CHAPTER 1

INTRODUCTION

For sustainable agriculture, there is a need for constant monitoring of soil quality and other parameters in our environment. However, in many remote areas, the north-eastern regions of India in particular, the soil quality monitoring facilities are very limited. Though India is primarily an agriculture based nation where approximately 50% of the total population are directly or indirectly involved, the sector needs extensive research and development for overall growth of the nation's economy. The monitoring of soil quality parameters therefore bears a great relevance as far as agricultural yield is concerned. It is with this background the introduction chapter deals with the importance of soil quality monitoring at the beginning of the chapter. The chapter then discusses different conventional techniques that are available for monitoring of soil quality parameters. The section also includes the disadvantages with the conventional sensing tools. Following this, the new section discusses the evolution of smartphone technology in the past three decades. In the next section, the need for disruptive technology mainly driven by smartphone-based sensing systems for monitoring of soil quality parameters has been discussed. The following section then illustrates the scope of the present thesis work. This section further summarizes the different works being carried out related to the development of smartphone based sensing systems for monitoring of various soil quality and agricultural parameters during the PhD work.

1.1 Need for soil quality monitoring for sustainable agriculture

Soil along with water and air quality plays a critical role in our ecosystem [1]. Water and air quality are primarily determined by the amount of various contaminations that directly affect the animal kingdom, and the natural ecosystem as a whole [2]. Soil quality is generally defined more broadly as *"the capacity of a soil to sustain biological productivity, maintain environmental quality, and promote plant and animal health"* rather than being restricted to the level of soil pollution [3]. In order to control the fertility and quality of the soil and the production processes of agricultural products, it is crucial to analyse the soil nutrients in a farmland [4, 5]. Soil has physical as well as chemical elements. It's physical property depends on the soil particle size, shape, and distribution etc. while its chemical property depends on pH value, macronutrients (nitrogen, phosphorus and potassium) and micronutrients (zinc, nickel, cobalt etc.) and total organic matter [5, 6]. The primary macronutrients of soil have a significant impact on agricultural quality and yield. Soil's macronutrients are referred to the major elements as they supply most nutrients to the soil and plants. Each macronutrient is crucial for maintaining the soil's health and enhancing the growth of the crops [7, 8]. For example, magnesium and nitrogen are crucial for agricultural growth. Potassium ensures the plant's rigidity and boosts its resistance against fungus and other infections, while phosphate helps the root of the plants to grow [8]. Micronutrients are also important plant nutrients that are present in tissue in minute levels yet are crucial for the growth and development of plants. These nutrients are necessary for the normal, healthy growth and reproduction of both plants and animals [9, 10]. Every micronutrient has a distinctive role within the plant organism. However, boron, iron, manganese, and zinc are the most essential micronutrients. The deficiency of these elements effects the chlorophyll production and flowering process of plants [11]. Hence monitoring of soil nutrients is important to improve the soil quality that determines the crop health. Additionally, monitoring of these nutrients helps to identify the nutrients that are deficient in agricultural farmlands, which subsequently would influence the choice of crops to invest in and the use of fertilisers. Therefore monitoring of various soil parameters is vital for effective production as well as for preventing pollution of groundwater from agricultural run-off.

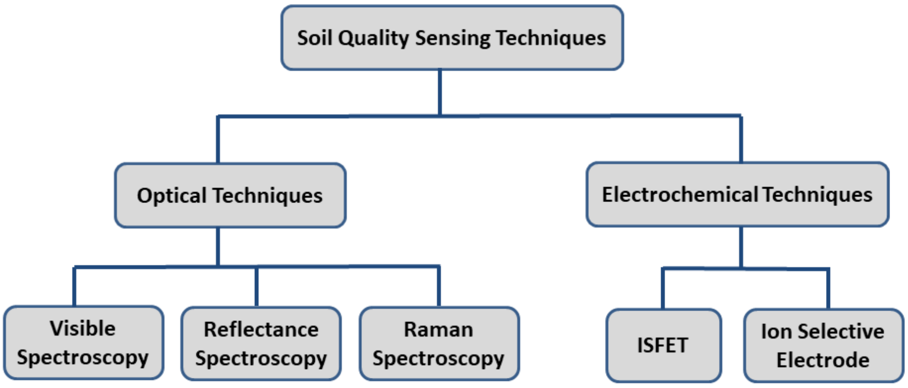

Figure 1.1: Classification of mostly used soil sensing techniques

1.2 Techniques available for monitoring of soil quality parameter

Conventional soil nutrient measurement procedures involve extraction and preparation of soil samples. The extracted samples are usually transported to the central soil testing laboratories for data sensing and analysis using the sophisticated instruments to estimate a particular soil parameter. Traditional methods of soil analysis require a number of instrumental techniques, including molecular emission spectroscopy, atomic absorption spectrometry (AAS), nuclear magnetic resonance (NMR) spectroscopy, high performance liquid chromatography (HPLC), and gas chromatography combined with mass spectrometry (GC-MS) [12]. Additionally, field-effect transistors and ion-selective electrodes are also utilised for electrochemical sensing [13, 14]. Out of all the available techniques, the majority of soil sensing involves optical and electrochemical techniques as shown in the flowchart in figure 1.1.

