Chapter 4

Smartphone as a Portable Detector, Analytical Device, or Instrument Interface

Diana Bueno Hernández, Jean Louis Marty and
Roberto Muñoz Guerrero

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69678

Abstract

The Encyclopedia Britannia defines a smartphone as a mobile telephone with a display screen, at the same time serves as a pocket watch, calendar, addresses book and calculator and uses its own operating system (OS). A smartphone is considered as a mobile telephone integrated to a handheld computer. As the market matured, solid-state computer memory and integrated circuits became less expensive over the following decade, smartphone became more computer-like, and more more-advanced services, and became ubiquitous with the introduction of mobile phone networks. The communication takes place for sending and receiving photographs, music, video clips, e-mails and more. The growing capabilities of handheld devices and transmission protocols have enabled a growing number of applications. The integration of camera, access Wi-Fi, payments, augmented reality or the global position system (GPS) are features that have been used for science because the users of smartphone have risen all over the world. This chapter deals with the importance of one of the most common communication channels, the smartphone and how it impregnates in the science. The technological characteristics of this device make it a useful tool in social sciences, medicine, chemistry, detections of contaminants, pesticides, drugs or others, like so detection of signals or image.

Keywords: smartphone, detection, chemistry, optical, medicine, mobile applications, instrumental interface

1. Introduction

Smartphones are similar to notebook computer with its own operating system, processor, internal memory, and high-quality camera lenses [1]. The smartphones are more accessible and cheaper than portable analytical devices. According to eMarketer, the number of smartphone users worldwide surpassed 2 billion in 2016 and it represents more than a quarter of the global population. For 2018, the mobile users will grow to more than 2.56 billion people or a third of the world's population. However, the latest annual Mobility Report from Ericsson indicated that nowadays, there are 84 million new mobile subscriptions, reaching a total of 3.9 billion of smartphone subscriptions. Mobile subscriptions are growing at around 3 percent year-on-year globally. And it have been estimated that there will be a 6.8 billion of smartphone subscriptions for 2022. This growth has a big impact, and it highlights the opportunity to create apps and other services to meet our necessities in a practical way. The smartphone ownership rates in emerging and developing nations are rising, 21% in 2013 and 35% in 2015. **Figure 1** shows a distribution of the smartphone users by countries [2].

The continuous improvement of smartphone electronics, the development of new app and the increase of users have stimulated research in the use of smartphone. Smartphone technology now includes a range of detection capabilities, thanks to the built-in camera, such as colorimetric detection [3], optical methods that are employed in an easy way and to share the information on real time, as well as quantification [4], monitoring [5], or mobile applications [6–8] developed to solve a problem such as freezing of gait in Parkinson's disease [9], glucose monitor [10], and to detect enzymes [11, 12]. Also, it is used to developed devices, a

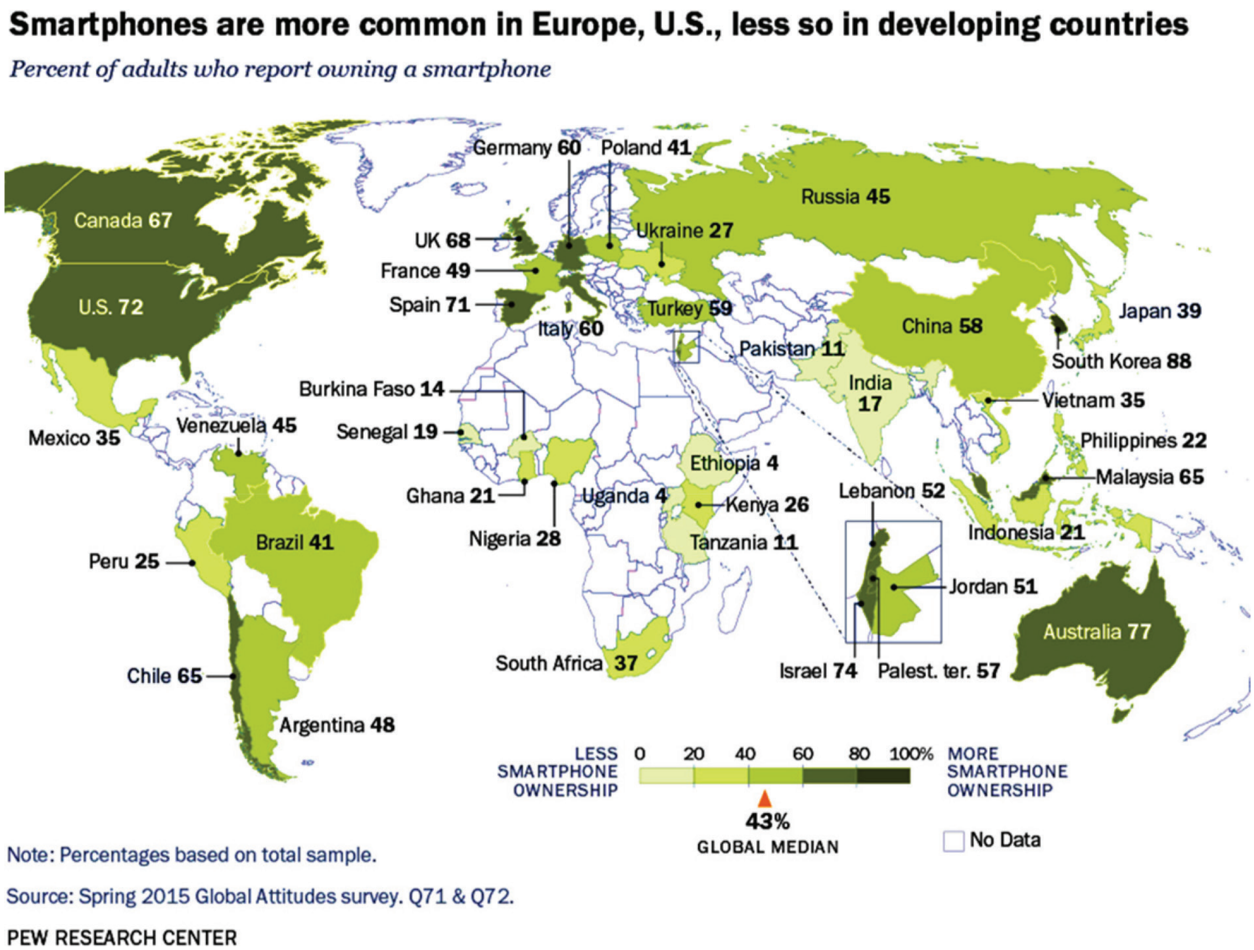

Figure 1. Smartphone's users in worldwide.

spectrophotometer [13, 14] and an electrocardiograph [15], and to create sensors or biosensors [1]. Some applications in healthcare, are: melanoma detection [16], cancer prevention [17], emergency signal detection [18], optical imaging techniques for diagnostics [19, 20], or detection [21]. Besides, in the environment, the smartphone has been used to analyze the quality of the water [22] to detect its salinity [23] or to detect mycotoxins [24, 25]. A complete revision of the applications in different area, devices developed, and limit of detection (LOD) of difference samples will be included in this review.

