





Review

Smartphone-Operated Wireless Chemical Sensors: A Review

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Abstract: Wireless chemical sensors have been developed as a result of advances in chemical sensing and wireless communication technology. Because of their mobility and widespread availability, smartphones have been extensively combined with sensors such as hand-held detectors, sensor chips, and test strips for biochemical detection. Smartphones are frequently used as controllers, analyzers, and displays for quick, authentic, and point-of-care monitoring, which may considerably streamline the design and lower the cost of sensing systems. This study looks at the most recent wireless and smartphone-supported chemical sensors. The review is divided into four different topics that emphasize the basic types of wireless smartphone-operated chemical sensors. According to a study of 114 original research publications published during recent years, market opportunities for wireless and smartphone-supported chemical sensor systems include environmental monitoring, healthcare and medicine, food quality, sport, and fitness. The issues and illustrations for each of the primary chemical sensors relevant to many application areas are covered. In terms of performance, the advancement of technologies related to chemical sensors will result in smaller and more lightweight, cost-effective, versatile, and durable devices. Given the limitations, we suggest that wireless and smartphone-supported chemical sensor systems play a significant role in the sensor Internet of Things.

Keywords: chemical sensors; biosensors; optical sensor; wireless; smartphone; wearable



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1. Introduction

1.1. Introduction to Wireless Chemical Sensor Technology

According to the International Union of Pure and Applied Chemistry's (IUPAC) definition, a chemical sensor is a device that transforms chemical information, ranging from the concentration of a specific sample component to overall composition analysis, into an analytically useful signal [1]. Chemical compound detection, measurement, and monitoring in various contexts have long been a key concern since this information is critical in various sectors, from environmental control to clinical diagnostics. The advancement of analytical test equipment technology, such as gas chromatography, mass spectrometry, and atomic absorption spectroscopy, among others, has made it possible to identify and quantify target analytes with great sensitivity and resolution. These characteristics make these instruments

indispensable for determining target molecules accurately, especially when they appear in complicated forms. On the other hand, analytical equipment has significant limitations that limit its widespread use; the instruments are often expensive, need trained operators, and cannot be utilized in the field with close monitoring of the target matrix. In this situation, the creation of simple technologies capable of meeting these critical needs is becoming increasingly vital. Chemical sensor research & development aims to meet these pressing requirements. Electronics is perhaps the most suited technology for sensor production at the present time, since signals can be easily captured, processed, stored, transferred, and utilized by end-users in electronics. As a result, current sensors are electronic devices that generate analogue or digital signals that carry messages about the analytes being detected. The sensing material (or receptor) and the transducer are the two essential parts of such devices.

The objective of a wireless sensor network (WSN) is to perform the task of detection, processing, and transmitting object tracking data in regions where network coverages are limited [2,3]. The device is made up of a large amount of stationary or portable sensor nodes that form a wireless network employing self-organization [4] and the multi-hop method [5]. WSNs are made up of geographically dispersed and independent sensors that are used to detect and monitor physical and environmental factors. They are helpful for collectively transmitting recorded data to a central place over the network. Some of the networks are bi-directional, meaning they gather data from remote sensors as well as manage sensor activity. Spatially scattered and specialized networks aid in the collection of various characteristics using unique sensors incorporated in the WSN. WSN technology was at first primarily motivated by military uses such as battlefield monitoring. Nowadays, such networks are employed in a variety of applications, including industry [6,7], agriculture [8,9], industrial process surveillance [6], machine health management [10], logistics [11,12], hospitals [13,14], environmental monitoring [15,16] and also for target tracking on the battlefield [17].

In general, sensor networks are made up of three components: sensor nodes, sink nodes, and user nodes. Sensor nodes are the basic network; they are in charge of data collection, analysis, storage, and transmission [18,19]. Sensors collect and convert physical characteristics into detectable electric signals from their environment. These qualities include temperature [20], mass [21], speed [22], pressure [23], and heat bodies such as humans [24]. A microprocessor converts electrical impulses into outputs related to a set of measurements. The output is sent to the receivers via the selected devices by the system. Depending on the functional complexity and rising functional needs, a system can employ a variety of sensors with varying capabilities.

Wireless chemical sensors are multifunctional devices that acquire (bio)chemical information from their immediate surroundings. They then analyze and transfer this chemical analytical data to a cloud device or gadgets using wireless technology, most commonly radio transmission [25]. Chemical sensors are classified into several categories based on the idea of transduction [25]. The electronic transduction process tracks the physicochemical changes on the electrode surface. Sensor outputs rely heavily on transduction principles. Examples of the list of chemical sensors include the chemresistor [26], ion-sensitive field effect transistor [27], chemical field effect transistor [28], enzyme field effect transistor [29], and optical surface plasmon resonance [30]. A chemical sensor is made up of two parts: a chemical detection phase and a transduction component. The essential performance factors are sensitivity, selectivity, robustness, power, size, and overhead. In general, wireless chemical sensors can be grouped as optical [31], electrochemical [32], electrical [33], and mass-sensitive sensors [34]. The transducer is a device that converts the chemical energy delivered by the analyte into a valid analytical signal.

The electrochemical interplay of an analyte at an electrode surface is converted into a voltage or current signal by electrochemical sensors. Electrochemical sensors can be classified into two different types: potentiometric sensors [35], which can measure the potential of ion-selective working electrodes against a reference electrode, and voltammetric sensors [36], which are capable of predicting the current flow at a constant or variable potential. Electrochemical sensors are also defined as amperometric; they estimate the current at a constant voltage [37]. By Faraday's law and the law of mass transfer, an

amperometric sensor gives a current signal proportional to the analyte's concentration. It has a linear response to the concentration of the analyte. A wide range of shapes are available for amperometric analyte detection. These devices are portable, with a compact size, low power, excellent sensitivity, and low-cost ranges [38].

To obtain analyte data, optical chemical sensors use optical transduction approaches. Optical absorption and luminescence are the most common mechanisms used in optical chemical sensors; however, sensors based on some of the other spectroscopies, along with optical characteristics such as refractive index and reflectivity are also established [39]. When the energy of an electrically excited state species is emitted in the form of light, it is called luminescence. The emission is termed fluorescence or phosphorescence based on the excited state, singlet, or triplet. Luminescent probes can be used to monitor the pH, CO₂, ammonia, O₂, and a variety of cations and anions. Because luminescence is fundamentally more sensitive than absorption as a sensing technology, luminescence-based detection outperforms absorption sensors in many contexts. It is important to attach analyte-sensitive fluorescence to a conventional optical fibre in order to convert it into an inherently fluorescence-based optical chemical sensor. The fluorescent marker molecules are added to the fibre platform to accomplish this. In biological applications, direct fluorescence detection is commonly employed. Autofluorescence spectroscopy is a non-invasive method for detecting pre-malignant changes in the epithelium, which is where most human malignancies begin. Reduced nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide (FAD) are the two intrinsic fluorophores that cause fluorescence. These species' fluorescence can be utilized to track cell function [40].

Optical sensors based on absorption might be colorimetric or spectroscopic in type. Spectroscopic absorption-based sensors detect the analyte by investigating its intrinsic molecular absorption. Spectroscopic identification has proven to be an effective approach to determining chemical species in various applications. Gases such as CO₂, CH₄, CO, NH₃, and NO₂ have all been detected using IR spectroscopy. In its most basic version, the method entails enclosing a sample of gas in an optical absorption cell and evaluating the absorption at specified IR wavelengths that correspond to the molecule's vibrational modes [40]. Optical chemical sensors may be divided into direct sensors [41] and reagent-mediated sensors [42]. The optical responsiveness of an interim agent, generally an analyte-sensitive dye molecule, is utilized to evaluate analyte concentration in reagent-mediated sensor devices. This approach is particularly beneficial when the analyte lacks a desirable inherent optical property, which is the situation for many analytes.