1.2.1 Optical sensing techniques

Optical sensing techniques are useful for fast and minimally invasive measurement of soil nutrients. These are **UV-Vis spectroscopy, infrared spectroscopy (IRS), reflectance spectroscopy and Raman spectroscopy**. In spectroscopic based techniques soil samples are radiated with a polychromatic radiation source and the amount of light that is diffusely reflected or absorbed by soil sample is measured to quantify the soil nutrients. The basic principle of spectroscopic based method is the interaction of light with matter. In matter the bond between molecules vibrate with some frequencies and the oscillation of a specific chemical bond is accompanied with a particular frequency and energy levels. When electromagnetic radiation is incident on medium, a particular frequency gets absorbed, some are transmitted while others are reflected. A spectrometer captures the transmitted or reflected radiation, creating a spectrum that reveals the amount of energy captured as a function of wavelength. Thus, by comparing the absorption peak of a particular molecule to the database of spectrums, it is possible to identify as well as quantify the molecule [15]. Numerous soil properties, including moisture [16, 17], organic matter [18], nutrients [19, 20], nitrogen content [21] and pH [22], can be determined rapidly and effectively using spectroscopic technique. Visible near-infrared and mid-infrared spectroscopy are also used to analyse soil properties, although these measurements are mostly conducted in a lab using prepared soil samples [23]. Along with visible and infra-red spectroscopy, Raman spectroscopy is another important analytical tool to measure different soil nutrients. It is a technique that includes measurement of the change in wavelength and intensity of scattered light upon interaction with the sample. The Raman spectrum obtained from a sample is a distinctive fingerprint of the sample that provides details regarding its chemical composition and identity. By using Raman spectroscopy available nitrogen [24], carbon materials [25], phosphorus [26], and other nutrients in soils [27] can be measured. Although these optical techniques provide highly accurate results, but continuous real-time analysis of farm soil cannot be done with these conventional techniques.

1.2.2 Electrochemical sensing techniques

Electrochemical sensing technique is another established and preferred sensing method for detection of various chemical compositions in soil sample. The electrochemical device operates by connecting an electrochemical transducer to a chemically selective layer known as a recognition element. The transducer transforms the chemical energy of the selective membrane into an electrical signal when the recognition layer comes into contact with the ion of interest [28]. Based on the applied electrical techniques, electrochemical sensors can be further divided into different subcategories- potentiometric analysis, which evaluates variations in membrane potential conductometric for determining the conductance changes; impedance-based sensors that monitor changes in resistance, and amperometric sensors to monitor current variations at the sensing membrane. The two electrochemical sensors that are most frequently used to measure soil nutrients are **ion-selective field-effect transistors (ISFET) and ion-selective electrodes (ISE)** [29]. ISEs are used for rapid measurements of nutrients in slurries, unfiltered soil extract, and naturally moist soils [30, 31]. ISEs with glass membranes are frequently used to measure pH other than soil nutrient detection. However, different polymer doped membranes are mostly used for detection of soil nitrogen, nitrate, potassium and phosphate [32]. Ion-selective field-effect transistors (ISFETs) are essentially ISEs connected to a field-effect transistor (FET). ISFET system is used for in-field measurements of soil nitrate in real-time in less than

5 seconds [33]. ISFET devices have proven to be capable of analysing different soil nutrients [34]. However, ISE based sensors have the drawbacks of frequent calibration requirements, the potential need for additional extraction solutions, and dependence on soil moisture for accurate nutrient measurements. Another drawback is that different soil characteristics, such as the texture type, particle size, volumetric water, organic matter, etc., have an impact on nutrient sensor response [35]. Although, there are various techniques available for detection of different soil nutrients but all these techniques have disadvantages in terms of sample preparation cost and time, laboratory confined methods, and the requirement of sophisticated instruments.

