A review of smartphone point-of-care adapter design

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In this review, we explore the potential of smartphone-based applications based on their unique ability to support portable, easy-to-use, precise, and efficient functions, which, in turn, makes lab-on-hardware a trending area of novel research. Smartphones can assist surgeons, physicians, biologists, chemists, ophthalmologists, and laboratory technicians in maintaining an easy-to-use, cost-effective, and integrated environment for treatment, diagnosis, and point-of-care (POC) applications. These POC applications can improve patients’ quality of life, offering patients a precise diagnosis and the correct treatment. This is a noble goal that aims to reduce costs and to increase the accuracy of sample testing, treatment, and diagnosis. Recent innovations have made major advances in smartphone adapters, providing portability, robustness, self-powered devices, small-sized adapters, and ease of usage. Lab-on-hardware is a progressing field, and smartphone imaging applications are increasingly expanding, resulting in POC applications with the latest and most advanced image analysis, enhancement, recognition, and other image processing techniques. The most recent studies in the field are explored to provide a solid background to interested researchers against which they can choose of application and/or adapter design they aim to develop, with a discussion of the methods reviewed here.

KEYWORDS
adapter design, lab-on-hardware, ophthalmic and biochemical/electrochemical applications, smartphone-based point-of-care adapters, surgical treatment and diagnosis

INTRODUCTION

Smartphone point-of-care (POC) applications arise in research due to many factors, such as on-site monitoring, rapid testing, and the cost of laboratory instruments, especially in remote areas.1-3 The ability to perform rapid quantitative and qualitative assessments of samples makes the ambitious software environment of smartphone devices very promising.4 To test the samples, an external hardware attachment known as an “adapter” or “cradle” is used.3,5 This adapter is designed with 3D printing technology, offering a variety of design shapes, suitability with smartphone backbones, and embedded optical elements inside the adapter core.2,6 Generally, there are two major approaches for the adapter design. The first approach targets a specified sample and implements the adapter design based on the sample; this approach requires previous knowledge of the sample properties and thus is sample dependent. The second approach focuses on the optical design criteria and thus is more flexible, and therefore, it is sample independent, ie, a variety of samples can be tested with this approach.7-10 While the first approach seems to dominate the research, the sample-independent approach can...
be implemented on a large scale and thus can be more suitable for industrial and/or commercial purposes. Many parameters should be considered in the design, such as, compactness, safety, driving power, imaging optics, illumination sources, and interchangeability, in addition to material usage, cost, and functional robustness.11 Smartphones possess distinctive capabilities, and the technology is growing to fulfill the demands of competence among different manufacturers. Thus, smartphones are usually accompanied by a several gigabyte memory, a processor, a built-in camera, Bluetooth technology, Wi-Fi network support, a touch screen, a long-lasting battery, a light-emitting diode (LED) flashlight, a microphone and speaker, and some built-in up-to-date applications.12 These key-enabling technologies strongly support the emerging field of smartphone sensing, with 3D printing technology and a well-designed software application. It is evident that smartphones will dominate the POC field, enabling an easy-to-use mobile application that can perform complicated laboratory tests without the need for very deep knowledge about the instrumentation and the complicated test procedures used by specialists in a large laboratory environment.13 Recent innovations verified that smartphone-based applications are very promising demonstrating precise measurements,14-18 a low limit of detection (LOD),19-23 a wide dynamic range,24-27 low power consumption, easy-to-use smart applications, a low coefficient of variation (CV%), a high regression coefficient (R²), high specificity, reliable sensitivity, rapid testing, cost-effective adapter designs, and high selectivity.28-32 These innovations include the major parts of POC applications, such as surgical treatment application (Section 3.2), surgical diagnosis (Section 3.1), ophthalmic applications (Section 3.3), biochemical applications (Section 3.4),33-35 environmental monitoring applications,36-42 biomedical applications,43-45 electrochemical applications (Section 3.5), colorimetric applications,46-49 imaging applications,50-54 and spectrometry applications.55 The trends of smartphone-based POC applications have grown rapidly, with more than 2000 research articles in the field being reported in 2018 to 2019.56 Most recently, the integration of Internet of Things (IoTs),57-60 machine learning and deep learning,61-68 5G networks,69-73 imaging algorithm open source software platforms,74 and wearable sensors75-80 with smartphone-based POC adapters innovated novel routes towards medical data communication, sharing, real-time monitoring, on-site diagnosis, rapid testing, and other applications. This growing integration will revolutionize personalized medicine and help in the treatment of many patients worldwide.81-83

2 MATERIALS AND METHODS

This section explains the methodology for the article selection process following some previous review strategies (eg, the works of Ratei et al,84 Khan et al,85 and Moher et al86). The articles were found in the following platforms: Google Scholar, Web of Science, ScienceDirect, ACM Digital Library, ResearchGate, IEEE Xplore, PubMed, ACS, MDPI, Nature, and Springer. The search criteria included the exact words “Smartphone Sensor,” “Smartphone Adapter,” “Mobile Adapter Design,” “Mobile phone Sensors,” “Mobile diagnosis,” “Smartphone point-of-care,” “Medical Application of Smartphone Adapter,” “Ophthalmic Applications of Smartphone Adapters,” “Biochemical Applications of Smartphone Adapter,” and “Smartphone Electrochemical Applications.” The search criteria took into account the publication years. This review focused on recent articles and included some past articles for their innovation. After performing the search on the specified databases, the result was 200 articles. Then, we removed similar articles, and a total of 25 were found. We screened 175 articles and excluded 30 articles because the articles did not fit into the scope of this review. After that, we examined 145 articles fully and excluded 15 articles because there was no focus on the adapter design. Finally, a total of 130 articles were included in this review. The article selection process is depicted in Figure 1.

3 RESULTS

Smartphone adapters are essential components in sensing, diagnostic, and POC studies.87-90 Therefore, a good, compact, and reliable design is mandatory for a small-scale lab-on-hardware device capable of performing rapid and accurate tests for samples of low concentration.91 Optical design is usually performed with small-scale optical elements such as lenses, apertures, prisms, optical fibers, waveguides, and mirrors. These sets of optical elements provide the following functions: magnification, filtering, and image enhancement by reducing distortion and by carrying out targeted focusing.92 The illumination of samples can be performed with the built-in flash LED on a smartphone, external LED embedded in the adapter, or external tunable or near-monochromatic laser diode.93 The red and green wavelengths are preferred for the fluorescence application and can be used together for multichannel fluorescence applications. The next step is to model the components in a 3D design environment using computer-aided design (CAD) software, such as SolidWorks and AutoCAD, and then to save the design in a proper format for 3D printing. Adapter assembly and finalization of the hardware parts are performed in this step. Finally, a smartphone application is implemented via the specific platform of the
The smartphone in use. These platforms fall into three major categories: IOS for Apple devices; Android for Samsung, Huawei, HTC, LG, and Google devices; and Microsoft for Microsoft devices and Nokia smartphones. This application controls, monitors, calculates, measures, captures images, videos, or any signal, and/or performs any required task depending on the type of application.