In this review has been illustrated the smartphone as a research tool to the detection and analysis, because these can be employed in interdisciplinary areas. One the most representative characteristics of the smartphone is that it allows the portability because of its size and its cost compared with commercials instruments. The smartphone sensors have the capacity to effectively serve as portable biofeedback devices for a diverse range of applications in science. Its processor allows you to collect, analyze, and process images or signals in an embedded way.

2. Applications of the smartphone

There have been many recent publications on the use of smartphone as portable detector, bioanalytical devices and instruments interfaces, among others. The use of smartphone had created opportunities for diagnostic, prognostic, detection, quantification, monitoring, control or make mobile applications, because it could be used to run routine test, does not need trained personal, its portability and is considered as a low cost device. Moreover, to have a complete overview of the real advantages, applications or characteristics of the smartphone, it is important to point out the problems with the sampling of real samples (biological, food, environmental), and these need conventional devices to compare the results.

Sometimes, a smartphone is coupled with a device that contains the components of an instrument in a simplified format. For analytical applications, the smartphone is used to control the experimental device and display the results on a dashboard in a tablet, television, computer or other screen and to communicate via USB port, Bluetooth or Wi-Fi between the smartphone and the analytical device. Some examples are described as follows.

2.1. Medicine

Smartphone offers potential for medical diagnosis [26, 27] and treatment of pathologies as a low cost system. There is an increasing interest to detect analytes of clinical interest as employing the mobile phone camera for DNA detection [28], DNA amplification uses the convective polymerase chain reaction technique, and the detection is carried out with the variation in the fluorescence. The fluorescence increment used the brightness of the image before and after the DNA amplification. If there is a difference between before and after the DNA amplification, the test is positive. This process can be used for screening hepatitis B virus plasmid samples.

In 2014, Guan et al. introduced a barcode design into a paper-based blood typing device by integrating with smartphone, and this device involved the use of hydrophilic bar channels treated with anti-A, B and D antibodies. These channels were then used to perform blood typing assays by introducing a blood sample. Blood type can be visually identified from eluting lengths in bar channels. A smartphone application was designed to read the bar channels, analogous to scanning a barcode, interpret this information, and then report the results to users [29].

The development of a microscope attached to smartphone was reported by Breslauer et al., and the authors demonstrated the applicability of this device for clinical diagnostics of *P. Falciparum* and *M. tuberculosis*, providing an important tool for disease diagnosis and screening, particularly in the developing world and rural areas where laboratory facilities are scarce, but mobile-phone infrastructure is extensive [30].

Surface plasmon resonance (SPR) detection system based on a smartphone was proposed by Preechaburana et al. where the authors demonstrated that the resolution of the device employing the smartphone is comparable with conventional analytical SPR. The assays were made for the detection of β2 microglobulin, biomarker for cancer, and were achieved a limit of detection of 0.1 mg/mL in urine [31]. More works about the use of the smartphone are presented in **Table 1**, where the samples detected and brief descriptions of the work are mentioned.

2.2. Chemistry

Nielsen reports that between 2009 and 2011 smartphone ownership for 13–17 year olds and 18–24 year olds went from 16 to 40% and from 23 to 53%, respectively, an increase of 100% approximately. Smartphone serves as powerful educational tool on a mobile platform, which encourages learning. The mobile applications, or "apps," have a wide range of functionalities and cover many disciplines. Collaboration through the interconnection of multiple chemistry apps has demonstrated that chemo-informatics is a tool to increase work efficiency, which can be utilized to raise the chemistry learning experience to a new level, and Chemspider app is a powerful handheld chemical search engine. This chapter [46] discusses apps that are available on smartphone, as these are more prevalent, affordable, and portable than comparable tablets or laptops.

A novel approach for an inexpensive and disposable colorimetric paper sensor array for the detection and discrimination of five explosives (triacetone triperoxide, hexamethylene triperoxide diamine, 4-amino-2-nitrophenol, nitrobenzene and picric acid) was presented by Salles et al. [47]. The colorimetric sensor was designed as a disposable paper array fabricated with potassium iodide, creatinine and aniline, which produces a chemical reaction, a specific color pattern for each explosive. The analytes were identified and classified for each explosive by the changes in the color patterns, which were extracted using a smartphone camera installed in a closed chamber to avoid the illumination interactions. A semiquantitative analysis was performed, and it was possible to use as low as 0.2 mg of explosives. Others detections with the smartphone are presented in **Table 2**.

Samples	Detection/quantification	Short description	References
Vitamin D	Measure physiological levels of 25-hydroxyvitamin D with accuracy better than 15 nM and a precision of 10 nM	The system consists of a smartphone accessory, an app and a test strip that allows the colorimetric detection of 25-hydroxyvitamin D using a novel gold nanoparticle-based immunoassay	[4]
Freezing of gait (FOG) is a motor symptom in patients with Parkinson's disease (PD)	98 FOG events were recognized, and seven FOG events were missed by the application. Sensitivity and specificity were 70.1 and 84.1%, for the Moore-Bächlin Algorithm, rising to 87.57 and 94.97%, for the second algorithm employed	In order to verify the acceptance of a smartphone-based architecture and its reliability at detecting FOG in real-time, 20 patients were studied. It consisted to make a video-recorded Timed Up and Go using the smartphone; the video was synchronized with the accelerometer to assess the reliability of the FOG detection system as compared to the clinicians. The algorithms employed were the Freezing and Energy Index (Moore-Bächlin Algorithm)	[9]
Salivary glucose	Detection range of 9–1350 mg/dL glucose at a response time of 45 s and LOD of 22.2 mg/dL	The assay consisted to immobilized glucose oxidase enzyme on filter paper strip (specific activity 1.4 U/strip); the enzyme reacts with synthetic glucose samples in presence of co-immobilized color pH indicator. Then, the changes in the filter paper based on concentration of glucose are detected. Once the biosensor was standardized, the synthetic glucose sample was replaced with human saliva	[32]
Salivary cortisol	LOD of 0.3 ng/mL. It provides quantitative analysis in the range of 0.3–60 ng/mL	The biosensor is based on a direct competitive immunoassay with peroxidase–cortisol conjugate by adding the substrate luminol/enhancer/hydrogen peroxide, and it produces a chemiluminescence reaction. The smartphone was used to detect the light generates by the reaction through the camera as image and the data handling via an application	[33]
Blood hematocrit	0.1% of hematocrit with a sensitivity of 0.53 GSV (a.u.)/hematocrit	Using an integrated camera in the smartphone, pictures of human blood in the microchannel were taken and analyzed by a mobile application. The characterization of the depth of the microfluidic channel demonstrated that a shallower depth of the microchannel enhanced the sensitivity of the hematocrit determination	[34]
Albumin in urine	5–10 $\mu g/mL^{-1}$ (which is more than three times lower than the clinically accepted normal range)	The test and control tubes are excited by a battery powered laser diode; its fluorescent emission is collected perpendicular to the excitation by a smartphone camera, through external plastic lens inserted in the camera lens. The images are digitally processed within one second through an Android application, with the purpose to quantify the albumin concentration in the urine samples	[35]