1.3 Problem statement of conventional techniques with reference to resource-limited environments and possible solutions

The monitoring of soil quality is often done in soil testing laboratory using standard laboratory techniques and benchtop measurement equipment. Soil samples from different locations are analysed in the central testing laboratory, however, if the sample collection area is located far away from the laboratory then the soil analysis procedure become costly and time-consuming. Numerous other technical obstacles also contribute to the failure of conventional soil quality monitoring in centralized laboratory facilities in addition to the cost factor. Advanced analytical tools including spectrophotometers and electrochemical sensors are conventionally used to test the soil quality and waste water in a laboratory environment. Additionally, in order to run these facilities technically skilled personal are required. Many commercial test kits are now available for soil analysis, however they only provide an approximate reading of the nutrient content (i.e., low, medium, and high), hence they are useful only for preliminary screening purposes [36–38]. Also, the colorimetric techniques of soil analysis method relies on how people perceive colour, which may differ from person to person [39]. Due to numerous financial and political constraints, it is not possible to build up soil testing laboratory facilities with the necessary expertise in many remote areas where agriculture is not the mainstream source of income. Farmers from these areas face many problems due to lack of adequate laboratory equipment and infrastructure facilities. Yet again, the application of the analytical instruments in resource-poor environments is limited by their size, price, weight, and need for external power sources. Due to geographical constant, many rural and remote areas in our country are still lacking soil quality monitoring programme. To initiate such programme it is important to have some basic knowledge of optimum levels of soil nutrients required for different kinds of crops. Field crop yields are severely impacted by diseases that are spread through the soil. Early detection is necessary for the application of agro-technical solutions and preventive materials, as well as for minimizing the number of treatments in disease-free areas [40]. Although the government approved soil quality monitoring laboratories are addressing these soil-related challenges, but there is a great demand for handheld, field portable and affordable soil quality monitoring facilities that are easily available to the farmers, regardless of their financial situation. In order to provide in-field sensing in rural and distant areas, it should be reliable and field deployable. It should have adequate communication capabilities to enable real-time data exchange with the central soil quality testing of governmental and non-governmental groups, enabling timely implementation of effective soil quality improvement programme. The monitoring facilities should be created and developed with a user-oriented approach in addition to all these technological and operational capabilities so that anyone with little or no scientific understanding can readily operate it. The majority of laboratory-grade analytical instruments for soil quality investigation are based on common optical concepts such light signal absorption and scattering from sample solutions or electrochemical method. Utilizing low cost technical solutions, numerous research organisations around the world have been working consistently to develop low cost and field-deployable sensing systems, and utilizing it for monitoring different parameters of agriculture and environment [41–44]. Although the existing remote sensing tools are more efficient, compact, and cost-effective than their benchtop equivalents, they still require, external computational facility for data processing and analysis which increases the overall cost in context of the resource poor regions. Also, the existing devices do not have the requisite connection facilities for many in-field sensing applications, such as monitoring soil and water quality, where real-time data sharing is essential. Earlier technological tools are inadequate to bring out the best in agricultural industries. The use of technology solutions in the infield sensing devices should be simple, and operated by the common people. Therefore it is an urgent need of such technologies in agriculture which can make a great change to farming business as well as provide a great benefit to the farmers by constructing a stress-free and cost-effective agricultural existence.

1.4 Evolution of smartphone technology and its penetration to human civilization

The smartphone has become the most dependable accompany in modern times, and it has a significant impact on how we deal in our daily lives. Over all the commercially accessible electronic devices, it is the most popular and commonly used mobile device in the world. Number of smartphone users increased globally by 49.89% in 2017-2022

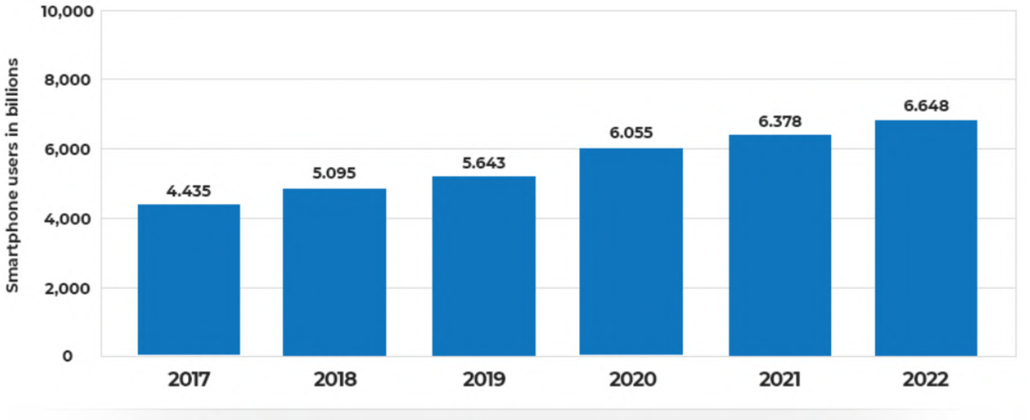

Figure 1.2: Number of smartphone users worldwide data from 2017-2022. (Source:Statistica)

as shown by statistics in figure 1.2. By end of 2022, there will be 6.648 billion smartphone users worldwide, which equates to 83.40% of the world's population. In total, 7.26 billion people worldwide or 91.08% of the world's population own smart or feature phones [45]. In contrast, India, with 1.38 billion smartphone users and a penetration rate of 31.8%, has the second-highest number of smartphone users in the world [46]. This data reveals that the smartphone is the most widely available electronic gadget worldwide, regardless of a nation's economic status. The wide spread adoption of this technology by our society is attributed to its accessibility and consumer-focused low-cost design strategy. Because of the extensive network and low cost, smartphones play a significant role in connecting people who are neglected from the mainstream of progress due to numerous political and socio-economic challenges. Various governmental or non-governmental groups are currently supporting multiple advancement as a result of the widespread use of mobile phones in emerging and poor nations [47].