3.1 Surgical diagnosis applications

These types of applications require either a video, an image, or an audio signal necessary for surgical diagnoses such as dermatoscopy, microscopy, endoscopy, laparoscopy, laryngoscopy, and otoscopy. The smartphone is employed to support the diagnosis function; an opto (acousto) mechanical adapter is attached to the smartphone camera, and thus, access to critical patient information is obtained with minimal cost, surgical procedure time, skills, and maximal adaptability. The features of the smartphone, including the camera, audio input/output, memory, information processing, and applications, make the diagnosis an easy-to-carry-out process, targeting tests for both severe and mild patient cases. To achieve the goal of diagnosis based on a smartphone, the adapter is usually designed for signal, image, and/or video processing. If the function of the adapter is identical for two or more sets of surgical diagnosis procedures, then the opto (acousto) part of the adapter can perform the same operations, thus eliminating the need for full adapter design when transitioning from one surgical procedure to another. On the other hand, the mechanical part is almost completely surgical dependent, targeting the tools required by the surgeon to perform operations and thus using these tools in the adapter, making the process of operation as smooth as possible. Visual inspection and diagnosis are needed for the cases where the patient is required to check his/her organs. Thus, the optical part of the adapter should achieve good image quality, yield good magnification, and meet the requirements of any mandatory image processing. In the case of in vivo operation requiring a video of an internal organ for the purpose of medical education or surgical assistance, the video can be stored and shared via Wi-Fi or the Internet, as shown in Figure 2. Smartphone otoscopy emerges as a solution for audiologists and otolaryngologists in making simple, practical, and cost-effective diagnoses for patients suffering from hearing problems, as in Figure 2A, see also the work of Jayawardena et al., where patients underwent a surgical diagnostic operation. The results were fascinating, as 59 patients out of 66 were able to achieve reliable audiogrametric measures. The smartphone flashlight can provide the necessary illumination for aesthetic dermatoscopy, as reported by Naimer (Figure 2B) who employed a smartphone for lesion visualization and the aesthetic removal of comedones and proved the functionality of this procedure. Video function is nonetheless vital to the diagnostics stage; an injured, infected, or improperly functioning organ can be visualized by video monitoring and recording, thus enabling a real-time visual guide and material crucial for consultancy, training, and teaching purposes, as depicted in Figure 2C, Brant et al. Commercially available adapters or research-oriented adapters are the two forms of smartphone adapters used in surgical diagnostics; smartphones can be integrated with microscopes to initiate image capturing or video recording or to employ special video and/or image

![Figure 1](image-url)
FIGURE 2  Surgical diagnosis applications of smartphone adapter. (A) iPhone-based otoscopy and laptop-based wireless endoscopic otoscopy, by Jayawardena et al.,99 adopted with permission from SAGE publishing; (B) A polarized dermoscope mounted on a cellular telephone enables accurate comedone manipulation, by Naimer,100 adopted with permission from Wiley; (C) Smartphone-endoscope adapter to capture video, by Brant et al.,101 under the Creative Commons Attribution License; (D) Smartphone attached to a microscope through a 3D printed adapter, by Fontelo et al.,102 under the Creative Commons Attribution License; (E) Smartphone microscope adapter, by Hartman et al.,103 under the Creative Commons Attribution License; (F) Smartphone attached to a microscope through an adapter, by Ekong et al.,104 under the Creative Commons Attribution License
processing techniques, as shown in Figures 2D, 2E, and 2F, for the works of Fontelo et al,102 Hartman et al,103 and Ekon et al,104 respectively.

A smartphone adapter designed for the purpose of surgical diagnostics should have external optics containing lenses, which, in turn, provide the required magnification, although the integration of smartphones with optical microscopes is increasing. However, for portability purposes and on-site diagnostics, this method is not very practical. Optical fiber imaging is nonetheless mandatory for in vivo imaging and surgery. Thus, integrating optical fibers with sufficiently good imaging optics and employing rapid software that can perform image and/or video processing in both real-time and on-demand applications guarantee the proper function of the adapter and increase the adaptability of smartphone-based diagnostic operations. The ability of smartphones to connect through the Internet makes them more reliable, especially when performing long-distance communication with expert surgeons worldwide or when teaching students about a specific surgical technique. Telemedicine and telepathology are emerging fields due to the possibility of realizing smartphone-based adapters that can be fabricated by 3D printers or CNC machines, employing the necessary optical elements and integrating the design for a unique purpose. This will benefit low-resource countries and remote areas the most. A summary of the adapter design is tabulated for comparison as shown in Table 1.

### 3.2 Surgical treatment applications

Herein, the mechanical part of the adapter plays the dominant role in specifying the nature of the operation to be performed on the patient. Probes, clippers, scissors, and other mechanical parts are the focus here, although the optics are still necessary to complete the function, as shown in Figure 3. For design purposes, a CAD environment is the most

| Application type                          | Smartphone | Method          | Software analysis | Ref. |
|-------------------------------------------|------------|-----------------|-------------------|------|
| Smartphone endoscopy                      | iPhone 5   | Commercial adapter |                 | 95   |
| Smartphone otoscopy                       | iPhone 6   | Commercial adapter |                 | 99   |
| Smartphone dermoscopy                     | Android    | Commercial adapter |                 | 100  |
| Smartphone nasopharyngolaryngoscopy       | iPhone 4   | Commercial adapter |                 | 101  |
| Smartphone telepathology                  | iPhone 5   | 3D printing     | Excel’s ANOVA    | 102  |
| Smartphone digital photomicrograph        | Samsung Galaxy S5; Google/LG Nexus 5 | Commercial adapter |                 | 103  |
| Smartphone telepathology                  | iPhone 4; 5 | Commercial adapter |         | 104  |
| Smartphone laparoscopy                    | iPhone 6s; SONY XPERIA; XZ | Commercial adapter | AirPlay         | 105  |
| Smartphone endoscopy                      | Samsung Galaxy S5 | 3D printing and assembly | Jave; Android; ZEMAX; SolidWorks | 106  |
| Smartphone neuroendoscopy                 | iPhone 4; 5; 6 | Commercial adapter | OsiriX          | 107  |
| Mobile endoscopy                          | iPhone 5s  | Commercial adapter | iMovie; Modica   | 108  |
| Fundus photography and videography        | iPhone 7   | 3D Printing     | iMovie           | 109  |
| Fundus photography                        | iPhone 5s  | Imaging         | D-Eye           | 110  |
| Ophthalmoscope                            | Galaxy S III | 3D Printing     | Java            | 111  |
| Retinal imaging                           | iPhone     | 3D Printing     | SolidWorks      | 112  |
| Smartphone screening                      | iPhone 5s  | Imaging         | EyeGo           | 113  |
| Smartphone ophthalmoscopy                 | iPhone 5s  | Imaging         | D-Eye           | 114  |
| Diabetic retinopathy                      | iPhone 5   | Imaging         | SPSS; D-Eye     | 115  |