Samples	Detection/quantification	Short description	References
Thyroid stimulating hormone (TSH)	0.31 mIU/L	Employing the methodology of the optimized Rayleigh/Mie scatter detection with the optical characteristics of a nitrocellulose membrane and gold nanoparticles for quantifying TSH levels. Using A miniature spectrometer, light-emitting diodes (LED) as light source and optical fibers on a rotating benchtop apparatus, the light intensity from different angles of incident light and angles of detection were measured. A bracket was designed to support the cell-phone and the embedded flash as the light source, through a collimating lens to illuminate the assays, and quantified the concentration of TSH in an iOS application, and it was verified using a code made in MATLAB	[36]
Cholesterol in blood	Cholesterol levels within 1.8% accuracy in the relevant physiological range (140 mg dl^{-1} to 400 mg dl^{-1})	A smartcard, smartphone Cholesterol Application for Rapid Diagnostics system. The system can quantify cholesterol levels from colorimetric changes due to cholesterol reacting enzymatically on a dry reagent test strip. The smartphone acquires the image of the test strip and an app that analyzes parameters such as hue, saturation and luminosity of the test area quantifies the cholesterol levels and displays the value on the screen	[37]
Glucose and urea	Glucose had a concentration ranges 30–515 mg/dl and 2–190 mg/dl for blood urea nitrogen (BUN)	Smartphone equipped with a color analysis application was combined with Vitros® glucose and urea colorimetric assays. Color images of assay slides at various concentrations of glucose or urea were collected and quantitated in three different spectral ranges (red/green/blue or RGB). When the diffuse reflectance data were converted into absorbance, it was possible to quantitate glucose or BUN	[38]
Kaposi’s sarcoma	It can detect DNA sequences from KSHV down to 1 nM	Kaposi's sarcoma (KS) is an infectious cancer occurring in immune-compromised patients, caused by Kaposi's sarcoma associated herpesvirus (KSHV). In this work, a smartphone accessory capable of detecting KSHV nucleic acids was developed. The accessory reads out microfluidic chips filled with a colorimetric nanoparticle assay targeted at KSHV	[39]
DNA molecules	Longer DNA samples imaged over a field-of-view of 2 mm	The images and the length quantification of single-molecule DNA strands using a fluorescence microscope installed on a mobile phone. An optomechanical bracket with lens, thin-film interference filters, laser-diode and a mobile phone application were designed to measure the lengths of DNA molecules labeled and stretched using disposable chip	[40]

Samples	Detection/quantification	Short description	References
DNA/RNA analysis	Replication of Staphylococcus aureus and λ-phage DNA targets in less than 20 min, in-flight	This approach exploits the ability to isothermally perform the polymerase chain reaction (PCR) with a single heater, enabling the system to be operated using standard 5 V USB sources that power mobile devices. Time-resolved fluorescence detection and quantification is achieved using a smartphone camera and integrated image analysis app	[41]
Glucose	~3.5μm	Khan et al. described a label-free, optical sensor capable to detect the changes in photoluminescence (PL) of a thin polymer film employing the glucose as the target molecule, the radiance changes of the quantum dots in PL of the UV excitation of the enzymatic reaction, allows quantifying the level of glucose	[42]
Protein	Bovine serum albumin (BSA) of 1.78μg/ml Thrombin of 2.97ng/ml	A smartphone-controlled biosensor system is developed with electrochemical impedance spectroscopy (EIS) to detect proteins for POC testing. Printed carbon electrodes and interdigital gold electrodes were modified with biocomponents as biosensors for quantification of the protein binding and enzyme activities by special antibodies and peptides immobilized on the electrodes	[43]
pH in sweat and saliva	Unmentioned	A smartphone camera and colorimetric detection of pH in sweat and saliva. Sweat pH can be correlated to sodium concentration and avoid the risk of muscle cramps. Salivary pH below a critical threshold is correlated with enamel decalcification, an acidic breakdown of calcium in the teeth	[44]
Escherichia coli and gonorrhea in human urine	10 CFU/mL for both	Anti-*Escherichia coli* or anti-*Neisseria gonorrhoeae* antibodies were conjugated to submicron particles. The bacteria-spiked urine samples were introduced to the inlet of paper microfluidic channel, which flowed through the channel by capillary force. Urobilin, the component responsible for the yellow appearance of urine and green fluorescence emission, was filtered by a microfluidic paper analytical device (μPAD). The extent of immunoagglutination was quantified by angle-specific Mie scatter under ambient lighting conditions, utilizing a smartphone camera as a detector	[45]

Table 1. Uses of the smartphone in medicine.

Samples	Detection/quantification	Short description	References
Lactate in oral fluid and sweat	0.5 mmol L^{-1} in oral fluid and 0.1 mmol L^{-1} in sweat	To develop a portable lactate chemiluminescent biosensor, based on the coupling of the enzymatic oxidation of lactate catalyzed by L-lactate oxidase with the luminol/H2O2/HRP CL system, using disposable analytical cartridges to allow measurement of the light produced by the enzyme reaction and a smartphone camera to detect the light	[48]
Liquids	Unmentioned	A handheld automated microfluidic liquid handling system is controlled by a smartphone, which is enabled by combining elastomeric on-chip valves and a compact pneumatic system, and it can automatically perform all the liquid handling steps of a bead-based HIV1 p24 sandwich immunoassay on a multi-layer PDMS chip without any human intervention	[49]
Cocaine	LOD of 0.25 mg/mL	An assay based on the gold nanoparticle conjugate (AuNPs) difference in affinity for single-stranded DNA (nonbinding) and double stranded DNA (target bound). The AuNPs and the aptamer were incubated prior to target addition to passivate the AuNPs surface. The adsorbed aptamer was able to bind the target to avoid nonspecific interactions. To facilitate the assay analysis, an android application for automatic colorimetric characterization was developed	[50]
H_2O_2 Glucose in phosphate buffer Artificial urine	1.75 μM 0.017mM 0.030mM	A handheld paper-based bipolar electrode-electro-chemiluminescence (P-BPE-ECL) system with a rechargeable battery as power supply and smartphone for readout of ECL signal is employed. In the case of the electro-chemiluminescence reaction, the carbon ink-based bipolar electrode and driving electrodes are screen-printed and the wax-screen-printing is employed to fabricate the microfluidic channels. The luminol/H2O2-based ECL reaction is applied to quantify the P-BPE-ECL system	[51]
Heavy metals	Cu (II)=0.29 ppm Ni (II)=0.33 ppm Cd (II)=0.19 ppm Cr (VI)=0.35 ppm	A 3D paper-based microfluidic device for colorimetric determination of selected heavy metals in water samples. The process is as follows: the samples are immersed into the paper chip and the sample streams reaching into the detection zones. Finally, the activation solutions are dropped to get metal chromogenic reactions that are captured by a camera cell phone and analyzed in a personal computer employing image processing and analysis software	[52]
Salmonella spp. *Escherichia coli* O157	10^5 CFU (colony forming units) mL^{-1}	Silica nanoparticles (SiNPs) were doped with FITC and Ru, conjugated to the respective antibodies and used in a conventional lateral flow immunoassay (LFIA). Fluorescence was recorded by inserting the nitrocellulose strip into a smartphone-based fluorimeter consisting of a LED, a fluorescence filter set and a lens attached to the integrated camera. The images were analyzed by exploiting the quick image processing application of the cell phone and enable the detection of pathogens within few minutes	[53]