In 1973, Martin Cooper from Motorola Company presented the first operational mobile phone. Since then due to the rapid evolution of the technology, mobile phone has become an inevitable part in our daily lives. In general, it can be divided into two categories- feature phones and smartphones. Besides the basic calling and texting capabilities of a feature phone, smartphones include additional functionalities capable of displaying images, streaming videos, sending emails, browsing the web, etc. Modern day smartphones are the outcome of a constantly evolving process that integrates new technologies into a compact design on a massive scale. Smartphones have similar processing and sensing capacities to more of expensive high-end devices due to its rapid manufacturing techniques. These not only improve communication, but also function as a portable computer with ever-improving hardware and sensors like ambient light sensor (ALS), display module, complementary metal-oxide semi-

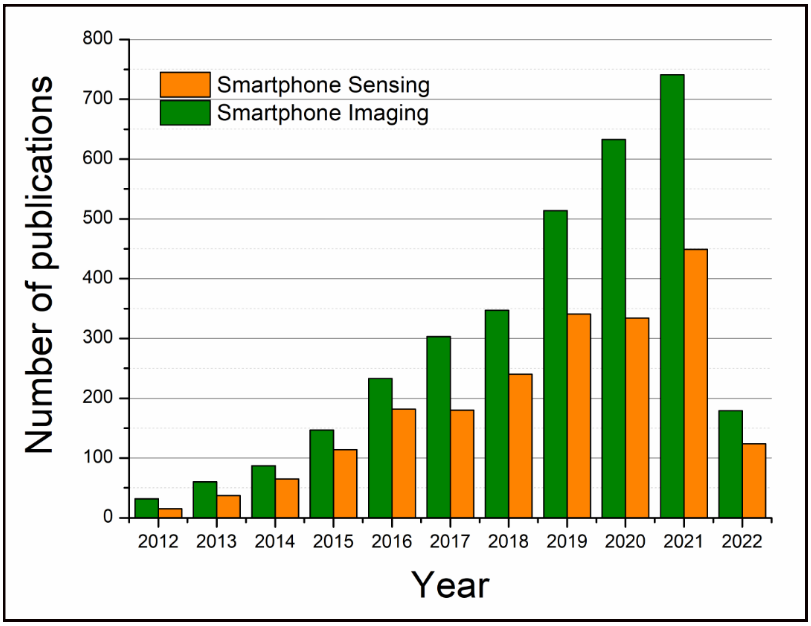

Figure 1.3: Graphical representation of number of research papers published on smartphone based sensing and imaging applications from 2012 to 2022. [Courtesy: Web of Science]

conductor (CMOS) module, LED flashlight, proximity sensor, USB port etc. with optimized software interface and long battery life. In addition to the integration of these sensors, open source tools like Android Studio and MIT App Inventor can be used to create user-oriented software or smartphone application. By developing these smart applications with the required algorithms, the sensing information from the phone's built-in sensor technology can be extracted and may be directly utilized for scientific purposes [48, 49]. Numerous research articles have been published throughout the years, taking into account the current status of smartphones in the social community and taking advantage of the integrated sensor modules in smartphones. The bar graph shown in figure 1.3 depicts the growth of research publications on smartphone based sensing and imaging from 2012-2022. In brief, it can be stated that the modern smartphone are portable personal computer (PC) that enables a user to develop various scientific instruments. Researchers all over the world are working constantly on transforming science and technology from the conventional to the need based sensing tool on a smartphone due to its enormous availability in nearly everywhere without any financial limitation.

1.5 3D printing technology and its role for the development of phone based sensing and imaging system

Along with smartphones, another manufacturing techniques like three-dimensional (3D) printing have gained popularity [50]. It is referred to as additive manufacturing technique by which three-dimensional objects are built layer by layer using a computer-generated design. Several types of 3D printing technology methods are available based on the applications such as fused deposition modelling (FDM), laser sintering and laser melting (SLS, SLM), stereolithography (SLA), directly ink writing (DIW), lamination (LOM), photopolymer jetting (Ployjet), and binder jetting (3DP) [51]. The commonly used FDM 3D printing process includes three main basic steps: digitally designing the 3D model, converting the model into printer-compatible print files, and fabricating the model by adding patterned layers of the printing material. The frequently utilised materials are polymers like polylactic acid (PLA) and polyethylene terephthalate glycol (PETG). To begin the 3D printing process, a design is created entirely in digital format by utilising CAD software, e.g. Solidworks, ZW3D etc. The 3D CAD model is then exported in STL (Standard Tessellatio Language) file format that contains the model's geometric features without including any information about colour or texture and the file can be shared with anyone. The finalized STL file is then loaded into a slicing software (such as Ideamaker, Cura, etc.) where it is processed into a set of G-code instructions that can be read directly by the 3D printer. 3D printing technology is gradually becoming the most important tool for scientific study that provides exceptional speed in the fabrication of low-cost, reliable prototypes that may be useful in biomedical, agricultural and environmental sensing applications [52, 53].