### TABLE 1 Smartphone adapter design comparison for surgical and ophthalmic applications
FIGURE 3  Surgical treatment applications of smartphone adapter. (A) Endoscopy Support Services ClearSCOPE\textsuperscript{116}; (B) Karl Storz Smart Scope\textsuperscript{105}; (C) Portable endoscope device, by Chatzipapas et al,\textsuperscript{117} adopted with permission from Elsevier Publishing; (D) Smartphone-based endoscope system setup, by Bae et al,\textsuperscript{118} under the Creative Commons Attribution License; (E) Photographs showing use of the iPhone and neuroendoscope, by Mandel et al,\textsuperscript{106} © copyright AANS 2018; (F) Mobile endoscope adapter (ClearSCOPE; Clearwater Clinical Limited, Ottawa, Canada)\textsuperscript{116}
appropriate tool for designing and testing the adapter. AutoCAD or SolidWorks is usually used to implement the adapter design. Then, after the design has been fully implemented on these platforms, a “.stl” file or other suitable format is extracted, and then, the design is ready for the fabrication stage. In the fabrication stage, the 3D printer or the CNC machine is linked (wired or wireless) with a personal computer (PC), and the CAD file is implemented for adapter fabrication. After the fabrication has been performed, the integration of the necessary mechanical parts and optics is handled in this stage. Using the necessary tools for integrating the fabricated adapter with the mechanical and optical parts, a smartphone software application is then setup to perform the required processing. The final smartphone adapter design is now ready to be used. Commercially available endoscopes utilize smartphone functions to obtain the desired surgical procedure with lightweight, easy-to-use, efficient, and integrated adapters. As shown in Figure 3A, the ClearSCOPE smartphone adapter employs the smartphone's camera to enable the video function, which is a requirement for endoscopic procedures. As shown in Figure 3B, the Karl Storz Smart Scope provides excellent image quality. As shown in Figure 3C, Chatzipapas et al. used commercial adapters (Karl Storz and ClearSCOPE) with a smartphone and a light source to perform laparoscopy; the work was designed for emergency departments and decision making regarding whether to perform “open” or “laparoscopic” procedures, and the results for 17 patients diagnosed and treated properly were astonishing. As shown in Figure 3D, an endoscope system was realized using a smartphone as an imaging sensor and a display suitable for the POC diagnostics, showing its importance in terms of mobility and flexibility. The smartphone endoscope can provide sufficient imaging performance as a diagnostic tool in a wide range of clinical and nonclinical settings. This system showed that researchers should try to build their own system rather than depend on commercial systems since the cost of purchasing commercial systems is approximately 50 times higher than what it would take to fabricate the device and use it safely and properly.

As depicted in Figure 3E, Mandel et al. using the ClearSCOPE endoscope adapter with different endoscope lengths, thicknesses, and angles, obtained very good results, reasoning that the patient's choice was based on the authors' knowledge, which may not be the case when different circumstances occur. The combination of smartphone technology and endoscopy can serve as an alternative technique for performing minimally invasive neurosurgical procedures. The pioneering employment of smartphone endoscopy will have a momentous influence in remote areas and developing countries, where the healthcare infrastructure is inadequate. Nonetheless, additional investigations are obligatory in clinical scenarios to precisely evaluate the actual practicality of smartphone-endoscope integration compared to typical neuroendoscopic equipment. As depicted in Figure 3F, Liu et al. used the ClearSCOPE endoscope adapter to inspect the practicality of employing smartphone endoscopic adapters in clinical practice. The use of mobile endoscopic adapters provides numerous possible benefits over the use of video towers, such as ease, speediness, cost-effectiveness, portability, and shareability. They had 13 experts that inspect 30 pairs of videos captured by both a smartphone and standard techniques, concluding that there were insignificant variances among any of the end points, with the implication that these videos are fairly equivalent. This demonstrates smartphone endoscopy as a viable assistant to current procedures. Endoscopy looks to be moving towards chip technology. Although smartphone technology promises outstanding behavior as manufacturers enhance camera quality and resolution, with affordable prices, clinical treatment has not yet been improved via the use of smartphone technology due to the limitations smartphones have in comparison to standard equipment, for instance, the small-sized screens of smartphones and the unusual procedures necessary since surgeons need to practice using new smartphone technology to overcome some unusual mistakes. The price and technology are two major points since the cost of operations will be greatly reduced due to smartphone technology being cheap and affordable. A summary of the adapter design is tabulated for comparison as shown in Table 1.

### 3.3 Ophthalmic applications

These types of applications are extremely sensitive and require high-precision optics to operate smoothly. Ophthalmologists use the smartphone adapter as an alternative technique for the diagnosis and treatment of eyes, as shown in Figure 4. Barikian and Haddock showed that examination of the pupil of the eye requires special lightning, as shown in Figure 4A. The traditional bright flashlight emission will cause the pupil to contract; thus, infrared light will be necessary to overcome this problem. Furthermore, special smartphone applications designed to control the brightness of light are required to perform ophthalmic operations smoothly. Retinal images are of satisfactory quality and can be interpreted; this means that the image quality needs further improvement. The field of view (FOV) in undilated pupils is limited to approximately 50°; therefore, increasing the FOV will make the smartphone adapter more reliable. Gomes and Ledbetter designed a smartphone ophthalmic adapter that was fabricated using 3D printing technology with a 40D lens, giving a large FOV and 3D video function. The adapter limitation is somewhat software related; thus, video downloading
Figure 4 Ophthalmic applications of smartphone adapter.
(A) Innovative method of capturing fundus images using a head-mounted 3D printed attachment, by Barikian et al.\textsuperscript{108} adopted with permission from Springer; (B) Video setup and 3D printed lens adapter to collect indirect ophthalmoscopy videos in a dog, by Gomes and Ledbetter\textsuperscript{109} adopted with permission from Wiley; (C) 3D printed retinal imaging adapter, by Hong\textsuperscript{112} adopted with permission from Springer