Samples	Detection/quantification	Short description	References
Salmonella	10^2 CFU mL^{-1} with a linear range up to 10^5 CFU mL^{-1}	Each microfluidic channel was preloaded with anti-Salmonella Typhimurium and anti-Escherichia coli conjugated. The paper microfluidic device was submerged into the Salmonella solutions led to the antibody-conjugated particles to immunoagglutinate. The immunoagglutination was quantified by evaluating Mie scattering from the digital images captured. A smartphone application was designed and programmed to allow the user to position the smartphone at specific angle and distance from the microfluidic device. Besides, an image processing algorithm was implemented to quantify the bacterial concentration	[54]
Amines	Less than 1ppm	Bueno et al. present the use of solvent cast cellulose acetate membranes to immobilize dyes and to employ the membranes as a plastic device to identify between different types of amines (triethylamine, isobutyl amine, isopentylamine). The device consisted of an array of membranes with five pH indicators (alizarin, bromophenol blue, chlorophenol red, methyl red and thymol blue). A smartphone was used to analyze the data, to capture the images and to extract the red, green and blue (RGB) components from the image to generate a unique color pattern	[55]

Table 2. Applications of the smartphone in chemistry area.

2.3. Food

A smartphone-utilized biosensor was developed for detecting microbial spoilage (Escherichia coli) on ground beef, without using antibodies, microbeads or any other reagents, toward a preliminary screening tool for microbial contamination on meat products and potentially toward wound infection. Near infrared LED was used to irradiate perpendicular to the surface of ground beef, and the scatter signals at various angles were evaluated utilizing the gyro sensor and the digital camera of a smartphone. The fluorescence microscopy experiments revealed that the antigens and cell fragments from E. coli bonded preferably to the fat particles within meat, and the size and morphologies of such aggregates varied by the E. coli concentration, concluded by Liang et al. [56].

Yu et al. designed a disposable lateral flow-through strip for smartphone to fast one-step quantitatively detect alkaline phosphatase (ALP) activity in raw milk. The strip comprises two functional components, a conjugation pad loaded with phosphotyrosine-coated gold nanoparticles and a testing line coated with anti-phosphotyrosine antibody. The dephosphorylation activity of ALP at the testing zone can be quantitatively assayed by monitoring the accumulated gold nanoparticles and induced color changes by smartphone camera, thus providing a highly convenient portable detection method, demonstrating the potential of smartphone for pathogen detection. Other application of the biohazard-free lateral flow-through testing strip is for the fabrication of rapid, sensitive and inexpensive enzyme or immunosensors for food contamination, food quality inspection or clinic [57]. Allowing the diagnosis or analysis, some elements detected in food are represented in **Table 3**.

Samples	Detection/quantification	Short description	References
L-glutamate dehydrogenase in wine and instant soups	0.5–5.0 mmol L^{-1} for image processing (linear range) The LOD was 0.05 mmol L^{-1} and 0.028 mmol L^{-1} by naked eye and image processing, respectively	A chromatography paper for the analysis of selected food compounds was developed by Monosik et al. The biochemical colorimetric assay utilizes enzymes from the dehydrogenase family coupled with diaphorase in the presence of a tetrazolium dye, MTT and NAD+. The product of the colorimetric reaction developed on the surface of the paper is observed by the naked eye and was captured by smartphone camera to get the data for a quantitative analysis	[58]
Anti-recombinant bovine somatotropin (rbST) in milk	An 80 % true-positive rate and 95 % true-negative rate were achieved	The rbST biomarker present in milk was captured by rbST covalently coupled to paramagnetic microspheres and labeled by quantum dot (QD)-coupled detection antibodies. The emitted fluorescence light from the QDs was captured using the cell phone camera. The fluorescence and dark-field microimages were analyzed using an Android application developed	[59]
Furfural in pale lager beers	12 μgL^{-1}	A disposable color changing polymeric films, the films are prepared by radical polymerization of 4-vinylaniline. The sensitive indicator monomer is the furfural-, the comonomer is 2-hydroxymethyl methacrylate and the cross-linker is the ethylene dimethyl methacrylate (EDMA). As sensing mechanism used the Stenhouse reaction, the aniline and furfural react in acidic media, generating a deep red cyanine product. The colorimetric response has been monitored using either a portable fiber-optic spectrophotometer or the built-in camera of a smartphone	[60]
Tetracycline (TC) in bovine milk	Concentration range of 0.5–10 μg mL^{-1}. LOD of 0.5 μg mL^{-1} and limit of quantitation of 1.5 μg mL^{-1}	An application named ColorConc was developed for the iPhone that utilizes an image matching algorithm to determine the TC concentration in a solution. The values of red, green, blue, hue, saturation, brightness were measured from each picture. The TC solution extracted from milk samples using solid phase extraction (SPE) was captured and the concentration was predicted by comparing color values with those collected in a database	[61]

Table 3. Smartphone in the detection of food contaminants or food compounds.

2.4. Environment

The contaminated water is a worldwide problem; for that reason, in 2013, Andrade et al. [62] proposed a digital image processing-based flow-batch analyzer for aluminum (III) and chromium (VI) determinations in natural water, employing a webcam with a charge coupled device (CCD) sensor and red, green, and blue (RGB) data. The method for determining aluminum is based on an Al (III) ion, and the reaction produces a yellow-colored complex in an acetate buffer. The determination of chromium is based on a Cr (VI) ion, which produces a violet-colored complex. The digital images were processing, and the RGB data were employed to build the analytical curves. The working ranges were from 10 to 600 μg/L for Al (III) and 10 to 300 μg/L for Cr (VI), and their limits of detection were 3.97 and 2.65 μg/L, respectively, for Al (III) and Cr (VI).