Electrical chemical sensors are often simpler, with the analytical signal arising from a difference in a material's electrical characteristics, such as the conductivity of a metal oxide semiconductor or organic semiconductor, produced by chemical interaction with the analyte [43,44]. Electrical sensors, particularly conductometric sensors, are the most commonly utilized for gas-sensing applications [43].

1.2. Smartphone Operated Wireless Chemical Sensors

Today's smartphones have multitasking operating systems, excellent performance microprocessors, a diverse range of sensors, and wireless communication technologies that are all highly popular and widely utilized across the globe. The earliest mobile gadget prototype combining telecommunications and computers goes back to the 1970s. However, it was only in the early 1990s that the first commercial smartphones appeared on the market, owing to the development of GSM-based technology (2G) and the transition of mobile telephone communication from analogue to digital. Furthermore, the emergence of rechargeable lithium-ion batteries in the 1990s aided in reducing the weight and cost of mobile phones. The first commercialized smartphone was the Nokia 1011, which debuted in 1992 and included a microphone as an integrated sensor. Then, with Apple's groundbreaking iPhone introduction in 2007, smartphones swiftly gained widespread acceptance.

In 2021, the world's smartphone users numbered around 6.378 billion, representing 80.63 percent of the global population. In all, 7.101 billion individuals own a smart or fea-

ture phone, accounting for 89.76 percent of the world's population. Generally, a smartphone comprises a variety of sensors, such as an accelerometer and a thermometer, to detect data from multiple sources, with the optical camera sensor being the most extensively utilized sensor by customers [45]. The smartphone usually also possesses a fast multicore processor, large memory, adequate battery, audio, USB port, and touch screen to provide powerful computation capability, large data storage, portable power supply, and convenient user interface to interact with the external world. Wireless data transfer methods also enable the transmission of acquired smartphone data to professionals or the cloud, allowing data management for local medical facilities in remote emergencies [46]. As a result, the exact integration of chemical sensing parts and a wireless link into a cohesive hybrid device is heavily influenced by the required application. The selection of wireless technology is heavily influenced by the connection needs of the analytical application, as well as the characteristics and limits of the chemical sensor's signal transduction process. Bluetooth [47], ZigBee [48], radio-frequency identification (RFID) [49], and near-field communication (NFC) [50] are the most often-utilized wireless technologies in chemical sensing nowadays. Smartphones now offer a wide range of advanced computing capabilities and networking options, indicating the migration of traditional desktop-based healthcare equipment to wireless smartphone-based solutions.

Researchers merely need to develop specific auxiliary installations on smartphones for analytical biosensing, which can include light sources, signal detectors, or simple instrumental linkages that provide power and process data, as the features of smartphones become more sophisticated [51]. In the past few years, smartphones have offered individuals mobile, cost-effective, and simple-to-operate technologies to interface with microfluidics and Lab on a Chip to construct analytical biosensors for point-of-care (POC) applications and mobile health [52,53]. The efficacy of smartphone-based analytical biosensors has already been shown in various applications, including medical examinations, pollution monitoring, and food hazard assessment. Figure 1 shows a schematic diagram of different smartphone-supported wireless sensor devices in the field of waste management, public safety, house automation, health care, water pollution, gas and water leakage detection, air pollution, and home diagnostics. Smartphone-assisted WCN is now a thriving academic and industry research field.



Figure 1. Applications of smartphone-based wireless sensors.

2. Methodology and Structure

This review was prepared using Google Scholar and the Web of Science, the online platform for research databases. The keyword “smartphone” was used in combination with “wireless chemical sensor”, “electrochemical sensor”, “Wireless electrical sensors”, “Wireless optical sensors”, and “other wireless chemical sensor”.

This review article provides an overview and introduction to the topic of WCS supported by the smartphone. It was prepared and arranged to provide information about the latest applications and developing trends in academic research in the WCS domains. The article is divided into four parts. This review’s methodology and structure are given in Section 2. Next, Section 3.1 provides an overview of the popular wireless electrochemical sensors utilized in research. This section is dedicated to outlining the fundamental findings of smartphone-assisted electrochemical sensor applications identified in the academic literature, such as water quality monitoring, universal wireless electrochemical detectors, NFC potentiostats, wireless point-of-need detection systems for microcystin-LR (MC-LR), portable smartphone-based electrochemical systems, smartphone-based reusable glucose meters, inkjet-printed electrochemical enzyme-based biosensors, and battery-free and flexible electrochemical sensors. Smartphone-integrated wireless electrical sensors and their applications are discussed in Section 3.2. Here, we discuss the implementation of wireless electrical sensors in wireless electric cars, wound treatment, wireless face masks, player’s workout security to detect meat spoilage, flexible pH sensors, a non-printed integrated-circuit textile (NIT), and its monitoring with the aid of a smartphone. Section 3.3 deals with popular wireless optical sensors merged with real-time tracking of measurements with a smartphone for various applications such as fluorescence analysers, wireless smart bandages, wireless fluorimeters, stretchable microfluidic devices, and wireless glucose monitoring using a smartphone. Subsequently, Section 3.4 describes other wireless chemical sensors using electrochemiluminescence towards fingerprint identification and biochemical sensing. The last part of the review (Section 4) deals with the summary and future perspectives on WCN. Tables 1 and 2 were used to tabulate various wireless chemical sensors supported by smartphones and various commercially available off-the-shelf chemical sensors integrated smartphones, respectively.

3. Wireless Chemical Sensors

3.1. Wireless Electrochemical Sensors

The most popular type of chemical sensor is the electrochemical sensor, which also uses wireless technology efficiently. This section describes various applications of wireless electrochemical sensors supported by smartphones, as shown in Figure 2. Electrochemical sensors based on smartphones are widely utilized in environmental applications for water quality monitoring. J Liao et al. created a system that consists of four key components: (i) a whole-copper electrochemical sensor, (ii) a hand-held detector, (iii) a smartphone with a bespoke application program, and (iv) a Cloud map website, as shown in Figure 3a [54]. The Pb^{2+} ion and chemical oxygen demands of this system were measured *in situ*. Such technologies could aid in the control of the detector, the visualization of testing findings in real-time, and the display of environmental contamination concentrations with geographic locations for public sharing and viewing. Since this smartphone-based system is cost-effective, compact, field-portable, and completely wireless, it has a lot of potential in resource-constrained settings. Recently, A. Ainla et al. have reported a new open-source “universal wireless electrochemical detector (UWED)” capable of performing multiple electroanalytical functions that includes chronoamperometry, potentiometry, square wave voltammetry, and cyclic voltammetry [55]. The detector uses the “Bluetooth Low Energy” protocol to communicate with a smartphone. This sensor displays the results of experimental parameters in real-time for the user and acts as a proxy for storing, processing, and transmitting data and testing methods (Figure 3b). As a result, the UWED is simple, compact, made of low-cost components, and fully wireless, opening up new possibilities for developing moderate diagnostics, sensors, and wearable devices.