and reading with a PC and image/video processing tools need to be improved, as shown in Figure 4B. Panwar et al.\textsuperscript{119} reviewed some adapter design methods, including a modified hand-held fundus camera used as a point-and-shoot camera, consisting of two LEDs, imaging optics, and a digital camera, which has the advantage of comparable outcomes with those of the standard fundus camera. An integrated adapter-detector-based hand-held ophthalmic camera, consisting of adjustable optics, a liquid crystal display (LCD) screen, a controller, and a universal serial bus (USB), has the advantage of high-definition (HD) image capturing. An adapter-based fundus camera system, consisting of a smartphone for displaying retinal images and illumination and imaging optics that are externally integrated with the system, has the advantage of capturing high-resolution images of the fundus and retinal nerves and then using application-driven software to enable printing and storing of the images. A smartphone-based fundus camera system, consisting of a smartphone and an external ophthalmic lens for acquiring retinal images using the smartphone’s flashlight for illumination, has the advantages of fast applications, large memory, image processing applications, and long-lasting batteries and can be used to screen abnormalities based on artificial intelligence (AI) algorithms. Wintergerst et al.\textsuperscript{110} compared dilated and undilated cases based on the smartphone fundus photography technique, using the ImageJ software for processing and data analysis, a Galaxy S4 smartphone, and conventional methods. They concluded that the conventional fundus photographic technique outperforms the smartphone.

To date, much advancement has been made by the manufacturers of smartphones, and thus, proper selection of the available smartphone technology promises a comparable performance between smartphone-based and conventional techniques. Bolster et al.\textsuperscript{120} reviewed the diabetic retinopathy (DR) screening methods based on a smartphone and concluded that although pilot studies and single-site trials have yielded hopeful results for the validation of smartphone-based DR assessment in comparison with reference standards, more efforts should be made to further develop the smartphone-based approach. Giardini et al.\textsuperscript{111} designed a smartphone ophthalmoscope that was integrated on a Galaxy S3 smartphone and employed Java programming to create software that enables video capture, magnification, and segmentation and enables creating measurements. Their ophthalmoscope can be employed for off-site screening and remote diagnostics. As shown in Figure 4C, Hong\textsuperscript{112} designed a 3D printed adapter for retinal imaging. The design was cost-effective, practical, and easy to handle. It included a 20D lens, for ophthalmic and clinical use in a low-resource environment. Furdo\textsuperscript{121} et al. used a smartphone and spherical Volk lens +20D to examine the eye fundus of 241 patients.
in South Sudan. They concluded that there is smartphone robustness in capturing images of the inner eye surface with high quality and reproducibility. Ludwig et al.\textsuperscript{113} employed 8 volunteers to perform 766 cases of ophthalmic screening. They proved the high quality of the output yielded by volunteers with little experience in obtaining excellent results in a sufficiently short period of time using the EyeGo smartphone application. Mamtora et al.\textsuperscript{114} used the D-EYE smartphone adapter (commercially available\textsuperscript{115}) and direct ophthalmoscopy to perform retinopathy and ophthalmic tests. They concluded that it is easier for students to operate smartphone adapters than to carry out direct ophthalmoscopy, with measurement accuracy percentages of 66 and 46, respectively. Russo et al.\textsuperscript{122} compared the smartphone adapter performance with that of a slit-lamp biomicroscope for DR using the D-EYE,\textsuperscript{115} adapter, and an iPhone and found comparable results for both cases. A summary of the adapter design is tabulated for comparison as shown in Table 1.