Gopinath et al. have mentioned that the ubiquitous nature of bacteria enables them to survive in a wide variety of environments and provides an overview of the bacterial detection systems that ranges from microscopic observation to smartphone-based detection. It work described that the first application using a smartphone to the detection and to visualize a single bacterium or virus was demonstrated by Zhu et al. [19]. The system was applied to E. coli as a proof-of-concept. Anti-E. coli antibodies were immobilized on the interior surface of a capillary tube [63]. **Table 4** describes some applications of the smartphone in the detection of elements in the environment.

Samples	Detection/ quantification	Short description	References
Catechols from a water sample of a river	Unmentioned	A smartphone-based colorimetric reader was coupled with a remote server for rapid on site analysis of catechols. A colorimetric sensor array composed of pH indicators, and phenylboronic acid was configured. The method identified the catechols with 100% accuracy and predicts the concentrations to within 0.706–2.240 standard deviation	[64]
Mercury contamination in water	3.5 ppb	An optomechanical device integrated to the camera module of a smartphone to quantify mercury concentration using a plasmonic gold nanoparticle (AuNP) and aptamer-based colorimetric transmission assay. It was possible to quantify mercury (II) ion concentration in water samples by using a two-color ratiometric method employing LEDs. Using this smart-phone-based detection platform, we generated a mercury contamination map by measuring water samples at over 50 locations in California (USA), taken from city tap water sources, rivers, lakes, and beaches	[65]
Calcium in water of the city net, mineral bottled, and natural-river	0.07mgL^{-1}	The studies were carried out using the chromogenic model formed by the reaction between Ca (II) ions and glyoxalbis (2-hydroxyanil). It produced orange–red-colored solutions in alkaline media. The colored complex was applied and validated using intensity of colors with factorial analysis, Fourier transform, principal component analysis and the digital image colorimetric method for the determination of Ca (II) ions	[66]
Bacteria in field water	10 bacterial cells per milliliter	The design, fabrication and testing of a low-cost, miniaturized and sensitive bacteria sensor based on electrical impedance spectroscopy method using a smartphone	[67]
Pesticide thiram	0.1 μM	Copper ions decorated NaYF4:Yb/Tm up conversion nanoparticles were fixed onto filter paper for the assay, and the blue luminescence was quenched by the addition of thiram. The differences of blue channel intensities were monitored by the smartphone camera and calculated to quantify amounts of thiram through a self-written Android program installed on the smartphone	[68]

Samples	Detection/ quantification	Short description	References
Trinitrotoluene in soil	50 mgL^{-1}	The built-in digital camera of a smartphone was used to capture the results from a rapid quantitative colorimetric test for trinitrotoluene (TNT) in soil. The colored product from the selective test for TNT was quantified using the relationships between the red, green, blue (RGB) values and the concentrations of colorimetric product	[69]

Table 4. Smartphone in environment detection.

2.5. Biosensors or devices

Smartphone has been widely integrated with sensors, such as test strips, sensor chips and handheld detectors. The biosensors or devices based on smartphone can mainly be classified into biosensors using optics, surface plasmon resonance, electrochemistry and near-field communication. The performances and advantages of these designs are introduced with their applications in healthcare diagnosis, environment monitoring and food evaluation with advances in micromanufacture, sensor technology and miniaturized electronics [70].

Using 3D-printing technology next to smartphone has provided the opportunity to turn any kind of smartphone into a portable luminometer to detect chemiluminescence derived from enzyme-coupled reactions. Roda et al. mentioned that the lactate oxidase was coupled with horseradish peroxidase for lactate determination in oral fluid and sweat. Lactate can be quantified in less than five minutes with detection limits of 4.5 mg/dL and 0.9 mg/dL in oral fluid and sweat, respectively. Devices based on smartphones offer an alternative to analytical performance with a cost-effective alternative for noninvasive lactate measurement. In the endurance sport and for monitoring lactic acidosis in critical-care patients [48], this can be used to detect and quantify the changes in the lactate with respect to the anaerobic threshold.

Recently in 2017, an improved design for a handheld smartphone-based spectrometer that works in both absorption and emission modes is proposed by de Oliveira et al. [71]. The device, named Spectrophone, comprises an embedded light source designed for absorption mode, a DVD for the diffraction grating, and a smartphone to process the image data acquired. User-friendly homemade software decomposes the pixels from shots of spectral images into their RGB and hue values. The spectrophone was applied to determine Fe^{2+} in medicine samples and Na^{+} in saline solution and natural water samples. No statistically significant differences were observed in comparison with commercial instruments with limits of quantification of 70 g/L and 60 g/L for absorption and emission modes, respectively.

Wang et al. [72] reported a multichannel smartphone spectrometer (MSS) as an optical biosensor that can simultaneously optical sense multiple samples with nanometer resolution. This optical sensor performed accurate and reliable spectral measurements by optical intensity changes at specific wavelength or optical spectral shifts. A custom smartphone Multiview App was developed to control the optical sensing parameters and to align each sample to the corresponding channel. The captured images were converted to the transmission spectra in the visible wavelength range from 400 to 700 nm with the high resolution of 0.2521 nm per pixel. The device was validated with the concentrations of protein and immunoassaying a type of human cancer biomarker, and the results showed that this MSS can achieve the comparative analysis detection limits, accuracy and sensitivity.

Vezzosi et al. employed a smartphone electrocardiograph (ECG) in evaluating heart rhythm and ECG measurements in dogs. A smartphone ECG tracing was recorded using a single-lead bipolar ECG recorder. Agreement between smartphone and standard ECG in the interpretation of tracings was evaluated. Sensitivity and specificity for the detection of arrhythmia were calculated for the smartphone. A perfect agreement between the smartphone and standard ECG was found in detecting bradycardia, tachycardia, ectopic beats and atrioventricular blocks. The smartphone ECG represents an additional tool in the diagnosis of arrhythmias in dogs, but it is not a substitute for a six-lead ECG. Arrhythmias identified by the smartphone ECG should be followed up with a standard ECG before making clinical decision [15].

Stedtfeld et al. developed the Gene-Z for the rapid and quantitative detection of genetic markers. The device is controlled by iPod Touch, to receive data and carried-out automated analysis and to report via Wi-Fi. This study presented data pertaining to performance of the device including sensitivity and reproducibility using genomic DNA from *Escherichia coli* and *Staphylococcus aureus* [73].

iHealth Lab Inc. has developed glucometers for smartphone, wireless smartphone glucometer, or mobile glucometer, which plugs directly into the smartphone's audio jack. iBGStar® from Sanofi and AliveCor®ECG for monitoring heart conditions are examples of commercial devices using the smartphone [1].