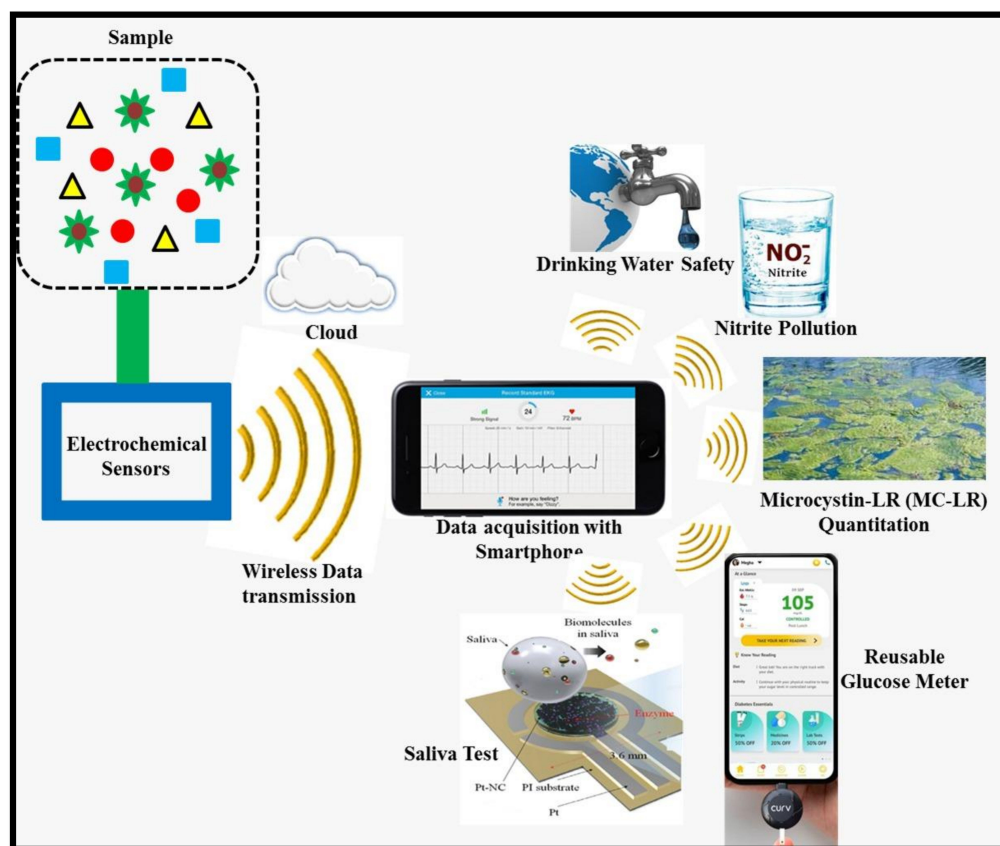


Figure 2. Applications of smartphone-based wireless electrochemical sensors.

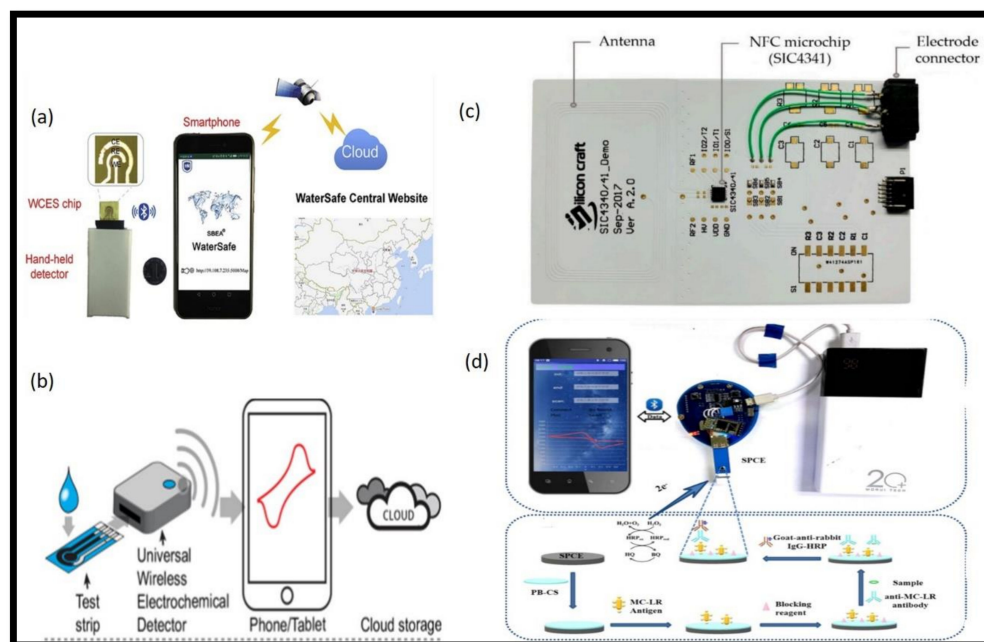


Figure 3. (a) Photograph of a smartphone-based water quality monitoring system, consisting of a WCES chip, a hand-held detector, a smartphone, and a WaterSafe central website [54]; (b) demonstration of how the UWED functions [55]; (c) hardware components consisting of a planar antenna, near-field communication (NFC) microchip, and connector for electrode interface [56]; (d) photograph of the SCEA showing the interface with MC-LR immunosensor and mobile power source [57].

In addition, specific systems successfully integrated into wireless chemical sensors exist. K. Krorakai et al. recently proposed the design of an NFC potentiostat for a smartphone connection and evaluated its analytical performance. The NFC potentiostat performs well in analytical tests such as cyclic voltammetry and chronoamperometry [56]. The NFC potentiostat (Figure 3c), which is compatible with smartphones, is low-cost, compact, and easy to use. As a result, the device can be built for on-site measurements in various disciplines. T. Guan et al. created a real-time, low-cost, portable and wireless point-of-need detection system for microcystin-LR (MC-LR) quantitation in response to the growing demand for portable and easy-to-use devices [57]. Its components include screen-printed carbon electrodes (SPCE), a smartphone-controlled electrochemical analyser, and an Android smartphone, as illustrated in Figure 3d. The smartphone-based device detects active toxicant screening to ensure drinking water safety, especially in resource-constrained areas. A smartphone with a user-friendly tool was used to operate the analyser, receive and analyse data, and display sensing results in real-time. With a detection limit of 0.00011 g/L, this method can reliably quantify MC-LR in the range of 0.001–100 g/L, and the results were compatible with LC–MS/MS. Using this smartphone-based approach, a preliminary MC-LR pollution map was also created by measuring water samples.

As previously reported, a portable smartphone-based electrochemical system was shown to be more suitable for tracking and analysing nitrite pollution in water [58]. A smartphone, hand-held detector, and modified SPCE were components of the system. To evaluate the smartphone's functionality, it was used in four applications: (1) to control the detector, (2) to show the detection data, (3) to connect the system to the cloud, and (4) to detect nitrite with a low detection limit of 0.2 M in a linear range of 1–500 M. As a result, it has a lot of potential for monitoring water quality, especially in low-resource countries. The work published by Berg et al. described the development of a wireless mobile unit containing an electrochemical detection module and a 3-channel high-voltage power supply designed for microchip CE; the device can be integrated and controlled by digital hardware. The lab-on-a-robot device has been used to navigate a global position, acquire an air sample, perform the analysis, and send the data to a remote location [59].

A new smartphone-based reusable glucose meter can measure glucose concentrations [60]. Custom-designed Android-based software is utilized in this system to present measurements in a simple and straightforward manner. Furthermore, a smartphone sensor can overcome issues including enzyme degradation, leaching, and hysteresis effects. AJ Bandodkar et al. demonstrated the effectiveness of the pellet-based sensing system in the development of a reusable, point-of-care sensor that fits around a smartphone and may be used in a variety of healthcare, environmental, and military applications [60]. Here, the operator loads the software, then uses the stylus to discharge an enzyme pellet onto the case's flat sensor strip before adding the sample. The data are subsequently acquired by the electronic module and wirelessly transmitted to the software program, which is then shown on the monitor. Subsequently, the deployed pellet is ejected, leaving the sensor with a clean, bare surface. In another work, the Hepatitis B Virus was detected using an NFC-enabled smartphone-based portable amperometric immunosensor (HBV). The device also enables amperometric detection of Hepatitis B surface antigens (HBsAg) by measuring the current from the $(\text{Fe}(\text{CN})_6)^{3-/4-}$ redox couple before and after the addition of HBsAg [61].