### 3.4 | Biochemical applications

A very broad concept is introduced here. Biological objects such as bacteria,\textsuperscript{123} viruses,\textsuperscript{124} and parasites\textsuperscript{125} are in the micrometer to submicrometer range; therefore, magnification is mandatory for visual inspection of these objects. Smartphone adapters are employed here for visual inspection, measurement, recognition,\textsuperscript{126} sensing,\textsuperscript{127} and disease diagnosis\textsuperscript{128-130} for conditions such as diabetes, cancer,\textsuperscript{131} and malaria.\textsuperscript{132,133} On the other hand, chemical agents, such as hormones,\textsuperscript{134-136} biomarkers,\textsuperscript{137,138} and reagents,\textsuperscript{139} are essential for biochemical processes; therefore, smartphone adapters were neatly designed for sensing, measuring, and monitoring these agents, as shown in Figure 5. As depicted in Figure 5A, Skandarajah et al.\textsuperscript{140} developed a smartphone-based microscope system that is able to perform submicron imaging and compared the performance of the smartphone with that of scientific camera, resulting in comparable images when the smartphone camera resolution was more than 5 megapixels. They tested various smartphones of the iPhone and Samsung series. The system is composed of light illumination (LED), a sample holder, objective and eyepiece lenses, and a plastic diffuser. The image processing software uses white-color balance before the image acquisition stage, which then involves color filtering, control, image processing, and storage. Huang et al.\textsuperscript{144} developed a smartphone-based device, composed of a commercial camera, a disposable unit, an external battery, and holders, to detect the influenza virus. The device performed well, and the authors suggested improvement techniques for achieving excellent performance. As shown in Figure 5B, You et al.\textsuperscript{141} developed a smartphone-based adapter with high sensitivity, LOD, and viable specificity for heart failure prognosis. The device included a software application enabling patients to perform remote prognoses at home. As depicted in Figure 5C, Álvarez-Diduk et al.\textsuperscript{142} proposed graphene quantum dot material for the fast screening of organic compounds. The adapter consists of a plastic body, strip hole, UV LED, and USB port. It uses a smartphone for power. It includes the following: the electric circuit of a 365-nm UV LED connected to the male USB port and a nitrocellulose paper strip with wax-printed circular areas. It yields an image of the sensing platform, where the fluorescent spot is observed in the middle of a mobile phone screen, and the sensing area, with yes/no (ON/OFF) being the typical result. The UV LED was used for fluorescent imaging, and the results were fascinating in terms of the adapter response. As depicted in Figure 5D, Roda et al.\textsuperscript{8} developed a smartphone adapter for targeting biospecific enzymatic reactions in biochemiluminescence applications. The image capturing and light quantification were performed by the smartphone. As shown in Figure 5E, Cui et al.\textsuperscript{143} validated the smartphone adapter for particle analysis in prostate-specific antigen (PSA) biomarkers, and their system was processed by MATLAB and a smartphone-designed application. The LOD was 0.125 ng/ml, and the smartphone-based biomarker has the potential for a wide range of biomarker detection methods. Liao et al.\textsuperscript{145} developed a smartphone-based adapter for polymerase chain reaction test evaluation that is used for the diagnosis of infectious diseases such as the herpes simplex virus in the vaginal canal of women by fast amplification of the nucleic acid. The device promised rapid diagnoses in minutes, while the conventional method may take a few hours. As depicted in Figure 6A, Lee et al.\textsuperscript{146} demonstrated a smartphone adapter that can be used to perform fluorescence microscopy, with an LOD of 1 pg/ml. The adapter consists of a microscope, a laser casing, a bandpass filter, a focusing knot, a phone, and sensor cases. Estradiol was detected with high sensitivity and selectivity. The design used red and green wavelengths to generate the fluorescence in the sample. As depicted in Figure 6B, Michelini et al.\textsuperscript{147} developed a smartphone-bioluminescent 3D cell biosensor for screening environmental/chemical samples, with an LOD of 0.15 ng/ml. The device also uses red and green wavelengths for achieving luminescence. They used ImageJ for parameter definition and image processing and the GraphPad Prism software for plotting data. It promises to have great advantages over conventional methods. As shown in Figure 6C, Ming et al.\textsuperscript{148} developed a smartphone quantum dot barcode reader that is able to detect HIV and hepatitis B for infectious disease diagnosis and detection. It demonstrated the ability of simultaneous pathogenic detection in less than 60 minutes. The adapter consists of two laser diodes, excitation and emission filters, two lenses (objective and eyepiece), a microwell chip, and a plastic body. The adapter is connected to the smartphone, and the group developed
FIGURE 5  Biochemical applications of smartphone adapter. (A) Transmission light microscope based on smartphone, by Skandarajah et al.\textsuperscript{140} under the Creative Commons license; (B) Smartphone-based adapter, by You et al.\textsuperscript{141} © copyright 2017 American Chemical Society; (C) 3D printed device with its different parts, by Álvarez-Diduk et al.\textsuperscript{142} under the Creative Commons license; (D) Smartphone Biochemiluminescence adapter, by Roda et al.\textsuperscript{8} © copyright 2014 American Chemical Society; (E) Cellphone-enabled image acquiring system, by Cui et al.\textsuperscript{143} © copyright 2018 American Chemical Society
FIGURE 6  Biochemical applications of smartphone adapter (A) by Lee et al.\textsuperscript{146} adopted with permission from Elsevier Publishing; (B) by Michelini et al.\textsuperscript{147} adopted with permission from Elsevier Publishing; (C) by Ming et al.\textsuperscript{148} © copyright 2015, American Chemical Society; (D) by Xiao et al.\textsuperscript{149} under the Creative Commons license; (E) by Wang et al.\textsuperscript{150} adopted with permission from the Royal Society of Chemistry; (F) by Wang et al.\textsuperscript{151} adopted with permission from Elsevier Publishing; (G) by Yang et al.\textsuperscript{152} adopted with permission from Elsevier Publishing; (H) by Zangheri et al.\textsuperscript{153} adopted with permission from Elsevier Publishing; and (I) by Zhang et al.\textsuperscript{154} adopted with permission from Elsevier Publishing
a custom algorithm for image processing and acquisition. As depicted in Figure 6D, Xiao et al\textsuperscript{149} developed a smartphone adapter as an aptamer-assay nanosensor for mercury contamination detection and readout. The adapter consists of a switch, a resistance, a battery, a LED, a microwell, a sample holder, an ambient light sensor and a plastic body. A light-meter application was used for signal detection, recording, and processing. The aggregation of gold nanoparticles leads to a color change. The adapter demonstrated rapid detection, with an LOD of 0.28 ng/ml. As shown in Figure 6E, Wang et al\textsuperscript{150} reported a smartphone-based microstrip ELISA detector; they used a custom-designed smartphone application (CDSA) to calculate the Human Epididymis Protein 4 (HE4) in urine and validated the calculations on a PC using MATLAB. The detector demonstrated rapid and accurate readings, showing the applicability of smartphone technology in biomarker detection and biotechnology. As depicted in Figure 6F, Wang et al\textsuperscript{151} developed a smartphone adapter that can perform multichannel spectral biosensing. They used a microplate embedded in a 3D printed plastic adapter containing a smartphone, a 96-well microplate, suitable aperture arrays, a white light source, an LED, and a battery with proper alignment for optical components. A smartphone application was developed using the Swift Programming Language to control the parameters of optical sensing. A specially designed MATLAB graphical user interface was developed for spectral data processing and analysis. Their multichannel smartphone spectrometer showed great potential in POC diagnostics, with a 0.2521 nm/pixel and a 0.6 pg/mL pixel resolution and LOD, respectively.

As shown in Figure 6G, Yang et al\textsuperscript{152} developed a smartphone adapter for human cortisol and C-reactive protein (CRP) measurement. The adapter consists of a 3D printed origami holder with space for sample insertion, a biomarker, and a fountain pen used for the analytical procedure. They used SolidWorks to design and then fabricate the device. ImageJ was used for image processing, and they created Android software with three functions: instruction, measurement, and database entry. It demonstrated rapid measurement, with an LOD of 0-100 ng/ml.