The method, adaptation of a smartphone's camera to function as a compact lens less microscope, is based on the shadow imaging technique where the sample is placed on the surface of the image sensor, which captures direct shadow images under illumination. The lens less imaging scheme allows for submicron resolution imaging over an ultrawide field of view. Image acquisition and reconstruction are performed on the device using a custom-built Android application, and constructing a stand-alone imaging device for field applications was presented by Lee and Yang [74].

Wireless chemical sensors are used as analytical devices in homeland defense, home-based healthcare and food logistics, and for that reason, Steinberg et al. [75] developed a portable potentiostat to perform mobile amperometric electrochemical measurements with wireless data transfer to other mobile devices. The developed device was compared with a model redox system, the reduction of hexacyanoferrate (III) and the commercial enzymatic blood glucose test strips.

A handheld and cost-effective cell phone-based colorimetric microplate reader uses a 3D-printed optomechanical attachment to hold and illuminate a 96-well plate using a light emitting diode (LED) array, which was proposed by Berg et al. [76]. The light is transmitted through each well and collected via 96 individual optical fibers. Then, the captured images are transmitted to the custom-designed app for processing using a machine learning algorithm, yielding diagnostic results, which are visualized by the user in same mobile application within less than 1 min per 96-well plate. This device was tested using FDA-approved mumps

IgG, measles IgG and herpes simplex virus IgG (HSV-1 and HSV-2) ELISA tests, working with 567 samples for training and 571 samples for blind. An accuracy of 99.6, 98.6, 99.4 and 99.4% for mumps, measles, HSV-1 and HSV-2 tests was achieved, respectively.

An optical fiber-based smartphone spectrometer incorporating an endoscopic fiber bundle is presented by Hossain et al. [77]. The endoscope allows transmission of the smartphone camera LED light to a sample, and the reflected spectra collected from a surface or interface is dispersed onto the camera CMOS using a reflecting diffraction grating. Spectral analysis of apples shows straightforward measurement of the pigments anthocyanins, carotenoid and chlorophyll, all of which decrease with increasing storage time.

Exploiting the abilities of the new technology, a mobile phone can serve the basic functions of a potentiostat in controlling an applied potential to oxidize electrochemiluminescence (ECL)-active molecules, while the resultant photonic signal is monitored using the camera. The excitation and detection processes are controlled by a software application which can also transmit the results via e-mail, which is the device presented by Delaney et al. [78].

3. Conclusion

Since the first smartphone was designed by IBM in 1993, several applications have been developed employing the smartphone as detector, scanner, quantifier and virtual interface, in medicine, environment, chemistry, food, biology, genetic, biotechnology, biomedical, instrumentation or computer sciences due to its portability, its price comparable with commercial devices or equipment and its own characteristics such as the camera, screen, to create mobile applications or the communication vias.

Detection of contaminants, pesticides, drugs, mycotoxins, vitamins, glucose, salivary cortisol, albumin, cholesterol, DNA molecules, proteins, bacterium, virus, cocaine, heavy metals, and amines in urine, water, blood, soil, and saliva are few examples of the immense quantity of the future applications, where the smartphone can be employed. This is motivated because the smartphone has become an indispensable device of our lives, increasing the number of users from day to day.

Author details

Diana Bueno Hernández[1,2]*, Jean Louis Marty[2] and Roberto Muñoz Guerrero[1]

*Address all correspondence to: dianaburh07@hotmail.com

1 Department of Electrical Engineering, Bioelectronics Section, CINVESTAV-IPN, Mexico

2 Université de Perpignan Via Domitia, BAE, Perpignan Cedex, France

References

[1] Roda A, Michelini E, Zangheri M, Di Fusco M, Calabria D, Simoni P. Smartphone-based biosensors: A critical review and perspectives. TrAC Trends in Analytical Chemistry. 2016;**79**:317-325

[2] Poushter J. Smartphone Ownership and Internet Usage Continues to Climb in Emerging Economies. Washington, DC: Pew Research Center; February 2016. pp. 1-44

[3] Ludwig SKJ, Zhu H, Phillips S, Shiledar A, Feng S, Tseng D, et al. The calibration of cell-phone camera-based colorimetric sensor array and its application in the determination of glucose in urine. Biosensors and Bioelectronics. 2015;**74**:1029-1037

[4] Lee S, Oncescu V, Mancuso M, Mehta S, Erickson D. A smartphone platform for the quantification of vitamin D levels. Lab on a Chip. 2014;**14**(8):1437-1442

[5] Aliev TA, Rzayeva NE, Sattarova UE. Robust correlation technology for online monitoring of changes in the state of the heart by means of laptops and smartphones. Biomedical Signal Processing and Control. 2017;**31**

[6] Messier R. Mobile computing. In: Ric M, Allan K, editors. Collaboration with Cloud Computing. Chapter 7. Massachusetts: Elsevier; 2014. pp. 115-133

[7] Mosa ASM, Yoo I, Sheets L. A systematic review of healthcare applications for smartphones. BMC Medical Informatics and Decision Making. 2012;**12**(67):1-31

[8] Rashvand HF, Hsiao KF. Smartphone intelligent applications: A brief review. Multimedia Systems. 2015;**21**:103-119

[9] Capecci M, Pepa L, Verdini F, Ceravolo MG. A smartphone-based architecture to detect and quantify freezing of gait in Parkinson's disease. Gait Posture. 2016;**50**:28-33

[10] Chun HJ, Park YM, Han YD, Jang YH, Yoon HC. Paper-based glucose biosensing system utilizing a smartphone as a signal reader. BioChip Journal. 2014;**8**(3):218-226

[11] Thom NK, Lewis GG, Yeung K, Phillips ST. Quantitative fluorescence assays using a self powered paper based microfluidic device and a camera equipped cellular phone. RSC Advances. 2014;**4**(3):1334-1340

[12] Chen A, Wang R, Bever CRS, Xing S, Hammock BD, Pan T. Smartphone-interfaced lab-on-a-chip devices for field-deployable enzyme-linked immunosorbent assay. Biomicrofluidics. 2014;**8**(6)

[13] Yu H, Tan Y, Cunningham BT. Smartphone fluorescence spectroscopy. Analytical Chemistry. 2014;**86**:8805-8813

[14] Wang Y, Liu X, Chen P, Tran TN, Zhang J, Chia WS, et al. Smartphone spectrometer for colorimetric biosensing. Analyst. 2016;**141**:3233-3238

[15] Vezzosi T, Buralli C, Marchesotti F, Porporato F, Tognetti R, Zini E, et al. Diagnostic accuracy of a smartphone electrocardiograph in dogs: Comparison with standard 6-lead electrocardiography. Veterinary Journal. 2016;**216**:33-37

[16] Kassianos AP, Emery JD, Murchie P, Walter FM. Smartphone applications for melanoma detection by community, patient and generalist clinician users: A review. British Journal of Dermatology. 2015;**172**:1507-1518