1.6 Literature review- Utilization of common smartphone sensors in agricultural and environmental sensing applications

Numerous researchers worldwide have exploited the high-end features of the smartphone like fast CPUs, high-resolution camera, global positioning system (GPS), ambient light sensor, etc. of the smartphones for various sensing and imaging applications [54, 55]. The ever improving sensor feature assist users to perform various tasks to detect different parameters at ultra-sensitive level. Smartphone-based systems have been actively developed for diverse applications in agriculture and environment

[56, 57]. The following sections provide a comprehensive description of the role of different inbuilt sensors of smartphones that have been used to develop sensing system for agricultural and environmental monitoring purpose.

1.6.1 Smartphone camera based monitoring systems

For all the smartphones, the built-in camera of the phones is an integral part with advanced imaging and processing technologies. The use of phone camera has several feature that include high-resolution imaging (over 12 megapixels), manual or auto exposure and focus control, ease of use, and programmability. Because of these advantages, diverse research has been carried out in the field of agriculture and food products [58]. Details of the work on monitoring of different parameters of agriculture and environment using smartphone's camera are outlined below.

Monitoring of soil health or quality is vital for better yields of good quality crops. There are several works related to the smartphone-based soil monitoring systems that have been reported in the recent literature. Moonrungsee et al. [59] have developed a colorimetric analyzer for monitoring of available phosphorus in soil using the camera of smartphone. In the reported work, soil samples with varying phosphorus concatenation have been prepared by treating chemically and then the quantification of the phosphorus content in each soil sample have been done from images taken by built-in digital cameras on smartphones. With a developed software program, the captured images have processed and analyzed the RGB color of the images. With this colorimetric analyzer based on mobile phone camera, the available phosphorus level in soil has been estimated with a detection limit of 0.01 mg/L. Another smartphone-based, low-cost, and miniaturized sensing tool has been proposed by Han et al. [60] for classification of soil color sensor. In this work, the CMOS camera of the mobile phone has been directly used as the sensor and the flashgun of the phone has been used as the light source. Along with some peripheral components like external lens and shading devices, a color calibration card, has been also assembled with the phone. The soil color information and calibration cards has been read from images taken by CMOS cameras of smartphones and converted into RGB signals. The RGB signals was processed further by a specially designed smartphone application from which the rapid soil classification could be achieved. In another work Siddiqui et al. [61] has proposed a smartphone based soil sample preparation and detection system for arsenic As(III) contaminated soil. An aptamer and AuNPs based colorimetric detection assay has been developed for the optical detection of the soil samples on a PDMS-chip. The target sample placed on the chip has been illuminated by the LED flash of the smartphone and the reflecting intensity has been collected in the form of a captured image by the smartphone's camera. For quantification of As(III) concentra-