As shown in Figure 6H, Zangheri et al\textsuperscript{153} developed a smartphone adapter as a biosensor for chemiluminescent (CL)–lateral flow immunoassay (LFIA) to quantitatively detect human saliva cortisol. The adapter consists of washing buffer and CL substrate reservoirs, an LFIA strip, an LFIA cartridge, an LFIA strip holder, a sample inlet space, and a plastic body. They used the MakerWare slicer software to define the parameters, the ImageJ software for image processing and special software for image acquisition and data handling. The adapter demonstrated rapid and sensitive diagnostics. As shown in Figure 6I, Zhang et al\textsuperscript{154} developed a smartphone adapter based on grating-coupled surface plasmon resonance (GC-SPR) for biosensing. The adapter consists of a filter, a filter holder, a polarizer, a gold sensor chip with a diffraction grating, a compact disk (CD) transmission diffraction grating, a substrate, a sample holder, an aperture, and a plastic body. It achieved an LOD of 32.5 ng/ml. As shown in Figure 7A, Cheng et al\textsuperscript{155} developed a smartphone adapter for the simultaneous detection of pathogens. The adapter consists of a plano-convex lens, white light LED, dual-LFIA minicartridge, and PMMA plastic body. The LOD was approximately 20 CFU/mL for Salmonella Enteritidis and approximately 34 CFU/mL for Escherichia coli (E. coli) O157:H7. As depicted in Figure 7B, Cho et al\textsuperscript{156} reported a smartphone-based fluorescence microscope; the adapter has a 480-nm bandpass filter, a 500-nm highpass filter, a micro lens, three white LEDs, an objective lens, a 3-V dual-battery, a switch, a chip platform, and a plastic body, thus enabling both internal and external in situ monitoring of the organ-on-chip. As depicted in Figure 7C, Guner et al\textsuperscript{157} designed a smartphone surface plasmon resonance (SPR) imaging adapter. The adapter consists of an SPR sensor chip, an external lens, a linear polarizer, a beamsplitter plate, a green (520 nm) LED, a multimode fiber optic cable, a collimator, 2 batteries, and a plastic body. It achieved a 12 m/pixel resolution for cell counting. As depicted in Figure 7D, Gallegos et al\textsuperscript{158} used a smartphone adapter as a biodetector. The adapter consists of a collimating lens, a tungsten incandescent lamp, a linear polarizing filter, a cylindrical lens, a diffraction grating, a pinhole, and an anodized machined aluminum body. It successfully detected an immobilized protein and antibody bindings. As shown in Figure 7E, Wang et al\textsuperscript{159} demonstrated a smartphone microplate reader for the detection of infectious diseases. The adapter contains a 96-well microplate holder, 2 LEDs, 2 aperture arrays, two batteries (9 V), a DC voltage regulator, a switch, and a plastic body, resulting in a high-diagnostics-performance device for clinical use. As shown in Figure 7F, Zhu et al\textsuperscript{160} innovated fluorescent smartphone imaging. The device is used for monitoring patients with HIV+. The adapter is composed of 3 LEDs, a lens, a color filter, a battery, and a plastic body. It successfully achieved a 10-m resolution.

### 3.5 | Electrochemical applications

These types of applications are extremely different in terms of the variety of chemical structures to be analyzed (samples) and the functionality of the smartphone application used to process the samples.\textsuperscript{161-167} Imaging techniques are not popular in this category, as the adapter consists of special electronics that are designed specifically to target a unique chemical compound.\textsuperscript{168-174} Using a smartphone proved to be cost effective (see Figure 12), and extremely accurate results
FIGURE 7  Biochemical applications of smartphone adapters. (A) Smartphone adapter and integration, by Chen et al., copyright 2017 American Chemical Society; (B) Smartphone-based fluorescence microscope, by Cho et al., adopted with permission from Elsevier Publishing; (C) Smartphone SPR imaging adapter, by Guner et al., adopted with permission from Elsevier Publishing; (D) Smartphone biodetector, by Gallegos et al., adopted with permission from the Royal Society of Chemistry; (E) Smartphone microplate reader, by Wang et al., adopted with permission from Elsevier Publishing; (F) Fluorescent smartphone imaging, by Zhu et al., adopted with permission from the Royal Society of Chemistry

were reported when comparing the performance of the smartphone-based adapters to those of laboratory equipment and devices with a low CV%, a high regression coefficient, lower costs, and a low LOD (see Figures 10 to 13). Zhao et al., as shown in Figure 8A, developed a fluorescent smartphone-based label-free sensor to detect Fe (III) by employing the quenching effect. The 3D printed adapter uses a 365-nm UV LED and a smartphone camera. The design was effective in comparison to the microplate reader, with recovery values of 90% to 108.5% and an LOD of 1.7 μM. Sun et al., as depicted in Figure 8B, developed two electrochemical smartphone-based biosensors with two different potentiostat designs for measuring potassium ferrocyanide and ferricyanide samples, with 5.7-mW and 4.3-mW peak power for the two designs, respectively. The adapter was compatible with a laboratory-grade instrument with a cost of less than $30 for each design. The design uses the smartphone audio jack for both communication and power, with cheap electronics and high reliability. Chen et al., as shown in Figure 8C, reported a smartphone colorimetric reader integrated with an ambient light sensor and a 3D printed attachment for liquid colorimetric assay readout. Zearalenone samples were the focus of the research. The design has the advantage of detecting changes in LED light in different liquid assays of the transmitted light intensities, making it easy to use and cost effective.

Park et al., as depicted in Figure 8D, reported a hand-held pathogen-detection smartphone-based device; the targeted samples were E. coli O157:H7 bacteria with a linear range of 10 to 106 colony-forming units (CFUs). Using the illumination sensor of a smartphone device, optical analysis, and measurements were performed on the E. coli samples.
The 3D printed adapter consists of a test tube holder, an LED holder, a portable low-power centrifuge, and a smartphone holder, and the samples were analyzed using the Lux Light Meter application on the Android platform. Shan et al.\textsuperscript{197} as depicted in Figure 8E, demonstrated a smartphone-based fluorescence microscope for mercury (Hg\textsuperscript{2+}) on-site detection, with a linear range of 1 nM to 1 μM and an LOD of 1 nM. The 3D printed adapter contains a 405-nm laser diode as the excitation source, a 20× micro-objective lens for magnification, an eyepiece that can connect the smartphone camera with the micro-objective, a 469-nm emission filter to remove scattered light, and a reflective mirror. The Z17 mini Nubia smartphone was used to capture the fluorescence image, which was then further processed by a smartphone application. Guo,\textsuperscript{198} as shown in Figure 8F, proposed a smartphone-based environment for the hosting, detecting, and data transferring and sharing of blood glucose and uric acid samples. It makes use of the IoT technology, cheap electronics, and a smart application. With the abovementioned technology, the smartphone works as both a display screen for on-site diagnosis, and a medical information transfer station for medical IoTs (mIoTs). The system can provide large health markets with a very promising solution. It combines biosensors, Internet communication, information processing, and family doctor participation to provide professional medical services to each healthcare consumer and patient. A summary of the adapter design comparison is found in Table 2.
4 | DISCUSSION

