communication interfaces, plug and play capabilities, automatic location, etc.) to adapt to the context of the environment.

Achieving a self-contained yet highly integrated mode of operation requires a holistic approach to sensor design, involving the use of state-of-the-art 3D design tools, finite element method, integration into MATLAB/Simulink, and the use of complete and accurate material data. Additionally, a key area being targeted by sensor innovators is the fusion of data obtained from different physical or chemical sensors to provide more comprehensive information than that obtained from either a single "logical" or "virtual" sensor.

All of the above trends will change our world in unprecedented ways. Together, developments in cloud computing systems, sensor technology, wearable devices, and smartphones will likely result in greater awareness of the environments in which we live, work, and play. It is not difficult to envision a world in which sensor networks transmit information about air pollution levels, weather conditions, radiation levels, and water quality in our immediate surroundings directly to our smartphones. Although some of these are urban applications, there is an equally large set of data streams that will be available in nature and sensitive environmental areas, such as wildfire detection, ozone level detection, melt rate detection, ice, and salinity. All this information will allow us to not only control environments but also understand them in new ways.

In any case, it is evident that -within environmental analysis- the monitoring and control of water quality is perhaps the most relevant aspect, given the paramount importance that water has in the daily life of all living beings. And in this field, smart sensors are (and will be even more so in the future) playing a transcendental role since they are able:

a) To identify whether waters are meeting designated uses. When chemical pollutants exceed maximum or minimum allowable concentrations, waters might no longer be able to support the beneficial uses such as fishing, swimming, and drinking for which they have been designated. Designated uses and the specific criteria that protect them together form water quality standards. Analytical chemists assess water quality by comparing the concentrations of chemical pollutants found to the legally established criteria, and so judge whether water streams are meeting their designated uses.
b) To identify specific pollutants and sources of pollution. Water quality monitoring helps link sources of pollution to a stream quality problem because it identifies specific problem pollutants. Since some activities tend to generate certain pollutants, a tentative link might be made that would warrant further investigation or monitoring.
c) To determine trends. Chemical constituents that are properly monitored (i.e., consistent time of day and on a regular basis, using consistent methods) can be analyzed for trends over time.
d) To screen for impairment. Finding excessive levels of one or more chemical constituents can serve as an early warning "screen" of potential pollution problems.

Ultimately, environmental sensors are crucial to making a more connected world possible. From providing information about our immediate environment to helping address global climate change, sensors and sensor networks are fundamentally changing our awareness of the environment around us. Environmental, industrial, commercial and personal spaces use increasingly intelligent sensor devices to drive new approaches to security, control and monitoring. Sensors are undergoing new development along a variety of dimensions: sensor capabilities are rapidly expanding while improving accuracy and reliability and reducing power consumption. Additionally, multisensor devices are becoming more common as devices are deployed more widely, and new levels of integration between multiple sensors and other components offer new possibilities. Furthermore, measurement, through emerging areas such as artificial intelligence and the Internet of Things, is now finding many applications in the design of systems of the future. A future in which sensors are even more autonomous and intelligent is clearly viable and will bring new possibilities for operational efficiency and cost reduction, as well as the development of new capabilities to protect the environment, human health, and the general wellbeing of our planet.

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FIGURE CAPTIONS:

Figure 1: Scheme of smart sensors used in Environmental Analytical Chemistry. ICT = Information and Communication Technologies.