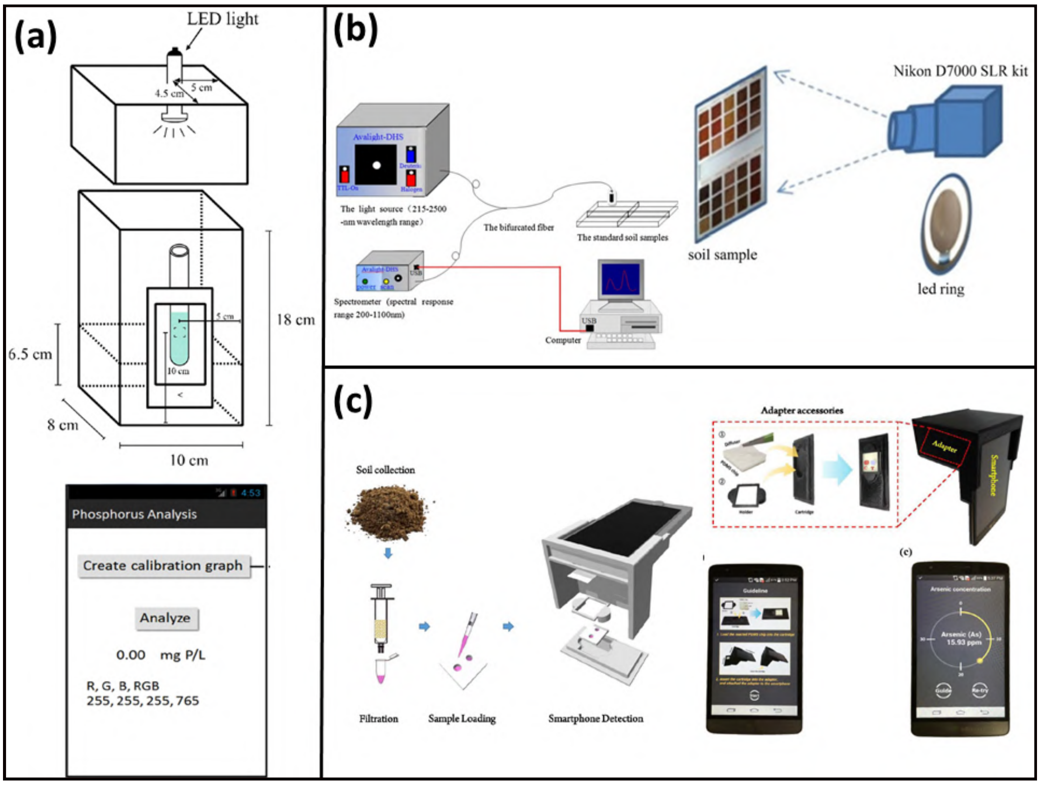

Figure 1.4: The development of smartphone camera based sensing platforms; (a) working of a smartphone camera based colorimetric sensing [59] with permission from Elsevier, (b) demonstration of smartphone camera based soil sensor, reproduced from [60] with permission from Elsevier and (c) demonstration of smartphone camera based arsenic detection system, reproduced from [61] with permission from MDPI.

tions of the samples, the RGB pixel values of the captured images has been spatially averaged, and subsequently the evaluated ratio of the green to red values (G/R) to correlate with the concentration of target analyte. Figure 1.4 shows the development of different smartphone camera based sensing used for soil quality analysis.

Smartphone applications have been widely developed to monitor the crops growth, its different parameters, and also for disease detection in farms. Recently, Vesali et al. [62] have developed a smartphone application for the estimation of chlorophyll content of a corn leaf. In this work, contact imaging method has been used to reduce the effects of ambient conditions on images of corn leaves. They have captured the light passing through a leaf by holding the leaves near to the camera lens of the smartphone. From these images the SPAD (Soil Plant Analysis Development) values they have estimated and correlated with leaf chlorophyll content which was extracted through an organic solvent method. The estimated SPAD values by their model were compared with a SPAD meter and the model has been successfully implemented on an app named SmartSPAD on the smartphone. Li et al. [63] have developed a handheld optical scanning smartphone-based platform for non-invasive diagnosis of late blight caused by Phytophthora infestans. The developed system

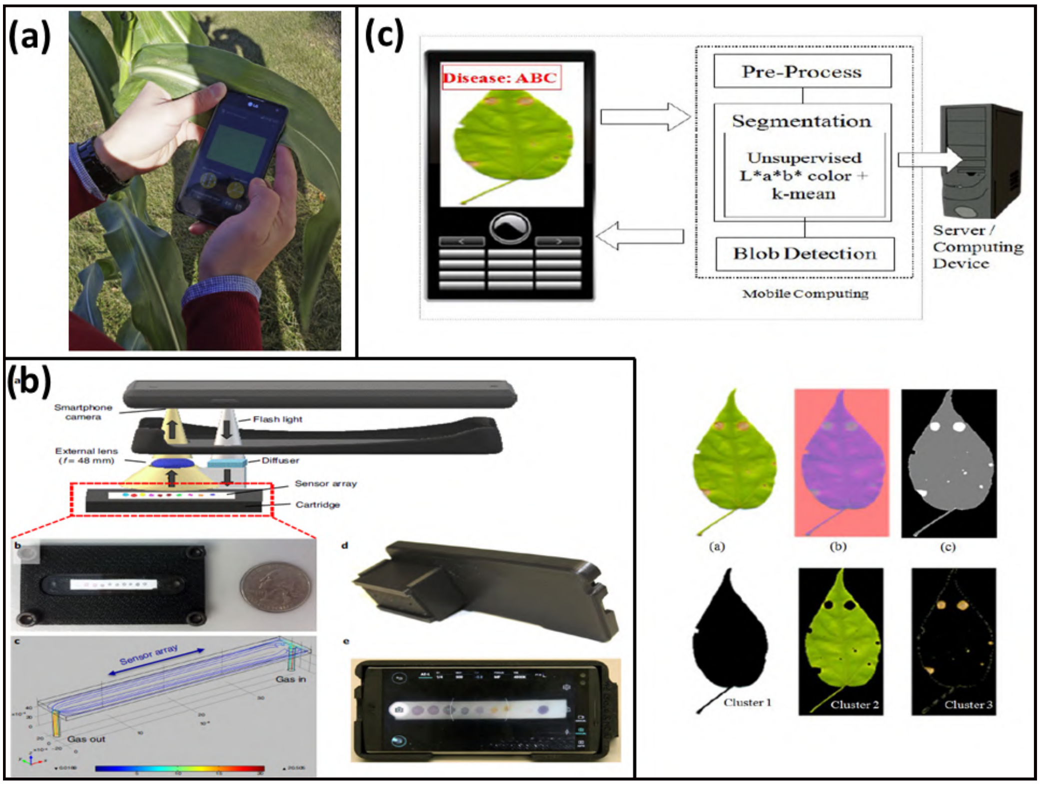

Figure 1.5: The development of smartphone camera based sensing platforms using image processing techniques; (a) working of a smartphone camera based leaf chlorophyll detection system [62] with permission from Elsevier, (b) demonstration of smartphone camera based leaf volatile compound detection system, reproduced from [63] with permission from Nature and (c) demonstration of smartphone camera based leaf disease identification system, reproduced from [64] with permission from IEEE.