Adapter design requires specialized skills in optical systems and targeted applications. The design should consider the cost of the adapter, the accessories, and the integrated optical and mechanical parts. The 3D modeling and design software should have the ability to be installed on a 3D printer or CNC machine using a “.stl” file format or other types of formats depending on the 3D printer software used. SolidWorks has the advantage of being easy to learn and compatible with 3D printing machines, as shown in Table 3. The image analysis is preferred to be integrated functionally with the smartphone application for portability and design practicality. We believe that the Xamarin platform and Ionic platform have great potential in the smartphone application industry, especially in POC research. This is because both platforms can be integrated with the three main categories of smartphone software, namely, Android, IOS, and Microsoft, thus making the smartphone application available for almost every smartphone software and not just the targeted one, as shown in Table 3, which reveals that researchers have made astonishing advancements on only specific smartphone platforms, that is, either Android or IOS, excluding the fact that smartphone applications should be designed for all three categories. We also suggest a simulation before the assembly and printing of the adapter, in which optical elements are set in optimal positions to perform the specified task, e.g., focusing, filtering, or image enhancement. In this way, the design can...
| Application type                        | Smartphone | Method          | Software analysis                          | Sample          | LOD             | Ref.   |
|-----------------------------------------|------------|-----------------|---------------------------------------------|-----------------|-----------------|--------|
| Smartphone fluorescent sensing          | iPhone 6   | 3D printing     | Color Picker APP                            | Fluoride Ions   | 2.0 μM          | 1      |
| Smartphone contamination                | LG-F470L   | 3D printing     | MATLAB; SolidWorks; Android                 | Cholesterol; bile acid | 20 mg/dL; 0.5 μmol/L | 7      |
| Biochemiluminescence                    | iPhone 5S  | 3D printing     | ImageJ                                       | Arsenic (As (III)) | 0.71 ppm       | 8      |
| IoT aldehyde sensor                     | Google     | 3D printing     | Grafana                                      | Formaldehyde    | 15 ppb          | 39     |
| Biodiesel                               | iPhone SE  | Digital image   | PhotoMetrix                                  | Methanol        | 90 mg/kg        | 41     |
| Smartphone DNA detection                | Google     | 3D printing     | AutoCAD, Primer 3                           | DNA             | 2.8 x 10^5      | 42     |
| Colorimetric spot test                  | iPhone 4   | Colorimetric    | NIST                                        | Synthetic cannabinoid AB-001 | 0.3 μg      | 48     |
| Fluorescent colorimetry                 | M1 Note, Meiz | Imaging | ImageJ                                       | Tetracyclines   | 4.5 ng/ml       | 55     |
| Quantitative detection                  | Huawei     | 3D printing     | SolidWorks, Android App                     | Zearalenone     | 0.08 μg/kg      | 74     |
| Bacterial sensing                       | HTC ONE X  | Imaging         | Android; Cloud Computing                    | E. coli         | 10 cells/ml     | 123    |
| Avatar DNA recognition                  | iPhone touch fifth generation | Imaging | Image Quant; ColorZip-code DNA | NR (see footnote b) |                | 126    |
| Multi-reagent immunosensor              | Samsung    | Fluorescence    | Android Programming                         | PSA; IgG; NF-κB | 1 ng/ml         | 127    |
| Barcode-like paper sensor               | Google     | Imaging         | Mobile Programming                          | Blood           | NR              | 128    |
| Infectious diseases detection           | iPhone & Android | Integration | CasaXPS, HIV p24 | Malaria | 1.1 nM          | 130    |
| Malaria diagnostics                     | iPhone     | Fluorescence    | nRF UART Application; AutoCAD; SolidWorks   | Malaria         | ~0.6 par/μL     | 132    |
| Malaria detection and reporting         | iPhone 5s  | Imaging         | MATLAB; REDCap                              | Malaria         | 20.6 par/ml     | 133    |
| Smartphone detection of luteinizing hormone | Galaxy Note 2 & Huawei Honor v8 & Xiaomi Mi | Image processing | Canny edge detection & fuzzy mean clustering | Luteinizing hormone | 2.0 mIU/ml | 134    |
| Salivary Cortisol Measurement           | Galaxy Note 1 | 3D printing and assembly | Android Software Developer; ImageJ | Cortisol       | 0.01 ng/ml      | 135    |
| Tableting reagents for medical diagnostics | iPhone 5s  | 3D printing     | MATLAB; ImageJ; SPSS                       | Hepatitis B Virus | 10 pmol/μL    | 139    |
| Submicron imaging                       | iPhone; Android | 3D printing | Mobile App                                  | Blood smears    | NA (see footnote c) | 140    |
| Detection of influenza virus            | LG Nexus 5X | 3D mounting     | Android Application; ImageJ; MATLAB         | Influenza A     | ~10 pg          | 144    |

(Continues)
| **TABLE 3** Continued |
|------------------------|
| **Heart failure prognosis** | Android 3D printing | UC-LFS App | Brain natriuretic peptide; suppression of tumorigenicity 2 |
| **Quantum dots screening** | Samsung Galaxy S7 3D printing | ImageJ | Graphene quantum dots; paraxon; 4-nitrophenol |
| **Prostate-specific antigen (PSA) biomarker** | Android 3D printing | MATLAB; Smartphone App | PSA |
| **Diagnostics of infectious diseases** | Samsung Galaxy S3 3D printing | MATLAB | Herpes simplex virus type 2 |
| **Fluorescent biosensor** | Samsung Galaxy S4 3D printing and assembly | ImageJ; SPSS | 17β-estradiol |
| **Bioluminescent 3D cell biosensor** | Nokia Lumia 1020 3D printing | ImageJ; GraphPad Prism | Tumor Necrosis Factor (TNFa) |
| **Quantum dot barcode reader** | Apple iPhone 4S 3D printing and assembly | MATLAB | HIV; hepatitis B. |
| **Mercury contamination detection and readout** | Android 3D printing | Light-Meter Application | Hg²⁺ (see footnote d) |
| **Microchip ELISA biosensor** | Sony Ericson i790 3D printing | CDSA; MATLAB | Human epididymis protein 4 (HE4) |
| **Biosensing spectrometer** | iPhone 3D printing | Swift; MATLAB | Bovine serum albumin (BSA); Human Interleukin-6 (IL-6) |
| **Biomarker biosensing** | Galaxy S3 LTE 3D printing | ImageJ; SolidWorks; Android Studio | Cortisol; C-reactive protein (CRP) |
| **Chemiluminescent biosensing** | Samsung Galaxy SII Plus 3D printing | ImageJ; MakerWare slicer | Cortisol |
| **Biosensing spectroscopy** | Unspecified 3D printing | Specially Designed | Endotoxins |
| **Pathogenic detection** | iPhone 5s 3D printing | SolidWorks; ImageJ | Salmonella Enteritidis; E. coli O157:H7 |
| **Fluorescence microscopy** | iPhone 5s 3D printing and assembly | SolidWorks; ImageJ; Stata/IC | γ-glutamyl transpeptidase (GGT) |
| **Smartphone SPR imaging** | Samsung I8552 Galaxy Win 3D printing | Android App; PCGrate | Mouse IgG; rabbit anti-mouse (RAM) IgG |
| **Smartphone biodetector** | iPhone 4 3D printing | iPhone App | Porcine immunoglobulin G (IgG) |
| **Infectious disease diagnostics** | iPhone SE 3D printing | iPhone App; MATLAB | 12 diseases; IgG |