Furthermore, by adding a multi-walled carbon nanotube to increase enzyme loading, Y Bai et al. created an inkjet-printed electrochemical enzyme-based biosensor device for point-of-care analyte detection, aimed at saliva testing [62]. Multi-walled carbon nanotubes were utilized as the enzyme carriers to improve enzyme loading. Enzyme immobility was achieved by crosslinking ink components (BSA and glutaraldehyde) between the printing layers in a layer-by-layer printing method. To avoid using a standard electrochemical cell, reagents for the enzyme-catalysed process were preloaded onto the working electrode. In addition, for real-time data processing on many occasions, a versatile Android smartphone application was developed. The micro-biosensor system has a wide linear range and a quick response time (less than 10 s). The sensor's high selectivity and stability show that it

can be used for saliva tests. Overall, the suggested sensor system in this study reveals a reliable and repeatable biosensor fabrication technique that can be used as a benchmark for comparable point-of-care biosensor systems. A smartphone-based, battery-free and flexible electrochemical sensor for detection of real-time calcium and chloride ions was created by G. Xu et al.; it can be coupled with an NFC module, on-site signal processing circuitry, and an all-printed stretchy electrode array [63]. This platform offers a battery-free, wireless, and flexible solution for smartphone-based electrochemical sensing systems that may be used to perform quick biofluid analysis.

Ji et al. created a hand-held, smartphone-assisted electrochemical module for sensitive glucose measurement in CV mode [64]. The system contains a smartphone to control the electrochemical module and a mobile electrochemical detector to conduct the CV. For the electrochemical module to execute the CV, a digital-to-analogue converter (DAC) was utilized to generate a triangle wave signal (VB) and a constant voltage (VA). Furthermore, a trans-impedance amplifier was used to adjust the voltage between the working and reference electrodes, and to measure the current outputs. Dang et al. devised a wireless pH-monitoring system with flexible electronics and extensible RFID coils for data transmission and processing which was combined with a smartphone [65]. Patients with cystic fibrosis, as well as athletes, should have their pH levels checked regularly. The sensor was volumetrically examined to detect pH changes in the 5–9 range, and it was discovered that it could detect pH changes in both non-stretched and stretched states.

Liu et al. have designed an impedimetric sensor for VOC monitoring based on a custom-designed apparatus for fixed-frequency impedance analysis [66]. The electron-transporting carrier is graphene, while the catalytic oxidation is done with ZnO. A smartphone application controls the entire system through Bluetooth. Ali et al. designed a potentiometric glucose sensor using ZnO nanowires coated with immobilized glucose oxidase [67]. An on-board microcontroller interprets the data, analyses the glucose concentration, and delivers the information as a text message to a mobile phone using the Global System for Mobile Communications (GSM) module.

3.2. Wireless Electrical Sensors

Various applications of wireless electrical sensors supported with a smartphone are illustrated in Figure 4. WCS, with the main advantages of using NFC, permits the fabrication of flexible electronics, and the battery-free device can be exploited in wireless biomedical systems. The sensor can be integrated with the components that perform diagnosis, visualization, and therapy in this system. Recently it was reported that the dressing could effectively inhibit bacterial growth, and these pitfalls can be overcome by accelerating the wound healing based on real-time monitoring of wound treatment by implanting WCS with NFC [68]. Furthermore, the created sensor can detect wound status using temperature, pH, and uric acid. Meanwhile, the dressing's drug delivery electrode is utilized to provide electrically controlled antibiotics for on-demand infection treatment. Wireless technology is vital to consider while building an electric car; it is less expensive and environmentally benign, and it dictates the features and performance that the system can achieve. R. Modak et al. have suggested a system that provides a simulation and prototype for a wireless battery management system for electric vehicles; the system monitors various battery characteristics and displays real-time data on Android smartphones and computers [69]. Here, battery parameters are examined (such as voltage, current, and temperature) to prevent future overcharging and deep drain of the battery. Several sensors can be used to conduct this observation. The ATmega16 controller receives the detected battery characteristics, such as voltage, current, and temperature data, which are then transferred to the cloud for analysis. The battery monitoring information can be viewed on PCs and Android smartphones. This can help us to improve the battery's efficiency and lifespan.

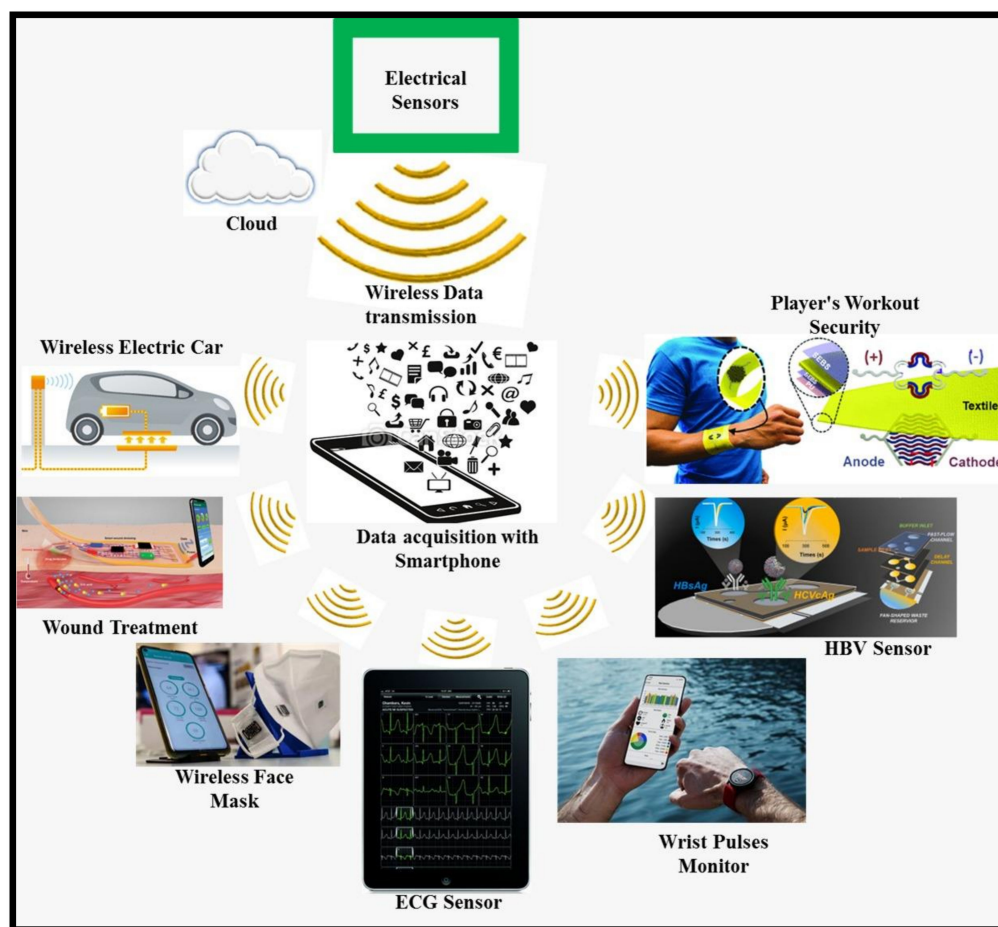


Figure 4. Applications of smartphone-based wireless electrical sensors.