consists of a disposable volatile organic compound (VOC) sensor array which has been integrated with the smartphone camera for digital quantification of relevant plant volatiles. The disposable VOC-sensor strip has been placed at the center of a 3D-printed cartridge and sealed tightly in order to create a leak-free space for gas exposure. One of the VOC markers, gaseous (E)-2-hexenal, has been emitted during P. infestans infection and a reaction was occurred in the sensor array consisting of plasmonic nanocolorants and chemo-responsive organic dyes. The sensor cartridge has been attached to the smartphone and then illuminated by flashgun of the phone to capture the images of the sensor array with the smartphone's camera. From the images of the resulted colored sensor arrays the plant volatiles has been detected at the ppm level within 1 min of reaction. Prasad et al. [64] have demonstrated a mobile vision system which helped to identify plant disease. In the reported work, real-time on-field imaging of diseased plant leaves has been done using a mobile phone camera, and after pre-processing, the images were transmitted to the laboratories. The image pre-processing step is necessary for saving transmission cost of the diseased leaf images to plant pathologists in remote laboratories. The leaf images were segmented by a clustering algorithm into three areas: background, non-diseased portion of the leaf, and diseased portion(s) of the leaf. After this step, leaf images were cropped to the location of the largest diseased patch on the leaf and transmitted over any available network to laboratory experts for further disease identification. Figure 1.5 shows the development of different smartphone camera based plant sensing using image processing techniques.

1.6.2 Smartphone ALS based sensing systems

The Ambient light sensor (ALS) of smartphone responds to any change in incident light intensity over a wide range of wavelength from 350 nm-1050 nm. The applicability of the smartphone's ALS has already been explored in many research fields [65]. The following literatures explain the applications of ALS of smartphone in various fields of agriculture and environment.

Water quality is a critical aspect of irrigation in agriculture. Water used for irrigation can greatly impact the farming depending on the type of chemicals present in the water. Salinity and pH are two important parameters in determining the quality of water for irrigation [66]. Smartphone based water quality monitoring systems have been developed by many researchers for specific applications. Hussain et al. [67] have developed a field portable phone-based turbidimeter for estimation of turbidity in various water sources. They have developed the system by illuminating the turbid samples with light from an infrared (IR) LED and the scattered light intensity from the samples has been recorded by the ALS of the smartphone. The designed sensor could accurately measures the turbidity value of the target medium over a wide range of 0-400 NTU with a sensitivity of 0.1 NTU. Using Mie-scattering theory, they have estimated the concentration of the suspended particles in the target medium by correlating with the scattered irradiation from the samples. Hussain et al. [68] have further demonstrated a smartphone-based salinity sensor for measuring the salinity level in water medium. In this work, for measurement of water salinity level, two different sensing schemes have been utilized and compared their performances. In the first scheme namely evanescent field absorption scheme, the light from flashgun of the smartphone has been coupled to a multimode optical fiber and a portion of the fiber has been uncladded to act as a sensing region. An evanescent field has been created at the core-air interface of the uncladded U-shaped optical fiber which is allowed to interact with a saline water sample placed in a glass cylinder. The interacted light signal has been modulated depending on salinity level of the target sample and further, the emerged-out signal from the fiber has been recorded by the ALS of the phone. In the second scheme mentioned as direct coupling scheme, light emitted by