[17] Ribeiro N, Moreira L, Barros A, Almeida AM, Santos-Silva F. Guidelines for a cancer prevention smartphone application: A mixed-methods study. International Journal of Medical Informatics. 2016;**94**:134-142

[18] Figueiredo IN, Leal C, Pinto L, Bolito J, Lemos A. Smartphone application for emergency signal detection. Medical Engineering and Physics. 2016;**38**:1021-1027

[19] Zhu H, Isikman SO, Mudanyali O, Greenbaum A, Ozcan A, Wang J, et al. Optical imaging techniques for point-of-care diagnostics. Lab on a Chip. 2013;**13**(1):51-67

[20] Skandarajah A, Reber CD, Switz NA, Fletcher DA. Quantitative imaging with a mobile phone microscope. PLoS One. 2014;**9**(5):e96906

[21] Navruz I, Coskun AF, Wong J, Mohammad S, Tseng D, Nagi R, et al. Smart-phone based computational microscopy using multi-frame contact imaging on a fiber-optic array. Lab on a Chip. 2013;**13**:4015-4023

[22] Sicard C, Glen C, Aubie B, Wallace D, Jahanshahi-Anbuhi S, Pennings K, et al. Tools for water quality monitoring and mapping using paper based sensors and cell phones. Water Research. 2015;**70**:360-369

[23] Hussain I, Das M, Ahamad KU, Nath P. Water salinity detection using a smartphone. Sensors and Actuators B: Chemical. 2017;**239**:1042-1050

[24] Bueno D, Muñoz R, Marty JL. Fluorescence analyzer based on smartphone camera and wireless for detection of ochratoxin A. Sensors and Actuators B: Chemical. 2016;**232**:462-468

[25] Bueno D, Istamboulie G, Muñoz R, Marty JL. Determination of mycotoxins in food: A review of bioanalytical to analytical methods. Applied Spectroscopy Reviews. 2015;**50**(9):728-774

[26] Kwon L, Long KD, Wan Y, Yu H, Cunningham BT. Medical diagnostics with mobile devices: Comparison of intrinsic and extrinsic sensing. Biotechnology Advances. 2016;**34**:291-304

[27] Wargocki P, Deng W, Anwer A, Goldys E. Medically relevant assays with a simple smartphone and tablet based fluorescence detection system. Sensors. 2015;**15**:11653-11664

[28] Lee D, Chou WP, Yeh SH, Chen PJ, Chen PH. DNA detection using commercial mobile phones. Biosensors and Bioelectronics. 2011;**26**:4349-4354

[29] Guan L, Tian J, Cao R, Li M, Cai Z, Shen W. Barcode-like paper sensor for smartphone diagnostics: An application of blood typing. Analytical Chemistry. 2014;**86**:11362-11367

[30] Breslauer DN, Maamari RN, Switz NA, Lam WA, Fletcher DA. Mobile phone based clinical microscopy for global health applications. PLoS One. 2009;**4**(7):e6320

[31] Preechaburana P, Gonzalez MC, Suska A, Filippini D. Surface plasmon resonance chemical sensing on cell phones. Angewandte Chemie International Edition. 2012;**124**: 11753-11756

[32] Soni A, Jha SK. A paper strip based non-invasive glucose biosensor for salivary analysis. Biosensors and Bioelectronics. 2015;**67**:763-768

[33] Zangheri M, Cevenini L, Anfossi L, Baggiani C, Simoni P, Di Nardo F, et al. A simple and compact smartphone accessory for quantitative chemiluminescence-based lateral flow immunoassay for salivary cortisol detection. Biosensors and Bioelectronics. 2015;**64**:63-68

[34] Kim SC, Jalal UM, Im SB, Ko S, Shim JS. A smartphone-based optical platform for colorimetric analysis of microfluidic device. Sensors and Actuators B: Chemical. 2017;**239**:52-59

[35] Coskun AF, Nagi R, Sadeghi K, Phillips S, Ozcan A. Albumin testing in urine using a smart-phone. Lab on a Chip. 2013;**13**(21):4231-4238

[36] You DJ, Park TS, Yoon JY. Cell-phone-based measurement of TSH using Mie scatter optimized lateral flow assays. Biosensors and Bioelectronics. 2013;**40**(1):180-185

[37] Oncescu V, Mancuso M, Erickson D. Cholesterol testing on a smartphone. Lab on a Chip. 2014;**14**(4):759-763

[38] Wu Y, Boonloed A, Sleszynski N, Koesdjojo M, Armstrong C, Bracha S, et al. Clinical chemistry measurements with commercially available test slides on a smartphone platform: Colorimetric determination of glucose and urea. Clinica Chimica Acta. 2015;**448**:133-138

[39] Mancuso M, Cesarman E, Erickson D. Detection of Kaposi's sarcoma associated herpesvirus nucleic acids using a smartphone accessory. Lab on a Chip. 2014;**14**(19):3809-3816

[40] Wei Q, Luo W, Chiang S, Kappel T, Mejia C, Tseng D, et al. Imaging and sizing of single DNA molecules on a mobile phone. ACS Nano. 2014;**8**(12):12725-12733

[41] Priye A, Wong S, Bi Y, Carpio M, Chang J, Coen M, et al. Lab-on-a-drone: Toward pinpoint deployment of smartphone enabled nucleic acid-based diagnostics for mobile health care. Analytical Chemistry. 2016;**88**:4651-4660

[42] Khan SA, Smith GT, Seo F, Ellerbee AK. Label-free and non-contact optical biosensing of glucose with quantum dots. Biosensors and Bioelectronics. 2015;**64**:30-35

[43] Zhang D, Lu Y, Zhang Q, Liu L, Li S, Yao Y, et al. Protein detecting with smartphone-controlled electrochemical impedance spectroscopy for point-of-care applications. Sensors and Actuators B: Chemical. 2016;**222**:994-1002

[44] Oncescu V, O'Dell D, Erickson D. Smartphone based health accessory for colorimetric detection of biomarkers in sweat and saliva. Lab on a Chip. 2013;**13**(16):3232-3238

[45] Cho S, Park TS, Nahapetian TG, Yoon JY. Smartphone-based, sensitive μPAD detection of urinary tract infection and gonorrhea. Biosensors and Bioelectronics. 2015;**74**

[46] Libman D, Huang L. Chemistry on the go: Review of chemistry apps on smartphones. Journal of Chemical Education. 2013;**90**:320-325

[47] Salles MO, Meloni GN, de Araujo WR, Paixão TRLC. Explosive colorimetric discrimination using a smartphone, paper device and chemometrical approach. Analytical Methods. 2014;**6**(7):2047-2052

[48] Roda A, Guardigli M, Calabria D, Calabretta MM, Cevenini L, Michelini E. A 3D-printed device for a smartphone-based chemiluminescence biosensor for lactate in oral fluid and sweat. Analyst. 2014;**139**:6494-6501