GY Li et al. have developed a hierarchical polyvinylidene fluoride hexafluoropropylene (PVDF-HFP)/ZnO composite nanofiber piezoelectric sensor, which offers a practical solution for high-precision detection and safety monitoring in the medical, rehabilitation medicine, and workout security fields [70]. Furthermore, this sensor has a Bluetooth low-energy transmitter that tracks the user's workout. It communicates the output signals wirelessly to a smartphone app and a Bluetooth low-energy sensor that can reliably detect imperceptible changes in the user's motions. In another work, a smart face mask is now utilized for maintaining personal health and limiting disease spread, but various problems must be overcome before it can be employed in a practical environment. J Zhong's group created a wireless smart facemask by combining an ultrathin self-powered pressure sensor and a small readout circuit with a standard facemask, giving the breath-monitoring device the benefit of readout circuit miniaturization, and making it portable and wearable. Subsequently, these devices turned out to be very cost-effective and helpful in healthcare by reducing patient discomfort [71].

NFC tagging technology has lately been applied to provide smartphones with non-line-of-sight sensing functions to strengthen environmental efforts, healthcare, and quality of life. To help customers, storage, and supply networks to avoid food spoilage, a precise, convenient, and low-cost technique to check the condition of the food is considered necessary. The identification of total volatile basic nitrogen, which includes biogenic amines and ammonia, is used in analytical procedures for evaluating meat deterioration. The fabrication of a sensor with appropriately high sensitivity to operate as a switch for an NFC tag for the purposes of detecting rotting food remains a hurdle. Zhong Ma et al. designed a nanostructured, conductive, polymer-based gas sensor with $R/R_0 = 225\%$ sensitivity to 5 ppm ammonia NH_3 and 46% and 17% to 5 ppm putrescine and cadaverine, respectively [72].

When the concentration of biogenic amines exceeds a predefined threshold, the gas sensor serves as a sensitive switch in the circuit of the NFC tag, allowing a smartphone to detect meat spoilage.

Food spoilage and medicine decomposition are caused by oxygen, which is handled commercially through modified atmosphere packaging. For commercial passive NFC tags, R Zhu et al. have presented the O₂-p-CARD, a wireless oxygen sensor made from solution-processed Fe^{II}-poly(4-vinyl pyridine)-single-walled carbon nanotube composites [73]. In reaction to oxygen at relevant quantities, a substantial irreversible attenuation in the reflection signal of an O₂-p-CARD was found, allowing non-line-of-sight monitoring of changes in atmospheric packing. These devices enable the measurement of cumulative oxygen exposure within packaging using a standard smartphone. An O₂ p-CARD has been shown to detect air entry into a nitrogen-filled vegetable package at ambient circumstances. This technique enables in-situ non-line-of-sight quality monitoring of oxygen-sensitive packaged products using a low-cost, heavy-metal-free, and smartphone-readable method.

The use of nanocomposites in single-wall carbon nanotubes and Nafion to construct high-performance, flexible pH sensors on flexible substrates in ambient air is reported by Jeon et al. [74]. The number of printed layers in multi-patterns regulated the electrical properties; therefore, pH sensors measuring changes in resistance of printed nanocomposite films were able to detect changes in a wide range of pHs from 1 to 12. After 200 cycles of bending tests with a curvature radius of 5 mm, the operational stability of the flexible pH sensors remained essentially constant, which is critical for integrating flexible pH sensors into wearable nanoelectronics. The chemical reaction is used to examine the sensing mechanism of chemiresistive pH sensors made of nanocomposites, as shown in Figure 5a. The hydrogen or hydroxide ions in the pH solution interact with the carbonyl and C-H bonds in the nanocomposite layer, causing positively charged carriers to be induced or withdrawn, respectively [74]. The team developed a real-time pH sensor installed into a drone application associated with a user's smartphone to assess the validity of the proposed pH sensors at a local scale. The system allows users to view the processed data using wireless communication and data-transmitting modules premised on a designed Android algorithm. Y. Yang et al. reported, as an alternative to printed circuit boards (PCB), a non-printed integrated-circuit textile (NIT) for biomedical and theranostic applications using a weaving process [75]. A fibre-type sweat sensor was also woven with strain- and light-sensor fibres (Figure 5b) to monitor bodily health and the environment simultaneously. The NIT is beneficial for routine healthcare, diabetic monitoring, and emergencies such as hypoglycemia, metabolic alkalosis, and even COVID-19 patient care [75].

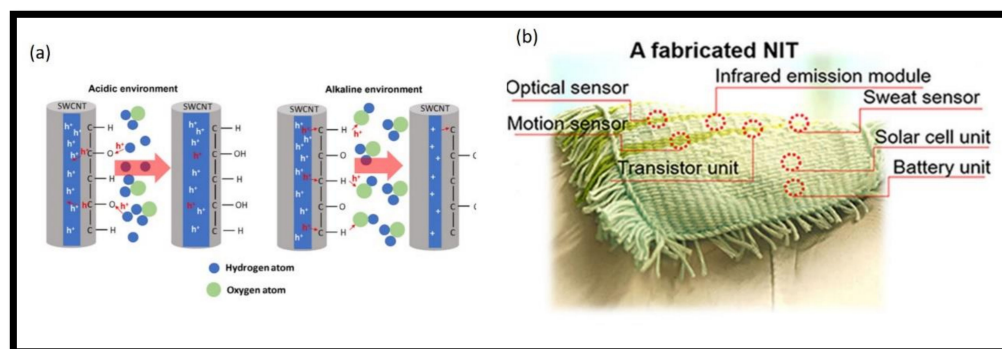


Figure 5. (a) Sensing mechanism of the chemiresistive pH sensors based on nanocomposites [74]. (b) Photograph of a fabricated NIT with a typical NIT-type IC [75].

3.3. Wireless Optical Sensors

Optical sensors with wireless platforms are appealing because of their simple diversity, absorption, lack of reference electrodes, high operational sensitivity, and fluorescence-based indication, which is required in some essential applications. Figure 6 shows an illustration

of various smartphone-supported wireless optical sensors. P Kassal et al. successfully detected pH changes using an external readout unit employing RFID via a wireless smart bandage for optical determination, allowing them to respond to the growing condition of chronic wounds (Figure 7a) [76]. The bandage is made by immobilizing cellulose particles within a biocompatible hydrogel that has been covalently modified with a pH indicator dye. This device could serve as a quick and non-invasive indicator of wound conditions, prompting an appropriate response from a healthcare clinician.



Figure 6. Applications of smartphone-based wireless electrical sensors.