(Continues)
**TABLE 3** Continued

| Method Description                      | Manufacturer/Software/Platform | 3D printing/Assembly | Unspecified/Tools | Fluorescent beads; White blood cell; Giardia Lamblia cysts | NA  |
|-----------------------------------------|--------------------------------|---------------------|------------------|----------------------------------------------------------|-----|
| Smartphone colorimetric reader          | HUAWEI Honor 6                 | 3D printing         | SolidWorks; MATLAB; Light Meter App | Zearalenone                                               | 160 |
|                                        |                                |                     |                  |                                                          | 195 |
| Smartphone biosensor                    | iPhone 4S                      | Imaging             | AutoCAD; ImageJ; Xcode | E. coli                                                  | 199 |
|                                        |                                |                     |                  |                                                          | 200 |
| Smartphone microfluidic                 | iPhone 4S                      | Assembly            | ImageJ            | PSA                                                      | 201 |
| Smartphone enzymatic biosensor          | iPhone 6                       | 3D printing         | SketchUp; MakerWare; ImageJ; GraphPad Prism | L-lactate                                               | 202 |
|                                        |                                |                     |                  |                                                          | 203 |
| Smartphone fluorescence polarization     | HTC                            | 3D printing         | SolidWorks; LightTools; Android App | Prostaglandin E2                                         | 204 |
|                                        |                                |                     |                  |                                                          | 205 |
| Smartphone microscope                   | Samsung Galaxy S5              | 3D printing         | cLEDscope App    | Unspecified                                              | 206 |
| Smartphone colorimetric reader          | iPhone 5s; Samsung Galaxy S3 mini | Assembly           | ImageJ; SigmaPlot | SBCR IA CRP; MTPR CRP IA; SBCR IA HRP; MTPR HRP IA | 207 |
|                                        |                                |                     |                  |                                                          | 208 |
| Smartphone mobiNAAT                      | Samsung Galaxy S3              | 3D printing; electronics; AND Studio; SolidWorks; Arduino platform; Lapse-It | Chlamydia trachomatis | NA                                                      | 209 |
| Smartphone colorimetric sensing         | iPhone 6S                      | Assembly            | Adobe illustrator CS4; ImageJ; Yamera | Chloride ions                                           | 210 |
|                                        |                                |                     |                  |                                                          | 211 |
| Smartphone sensing                      | iPhone 4                        | Assembly            | ImageJ            | BSA protein; Trypsin enzyme; Pumpkin pollen grains      | 212 |
|                                        |                                |                     |                  |                                                          | 213 |
| Smartphone microscopy                   | Huawei TIT-AL00                 | Fabrication         | Mobile App       | Bisphenol A                                              | 214 |
|                                        |                                |                     |                  |                                                          | 215 |
| Smartphone fluorescence                 | iPhone 5s                      | 3D printing         | iPhone App       | RBC smear, Pap smear, monocot root; broad bean epidermis | NA  |
|                                        |                                |                     |                  |                                                          | 216 |
| Smartphone microscopy                   | Nubia Z9 mini                  | 3D printing         | Mobile App; MATLAB | CD4                                                      | 217 |
|                                        |                                |                     |                  |                                                          | 218 |
| Label-free testing                      | MotoX-XT1575                   | 3D printing         | SolidWorks; OpenCV; Android Studio; Medcalc; Stata; Graphpad Prism | CD4                                                      | 219 |
|                                        |                                |                     |                  |                                                          | 220 |

(Continues)
TABLE 3  Continued

| Chemiluminescence biosensor | Smartphone biomarker | Chromatography imaging | Disease detection | Smartphone spectrometer | Computational microscopy |
|-----------------------------|----------------------|------------------------|-------------------|-------------------------|-------------------------|
|                             | Samsung Galaxy SII   | Huawei Honor 6         | Samsung S6812     | Motorola Nexus 6        | HTC 1                   |
|                             | Plus                  | 3D printing            | 3D printing       | 3D printing             | 3D printing             |
|                             | ImageJ; GraphPad Prism| Android App            | MATLAB; winCATS   | Zemax; MATLAB            | Autodesk Random         |
|                             |                      |                       | Butyrylcholinesterase (BChE); Ellman | Bovine serum albumin (BSA) | Mobile App | Rhodamine 6G; books software-programmed adapters with a cost of less than US $2000 for the first prototype, including the optical components, mechanical components, 3D printed adapters, electronics, and software design and simulation.

The comparison metrics of the smartphone-based adapters are plotted in Figures 10 to 13. The CV% in most of the reported studies is under 5%, demonstrating the great reliability of smartphone-based adapters in comparison to laboratory equipment, as shown in Figure 10. The limit of detection for most of the reported literature is very low, offering low-sample-concentration samples in the range of μM and reaching even pM, which is very encouraging for POC applications, as shown in Figure 11.
FIGURE 10 Coefficient of variation (CV%) for reported literature

FIGURE 11 Limit of detection (LOD) in μM for reported literature

The cost of smartphone-adapters for most of the reported literature is very low, lower than $100, offering great reliability and a cheap alternative to laboratory equipment, reducing the cost of testing if the smartphone-based adapters are adopted, as shown in Figure 12. The regression coefficient ($R^2$) is a correlation function ensuring the matching of the data with a standard model. In the case of smartphone-based adapters, the $R^2$ coefficient indicates a high level of matching
between the smartphone-based adapters and laboratory equipment. For most of the reported research, the $R^2$ is in the range of 98% to 100%, as shown in Figure 13.

5 | CONCLUSIONS

Smartphone adapters will become the most valuable resource for every smartphone user who lives in a remote area and is unable to afford the costs of ordinary laboratory tests or clinical operations. In addition, the development of adapter design promises great enhancements and modifications for targeting specific chemical compounds, diseases, viruses, bacteria, and parasites in the near future. With the help of software design, smartphone POC applications will be more reliable
in terms of rapid testing, calculation, measurement, and diagnosis with low concentration samples, as well as accurate reading of these samples.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Taif Alawsi designed the study and wrote the manuscript. Zainab Al-Bawi supervised the work and reviewed the manuscript.

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