[49] Li B, Li L, Guan A, Dong Q, Ruan K, Hu R, et al. A smartphone controlled handheld microfluidic liquid handling system. Lab on a Chip. 2014;**14**(20):4085-4092

[50] Smith JE, Griffin DK, Leny JK, Hagen JA, Chávez JL, Kelley-Loughnane N. Colorimetric detection with aptamer-gold nanoparticle conjugates coupled to an android-based color analysis application for use in the field. Talanta. 2014;**121**:247-255

[51] Chen L, Zhang C, Xing D. Paper-based bipolar electrode-electrochemiluminescence (BPE-ECL) device with battery energy supply and smartphone read-out: A handheld ECL system for biochemical analysis at the point-of-care level. Sensors and Actuators B: Chemical. 2016;**237**:308-317

[52] Wang H, Li YJ, Wei JF, Xu JR, Wang YH, Zheng GX. Paper-based three-dimensional microfluidic device for monitoring of heavy metals with a camera cell phone. Analytical and Bioanalytical Chemistry. 2014;**406**:2799-2807

[53] Rajendran VK, Bakthavathsalam P, Jaffar Ali BM. Smartphone based bacterial detection using biofunctionalized fluorescent nanoparticles. Microchimica Acta. 2014;**181**:1815-1821

[54] Park TS, Mccracken KE, Li W. Smartphone quantifies Salmonella from paper microfluidics. Lab on a Chip. 2013;**13**

[55] Bueno L, Meloni GN, Reddy SM, Paixão TRLC. Use of plastic-based analytical device, smartphone and chemometric tools to discriminate amines. RSC Advances. 2015;**5**(26)

[56] Liang P-S, Park TS, Yoon J-Y. Rapid and reagentless detection of microbial contamination within meat utilizing a smartphone-based biosensor. Scientific Reports. 2014;**4**(5953):1-8

[57] Yu L, Shi Z, Fang C, Zhang Y, Liu Y, Li C. Disposable lateral flow-through strip for smartphone-camera to quantitatively detect alkaline phosphatase activity in milk. Biosensors and Bioelectronics. 2015;**69**:307-315

[58] Monošík R, dos Santos VB, Angnes L. A simple paper-strip colorimetric method utilizing dehydrogenase enzymes for analysis of food components. Analytical Methods. 2015;**7**(19):8177-8184

[59] Ludwig SKJ, Zhu H, Phillips S, Shiledar A, Feng S, Tseng D, et al. Cellphone-based detection platform for rbST biomarker analysis in milk extracts using a microsphere fluorescence immunoassay. Analytical and Bioanalytical Chemistry. 2014;**406**:6857-6866

[60] Rico-Yuste A, González-Vallejo V, Benito-Peña E, de las Casas Engel T, Orellana G, Moreno-Bondi MC. Furfural determination with disposable polymer films and smartphone based colorimetry for beer freshness assessment. Analytical Chemistry. 2016;**88**:3959-3966

[61] Masawat P, Harfield A, Namwong A. An iPhone-based digital image colorimeter for detecting tetracycline in milk. Food Chemistry. 2015;**184**:23-29

[62] Andrade SIE, Lima MB, Barreto IS, Lyra WS, Almeida LF, Araújo MCU, et al. A digital image-based flow-batch analyzer for determining Al(III) and Cr(VI) in water. Microchemical Journal. 2013;**109**:106-111

[63] Gopinath SCB, Tang TH, Chen Y, Citartan M, Lakshmipriya T. Bacterial detection: From microscope to smartphone. Biosensors and Bioelectronics. 2014;**60**:332-342

[64] Wang Y, Li Y, Bao X, Han J, Xia J, Tian X, et al. A smartphone-based colorimetric reader coupled with a remote server for rapid on-site catechols analysis. Talanta. 2016;**160**:194-204

[65] Wei Q, Nagi R, Sadeghi K, Feng S, Yan E, Ki SJ, et al. Detection and spatial mapping of mercury contamination in water samples using a smart-phone. ACS Nano. 2014;**8**(2):1121-1129

[66] Lopez-Molinero A, Cubero VT, Irigoyen RD, Piazuelo DS. Feasibility of digital image colorimetry: Application for water calcium hardness determination. Talanta. 2013;**103**:236-244

[67] Jiang J, Wang X, Chao R, Ren Y, Hu C, Xu Z, et al. Smartphone based portable bacteria pre-concentrating microfluidic sensor and impedance sensing system. Sensors and Actuators B: Chemical. 2014;**193**:653-659

[68] Mei Q, Jing H, Li Y, Yisibashaer W, Chen J, Nan Li B, et al. Smartphone based visual and quantitative assays on upconversional paper sensor. Biosensors and Bioelectronics. 2016;**75**

[69] Choodum A, Kanatharana P, Wongniramaikul W, Nic Daeid N. Using the iPhone as a device for a rapid quantitative analysis of trinitrotoluene in soil. Talanta. 2013;**115**

[70] Zhang D, Liu Q. Biosensors and bioelectronics on smartphone for portable biochemical detection. Biosensors and Bioelectronics. 2016;**75**:273-284

[71] de Oliveira HJS, de Almeida PL, Sampaio BA, Fernandes JPA, Pessoa-Neto OD, de Lima EA, et al. A handheld smartphone-controlled spectrophotometer based on hue to wavelength conversion for molecular absorption and emission measurements. Sensors and Actuators B: Chemical. 2017;**238**:1084-1091

[72] Wang LJ, Chang YC, Sun R, Li L. A multichannel smartphone optical biosensor for high-throughput point-of-care diagnostics. Biosensors and Bioelectronics. 2017;**87**:686-692

[73] Stedtfeld RD, Tourlousse DM, Seyrig G, Stedtfeld TM, Kronlein M, Price S, et al. Gene-Z: A device for point of care genetic testing using a smartphone. Lab on a Chip. 2012;**12**:1454-1462

[74] Lee SA, Yang C. A smartphone-based chip-scale microscope using ambient illumination. Lab on a Chip. 2014;**14**(16):3056-3063

[75] Steinberg MD, Kassal P, Kereković I, Steinberg IM. A wireless potentiostat for mobile chemical sensing and biosensing. Talanta. 2015;**143**:178-183

[76] Berg B, Cortazar B, Tseng D, Ozkan H, Feng S, Wei Q, et al. Cellphone based hand held microplate reader for point of care testing of enzyme linked immunosorbent assays. ACS Nano. 2015;**9**(8):7857-7866

[77] Hossain MA, Canning J, Cook K, Jamalipour A. Optical fiber smartphone spectrometer. Optics Letters. 2016;**41**(10):2237-2240

[78] Delaney JL, Doeven EH, Harsant AJ, Hogan CF. Use of a mobile phone for potentiostatic control with low cost paper-based microfluidic sensors. Analytica Chimica Acta. 2013;**803**:123-127