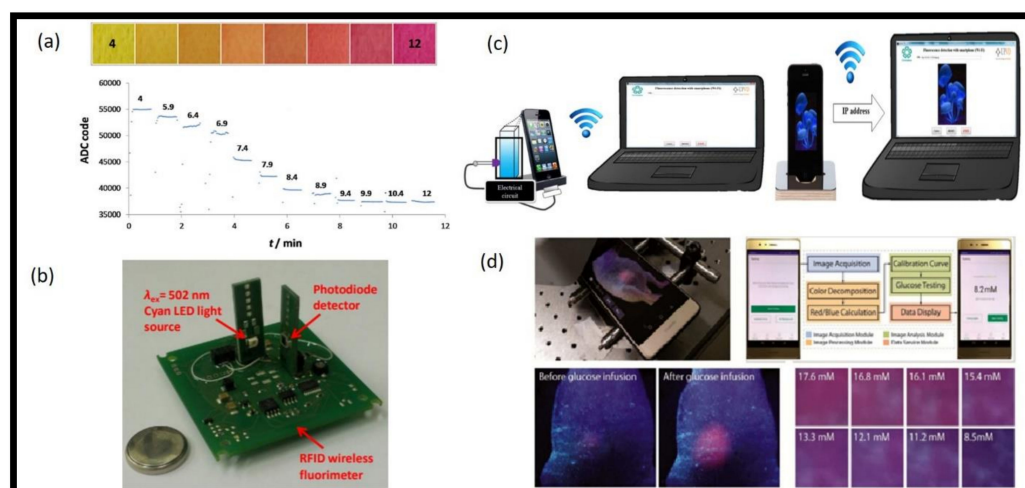


Figure 7. (a) Response of the smart bandage readout electronics to increasing pH values of standard buffer solutions (pH 4–12) [76]. (b) Photograph of the RFID/NFC wireless fluorimeter [77]. (c) Fluorescence analyser developed based on smartphone camera; interface designed for the fluorescence analyser based on smartphone camera [78]. (d) In vivo continuous glucose monitoring in live mice using PD4Gx transducer and smartphone [79].

Wireless chemical sensors are increasingly being used as analytical instruments in areas such as healthcare monitoring, wearable sensing (sweat analysis), and the Sensor Internet of Things. Fluorescence-based sensors trailed behind other transduction mechanisms in such wireless contexts. Kassal et al. introduced a new low-cost, highly portable wireless fluorimeter for measuring optical chemical fluorescence intensity [77]. By RFID or NFC, the fluorimeter is configured and interacts wirelessly with mobile devices or personal computers (Figure 7b).

The researchers created a soft, stretchable, microfluidic device that can detect four analytes in sweat simultaneously: lactate, pH, glucose, and chloride as well as sweat volume and rate [80]. This microfluidic device is made up of three parts: an adhesive layer with sweat capture apertures, a complement of channels and reservoirs with reagents for paper-based colorimetric analysis, and electronics with a magnetic loop antenna for wireless NFC. Sweat is collected in a series of microchannels and reservoirs that employ capillary action and natural pressure to transport sweat to different parts of the body for analysis. When the smartphone is in close proximity to the NFC-enabled device, the camera is automatically activated and a digital image is captured. Human testing on the body revealed great biocompatibility and minimal discomfort or skin irritation.

The use of a smartphone as a fluorescence analyser device was presented as a unique manner to quantify ochratoxin A (OTA) concentrations by D. Bueno et al. [78]. A personal computer analyses the fluorescence image data from the smartphone camera, and the images are then rendered in their Red, Green, and Blue (RGB) components (Figure 7c). Because OTA is naturally fluorescent, it emits blue fluorescence through the solution with OTA, which is recorded using a smartphone camera, but no fluorescence was noticed in the blank solution [78]. In MATLAB R2011a, a graphical user interface was created to process the collected images with a linear range of 2–20 g/L and a detection limit of 2 g/L. As a result, a fluorescence analyser device powered by a smartphone is also possible [78].

Optical approaches for measuring glucose can be extensively investigated, including absorptiometry, fluorescence, and surface plasmon resonance. However, due to the restricted efficiency of optical sensors and the large apparatus required, these strategies have not had the practical success of electrochemical approaches for point-of-care testing. K. Sun et al. demonstrate how an ultrasensitive optical transducer may be utilized for wireless glucose monitoring using a smartphone [79]. The optical transducer is made up of oxygen-sensitive polymer dots (Pdots) and glucose oxidase, which detects glucose when oxygen is used in the glucose oxidation process (Figure 7d). The transducer's sensitivity was increased thanks to the careful design of Pdots with an ultralong phosphorescence lifespan. As a consequence, visual pictures of subcutaneous glucose levels collected with a smartphone camera might be used to differentiate between euglycemia and hyperglycemia [79].

One of the most challenging difficulties in nanobiotechnology is the fast and effective on-site wireless assessment of toxic materials or biomarkers. Gautam et al. describe a unique, smartphone-based, portable, and wireless optical system for quick, quantitative, and on-site measurement of target analytes. In this study, gold nanoparticles and an enzyme, horseradish peroxidase, were used as analytes that produced colorimetric signals in response to two model target chemicals, hydrogen peroxide, and melamine. The device's integrated electronic circuit converts the colorimetric signal provided by the existence of the target molecules to an electrical signal. The transformed electrical signal is then wirelessly analysed using a multimeter in the smartphone, which analyses the data and shows the results, comprising the analyte concentration and relevance. This portable device offers tremendous promise as a programmable and miniaturized platform for quick and on-site detection of numerous analytes in point-of-care testing [81]. Table 1 shows various wireless chemical sensors supported by smartphones.

Table 1. Wireless Chemical Sensors.

Analyte	Recognition Element	Types of Chemical Sensor	Smartphone Interface System	Application	Ref.
Pb ²⁺	Cu working electrodes	Wireless electrochemical sensors	Bluetooth	Water quality monitoring and spatial mapping	[54]
NO ₂ [−]	GO.	Wireless electrochemical sensors	Bluetooth	Water quality monitoring and spatial mapping	[58]
Ca ²⁺ and Cl [−]	Carbon ink	Wireless electrochemical sensors	NFC	Rapid analysis of various biofluids.	[63]
hexacyanoferrate(III) glucose	GOx	Wireless electrochemical sensors	RFID	Direct whole blood testing	[82]
White blood cell	PVDF filter membrane	Wireless electrochemical sensors	Bluetooth	Sports	[83]
pH	Single-wall carbon nanotubes	Wireless electrical sensors	Bluetooth	Real-time pH sensor system	[74]
NH ₃	Conductive polymer	Wireless electrical sensors	NFC	Detecting food spoilage	[72]
NH ₃	Nanowires	Wireless electrical sensors	Bluetooth	Flexible ammonia (NH ₃) sensors	[84]
CO, CO ₂ , SO _x , NO _x , O ₂	MO _x	Wireless electrical sensors	ZigBee	Environmental, pollution	[85]
Ethanol	PEDOT: PSS	Wireless electrical sensors	RFID	General	[86]
VOCs	ZnO-graphene modified electrodes	Wireless electrical sensors	Bluetooth	Sports (acetone), other	[66]
Methanol	CNT	Wireless electrical sensors	Bluetooth	General	[87]
Sevoflurane	MWCNT-loaded Polypyrrole	Wireless electrical sensors	ISM/SRD	General	[88]
Potassium ion	Optode membranes	Wireless optical sensors	RFID	Chemical analysis	[89]
Glucose	Bis-boronic acid fluorescent indicator	Wireless optical sensors	NFC	Implantable, glucose monitoring	[90]
pH	Bromocresol green	Wireless optical sensors	RFID	General	[49]
Acetic acid vapor	Bromophenol blue	Wireless optical sensors	ISM/SRD	Environmental, gas	[91]
O ₂	Pt octaethylporphyrin	Wireless optical sensors	RFID	Food quality	[92]
NH ₃ , H ₂ O ₂ , cyclohexanone		Wireless optical sensors			
Melamine and hydrogen peroxide	Gold nanoparticles and an enzyme, horseradish peroxidase	Wireless optical sensors	Bluetooth	Rapid and on-site detection of various analytes	[81]
pH indicator dye 4-[4-(2-hydroxyethanesulfonyl)-phenylazo]-2,6-dimethoxyphenol	-	Wireless optical sensors	RFID	Wound care	[76]
H ₂ S	-	Wireless optical sensors	Wireless	Quantitative monitor of H ₂ S in wastewater	[93]
O	-	Wireless optical sensors	Wireless	Detect OTA in beer samples	[78]

3.4. Wireless Other Sensors

Electrochemiluminescence (ECL) is an extremely sensitive detection technique [94], in which electrochemical reactions produce electrogenerated compounds on the electrode surfaces when a specific voltage is applied. These compounds then produce an excited state via electronic delivery by reacting with specific components pre-buried just above the electrodes and then descend from the excited state to the initial state, where the luminescence occurs [94]. ECL is now being studied in a variety of ways, from basic research to its use as a foundation for light-emitting sensors and an analytical detection technique. ECL offers the benefit of ultra-sensitivity and reduced background signal, since it does not need an auxiliary excitation light source. Furthermore, the ease of voltage application, quick measurement, localized light emission, and cost-effective set-up helps to minimize instrumentation. In this case, the smartphone could be a cheaper substitute for traditional ECL instruments such as the photomultiplier tube. Smartphones often feature robust data transmission features as well as computational capabilities for imaging data storage and processing. ECL has been used in analytical chemistry and biosensing for many years. Nowadays, as one of the most extensively used mobile devices, the smartphone

has presented an appealing solution as a simple but effective sensing platform to meet the needs of on-site monitoring.

ECL on a smartphone was proposed for fingerprint identification and biochemical sensing was reported by S. Li et al. [95]. The smartphone-based system combined both electrochemical excitation and optical analysis “all in one phone” by incorporating built-in functionalities. The viability of this phone-based ECL system for biological sensing was improved by additional features such as luminescence analysis of nicotine and trinitrotoluene (TNT). Finally, the phone was able to detect foreign compounds on fingerprints, such as nicotine and TNT, in real-time. According to the findings, the system performed well in ECL, particularly in the realms of biochemical sensing and image analysis. Since fingerprints are commonly used to unlock phones, combining fingerprint imaging and sensing on a smartphone might help to advance individual medicine, public health management, and mobile treatment evaluation. X. Ma et al. developed a wireless single-electrode ECL system for the first time by combining single-electrode ECL with wireless energy transmission [96]. A wireless energy-transfer component, a single-electrode ECL device, and a diode make up the whole system. In this approach, the electric current is provided by wireless energy transfer and then rectified by the diode. A PMT detector with a limit of detection of 0.26 M is used in this system to produce a linear response of hydrogen peroxide from 1 to 150 M. Furthermore, the smartphone was used as a detector for real-time detection.

Molecular microscopy approaches are another popular application of wireless chemical sensors supported by smartphones that rely on colorimetric, fluorescent, or luminescent detection methods, which are usually paired with staining of the sample or part of its components. Microscopy images are subsequently evaluated by a qualified specialist or, more recently, by image analysis and machine learning [97,98]. Miniaturized biosensors have recently become popular as point-of-care devices due to their dependable, sensitive, and quick detection of biomolecules as well as their portability. Smartphones’ recent progress in camera and processor technology is being eagerly assimilated with biosensing applications, and this can be a massive benefit for healthcare diagnosis because of their widespread availability. Elsherif et al. created a contact lens-based glucose sensor for continuous tear sample assessment at physiological pH [99]. A glucose-specific phenylboronic acid-modified hydrogel was placed into a commercial contact lens, and the hydrogel swelled when it came into contact with the glucose molecule. The regularity of the dielectric microstructures varies as the hydrogel swells, resulting in a shift in the diffraction pattern of transmitted light. A smartphone’s photodetector captured the reflected light, which can identify glucose in the range of 0–50 mM in 3 s with a sensitivity of 10 nm mM^{−1}. However, before it can be used in clinical settings, the sensor must correct signal interference caused by mechanical strains. It is interesting to note that smartphones are linked to a satellite-based wireless communication system that can be used to build a wireless sensor network. Smartphones generally have GPS built-in that could be used to track analyte distribution over a vast geographic area. Ozcan et al., for instance, have created an optomechanical interface for a smartphone that weighs about 40 g [100]. This gadget featured wireless data connectivity and was used to spatially map mercury (II) ion distribution in the Los Angeles coastal area. This system achieved a detection limit (LOD) of 3.5 ppb for Hg²⁺.

In order to identify the presence of various biological materials, a variety of nanomachines could be placed inside the human body. A wireless body-area network is a network established by this heterogeneous group of wireless body nanosensor nodes (WBAN). Each WBAN is made up of a collection of wireless nanosensor nodes and a unique nanointerface. The nanointerface can largely collect from all nanosensor nodes and perform first-level aggregation before sending it to the data centre for further acquisition and application. The major objectives of WNSN healthcare applications are to assess, monitor, and avoid unhealthy situations such as the presence of viruses on grains, cells, or DNA variants. Nanosensors can be placed in the patient’s environment to track their daily activities and notify emergency personnel if they exhibit any unusual changes in their mindset. WNSN

health applications can also identify the presence of specific molecules, toxins, or viruses and alert a control agent.

In contrast to the above findings in the development of sensor and smartphone systems, Table 2 shows a few commercial off-the-shelf sensors assisted by smartphones. The implementation of a smartphone app to digitize the colours of a colorimetric sensor array is reported by J. Hong et al. [101]. A traditional colorimetric sensor array is made up of several paper-based sensors that report detection findings in terms of colour change. The analysis of colour changes is usually carried out with the naked eye, which can lead to inaccuracies due to human subjectivity and environmental factors. In this work, smartphones have been used to find solutions because they can perform spectrometric operations. S. Srivastava et al. have reported on the development of on-the-spot heavy metal concentration detection in drinking water samples that is ultra-portable, quick, cost-effective, and simple to operate [102]. The proposed method integrates commercially available heavy metal detection kits with newly built spectrometer-based outputs for concentration estimation, quality rating, and automatic data collecting. The created spectrometer can be used in conjunction with an Android app on a smartphone or independently. M. Rossi et al. have produced an air-quality-measuring and natural gas-leakage approach that relies on a wireless sensor network [103]. The platform is constructed on catalytic off-the-shelf gas sensors and uses a new sampling and processing technique that allows for a one-order-of-magnitude reduction in energy consumption. The created wireless sensor network was additionally expanded with the use of a smartphone to allow data exchange over the internet and to improve the whole system's mobility.

Table 2. Smartphone assist commercial off-the-shelf wireless sensor.

S. No	Role of Smartphone	Commercial Sensors	Application	Reference
1	Measure temperature, pressure, carbon monoxide	Sensordrone	Environmental monitoring	[104]
2	Breath analysis	Mobile spirometers	Human behaviour analysis	[105]
3	Hazardous chemical detection	environmental mobile device	Environmental monitoring	[106]
4	Digitizes the colours of the colorimetric sensor array	colorimetric sensor	Point-of-care (POC) diagnosis	[101]
5	Spectrometer-based readout	spectral sensor (AS7262)	Onsite heavy metal concentration measurement in drinking water samples	[102]
6	Data storage and transmission	Electrochemical sensors	Real-time water quality monitoring system	[107]
7	Built large scale sensor network	MiCS-OZ-47 sensor	Environmental monitoring	[108]
8	Identification and detection of chemical, biological, and explosive (CBE) materials	Explosives sensing kits	Defence	[109]
9	Data sharing over the internet and to enhance portability	Gas sensors	Environmental monitoring	[103]
10	Control the analyser, receive and analyse data, and display detection results in real-time	ARM STM32 microcontroller	Point-of-need detection of microcystin -LR	[57]

4. Summary and Outlook for Future

As a result of the advent of new technologies, mobile phone instrumentation and monitoring applications have advanced significantly over the last decade. This evolution has occurred for two primary reasons: novel sensors embedded on smartphones can detect an increasing number of physical quantities, and additional wireless connection options as well as sophisticated visual platforms are available to send research findings. A wide range of mobile phone sensors have been developed and are used daily.

This review paper summarized wireless chemical sensors on smartphones for biological and chemical detection. Smartphone-based sensor systems have been broadly

categorized as follows: (1) electrochemical biosensors on smartphones that use portable electrical detectors to evaluate amperometric, potentiometric, and impedimetric parameters for chemical detection in water-quality monitoring, a “universal wireless electrochemical detector (UWED)” capable of performing potentiometry, chronoamperometry, cyclic voltammetry, and square wave voltammetry; a design of an NFC potentiostat for smartphone connection and evaluation of its analytical performance; smartphone-based device detection used for active toxicant screening to ensure the safety of drinking water, tracking and analysing nitrite pollution in water, determination of global positions, acquisition of an air sample, performance of analysis, and sending of data to a remote location, a pellet-based sensing system used in the development of a reusable, point-of-care sensor that fits around a smartphone and may be used in a variety of healthcare, environmental, and defence applications; an inkjet-printed electrochemical enzyme-based biosensor device for point-of-care analyte detection, designed for saliva tests, and a smartphone-based battery-free and flexible electrochemical sensor to detect real-time calcium and chloride ions were created.

(2) Smartphone-supported electrical chemical sensor for wound healing for real-time monitoring of wound treatment, which is especially important in wireless-based biomedical systems where the sensor integrates monitoring, diagnosis, and therapy; a simulation and prototype for a wireless battery management system for electric vehicles that monitors various battery characteristics and displays real-time data on Android smartphones and computers; a practical solution for high-precision detecting and safety-monitoring in medical, rehabilitation medicine, and workout applications; a wireless smart face mask for maintaining personal health and limiting disease spread; the detection of the Hepatitis B Virus using an NFC-enabled smartphone-based portable amperometric immunosensor; monitoring of human wrist pulses with a wireless module and smartphone, demonstrating rapid response, high sensitivity, and medical applications; a simple and efficient method for displaying the visualization of real-time ECG signals transmitted wirelessly using a developed ECG sensor on a smartphone; diagnosis of tachypnea with good sensitivity and specificity; and a non-printed integrated-circuit textile for biomedical and theranostic applications.

(3) Wireless optical sensors supported with a smartphone were discussed for applications such as a quick and non-invasive indicator of wounds; a fluorescence analyser device was also discussed. These applications were exceptional due to their features of wireless, battery-free sensor systems, lack of need for contact, advanced computing ability, and simple user interface. In summary, these smartphone-integrated wireless optical sensors can provide advanced mobile systems for performing, analysing, controlling, and displaying sensor processes for numerous applications.

Many active wireless systems have radios that receive, generate, and transmit radio-frequency waves. Active radios need a power supply, which is typically a battery. Active systems often have the capacity to exchange data at high rates and across great distances while using energy. WCS, for example, based on Bluetooth or ZigBee technology, will have an active transceiver capable of communicating with a master controller, reading device, or other sensors in the network across long distances [48,110]. As a result, active WCSs must include a battery or some other form of energy supply to operate both the sensor electronics and the data transfer. On the other hand, passive transponders interact with an interrogator by reflection or modification of the radio-frequency electromagnetic field created by the reader and, as a result, do not always require the presence of radio [111]. Notably, the passive transponders do not require a battery, and this form of passive operation is available with all Radio Frequency Identification (RFID) [112,113]. On the other hand, near field communication (NFC)-based sensors [114] are also used because of their compact sizes and minimal energy usage. However, all passive sensing devices have a relatively small read range compared to active radio systems, from a few centimetres by NFC to several meters by RFID. Furthermore, if there is no battery, the sensor cannot write data to memory on its own.

The application-dependent fabrication of chemical sensors is based on their sensing mechanism, materials, immobilization process, and wireless technology selection. These are correlated with many factors, such as detection limit, sensitivity, power consumption, bat-

tery life, data rate, and so on. Several of the wireless sensors studied employed proprietary wireless modules, but the research emphasis has turned to standard wireless communication protocols such as Bluetooth, ZigBee, RFID, and NFC. Smartphone-compatible radio standards, such as Bluetooth and NFC, are becoming increasingly popular as the platforms of choice for chemical sensor researchers due to the pervasiveness of smartphones. In the coming years, possible advancements in mobile phone devices may include improved operating systems for data acquisition, user-friendly processing for all consumers, implementation in remote areas, advanced technologies for enhanced power-processing, and reduced power consumption. In addition, the development of new technologies towards smart display with even more energy efficiency and flexibility may allow these sensors to merge with smartphones to enable faster battery charging and rapid wi-fi connectivity.

In order to facilitate their connectivity with wearable items such as bracelets, watches, earrings, necklaces or various types of textiles, the circuit footprint is typically on the order of several mm². Additive manufacturing techniques such as ergonomic casings and enclosures, conductive screen-printing of electrodes, sensors, and antennae, embroidering conductive wires into fabrics, or flexible/stretchable electronics have all been used to promote integration. The hardware part includes ultra-low-power electronics, optimized circuit routing, etc.; transmission protocol or software viz. optimized device states and updated MAC protocols, energy-efficient routing protocols, and friendly and hybrid network methods used to reduce energy consumption. Other factors, including antenna size constraints, poor antenna-coupling conditions, and the impact of the human body on the antenna radiation all limit performance and affect the amount of energy accessible. Alternative ideas, such as the use of artificial electromagnetic bandgap implanted antennas to improve the efficiency of the antenna in contact with the individual, have been explored. Some areas for improvement have been highlighted. The combination of RFID modules with WSN nodes will result in a higher density of components, all of which will utilize the same spectrum. As a result, the amount of interference in the transmission medium will rise, posing a research problem. Furthermore, the data transmission or the introduction of a multi-hop network capability to increase the range of an RFID-WSN network, among other things, are demonstrated as potential solutions to this problem. Furthermore, RFID-WSN simulators have been discovered, which can aid in the development of these systems.

WSNs are utilized for sensing the environment and placing objects or persons, whereas RFID networks are targeted at determining the presence of tagged things. On the one hand, RFID provides a number of capabilities, such as recognizing and monitoring objects and the detection of energy from radio frequency signals, which can help a WSN overcome some of its shortcomings. The combination of RFID with WSN, on the other hand, allows RFID technology to extend its read range and become part of a strongly interconnected network using a more widely used protocol, such as IP. A supervisor microcontroller, an RFID reader, and an RF transceiver make up a comprehensive WSN node. This microcontroller is in charge of the reader and the remaining node's elements. A microcontroller, a sensor, and an RF front-end to connect with other nodes or tags make up an integrated RFID tag with WSN features. These tags broadcast their ID and data from the sensor they are linked to.

The Internet of Things is becoming a reality, but there are still a number of obstacles to overcome before it can be widely accepted. RFID and WSN are two of the most important technologies for the Internet of Things. Some unsolved issues that may pique the interest of academics remain; resolving them may allow these two technologies to go from research concepts and prototypes to robust and strong solutions that benefit everyone. For various detection techniques, a variety of chemical sensors may now be incorporated into a smartphone. The notion of a smartphone-based sensor system, on the other hand, is fairly recent, and the devices are commonly shown in laboratories using standard testing. In reality, chemical sensors on smartphones must be built for point-of-care detection beyond the laboratory environment with little user interaction as portable detecting platforms. Further work should be done in sensor manufacturing, data transmission, and smartphone processing algorithms to boost performance while maintaining portability and cost-effectiveness.

Smartphone-assisted wireless chemical sensors, we think, will play a significant role in individualized point-of-care monitoring for applications in solving environmental pollution, illness diagnosis, and water quality management.

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