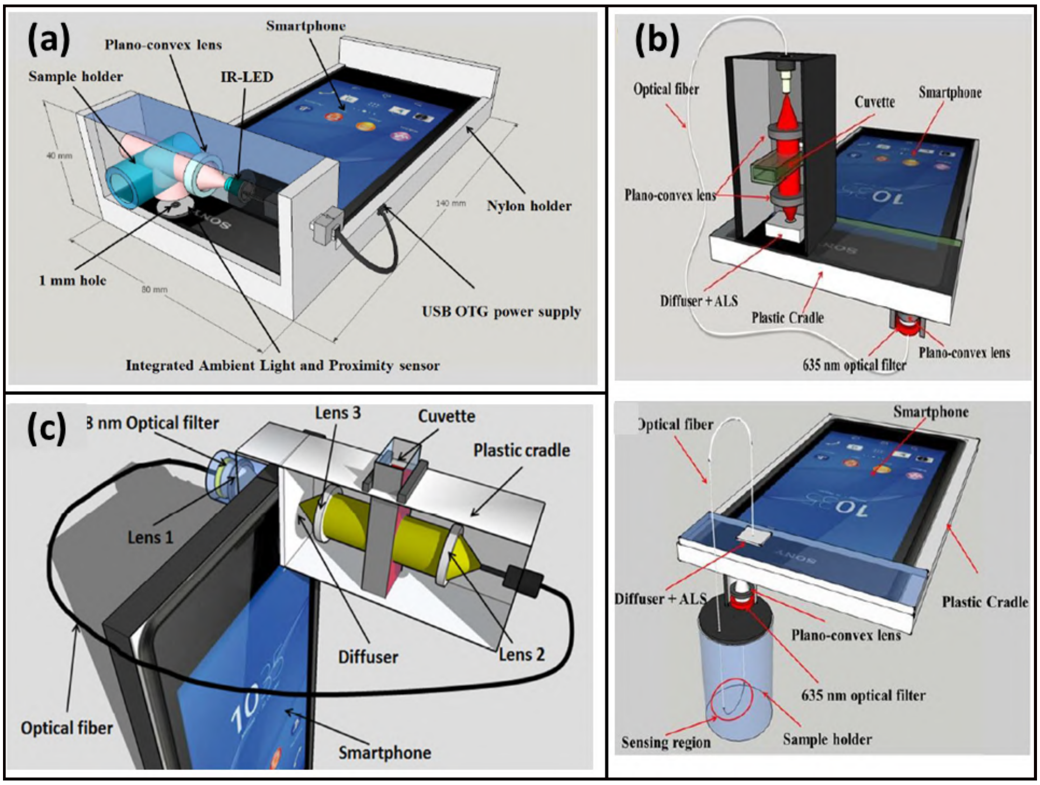

Figure 1.6: The development of different smartphone ALS based water quality monitoring systems; (a) working of a smartphone ALS based turbidimeter [67] with permission from Royal Society of Chemistry, (b) demonstration of smartphone ALS based water salinity measurement system, reproduced from [68] with permission from Elsevier and (c) demonstration of smartphone AlS based fluoride detection system, reproduced [70] with permission from American Chemical Society.

specific wavelength LEDs has been allowed to pass through the water sample and the modulated light signal has been recorded directly by the smartphone's ALS. The performance of the sensor from both the schemes has been compared and the sensitivity, linearity, dynamic range and limit of detection of the sensor has found to be better in evanescent wave coupling scheme. Such type of water salinity measuring sensing tools is very useful for monitoring of water used for irrigation purpose. Fluoride being a very reactive element has both positive and negative effect on plant health. The high concentration of fluoride ion that is mostly found in ground water is toxic for all living organisms [69]. Therefore, monitoring of fluoride level in nearby regions of agricultural farmlands is necessary. Hussain et al. [70] further have reported a robust, field-portable and low-cost smartphone platform for detection of fluoride level in ground water. The 3D printed sensing system is consisted of external lenses, optical fiber and the ALS sensor of a smartphone as a detector. A user-friendly android application has been developed for detection and analysis of fluoride concentration in water. In that setup, the light signal from the LED flash of the phone has been coupled to a fiber through an optical filter and the light has been allowed to pass through the water sample placed between a lens systems. The transmitted light from the ALS of the phone has been recorded and further estimated the fluoride concentration from a calibrated equation preloaded on the smartphone application. Figure 1.6 shows the development of different smartphone ALS based water quality monitoring systems using different techniques. Pest detection system is critical for good in agricultural yield. Qiangqiang Fu et al. [71] have reported an ambient light sensor (ALS) based smart phone colorimetric reader for monitoring of Organophosphate pesticides (OPs) in plants. In the reported work, Acetylcholinesterase (ACHE) CDs has been used for the testing of Ops in a 3D printed smartphone CD reader. In the reader, light from a LED of wavelength 645 nm is allowed to fall on different kinds of chemically treated Ops which has been placed on ACHE CDs. The CDs has been inserted into the ALS based CDs reader and the transmission light intensity has been measured using a free smart application Light Meter. The absorbance of ACHE CDs obtained with the smartphone CD reader has been compared with the absorbance obtained with gas chromatography-mass spectrometry (GC-MS) and Ellman assay and 92.86% of correlation has been obtained between both measurements. Daniel Gaviria-Palacio et al. [72] have reported a smartphone-based sensing tool using embedded ambient light sensor to estimate leaf chlorophyll by light transmission method. In the reported work, 3D printed adapters has been used to locate the plant leaves in the setup where light emitted from a 663 nm wavelength LED has been measured by the smartphone light sensor. The transmission spectra from Sorghum (Sorghum bicolor (L.) Moench) plant leaves obtained with the ALS has been analyzed using a freely available application- Physics Toolbox Sensor. The performance of the smartphone sensor has been verified by comparing the results with standard spectrometer. This type of smartphone-based system utilizing the built-in ALS of smartphone can be applied to measure specific leaf light transmission, which was associated to chlorophyll presence. Baue et al. [73] have reported a novel smartphone application “Smart fLAIr” (fast LAI retrieval), for a low-cost in-situ Leaf Area Index (LAI) estimation with use of smartphone ALS. In this work, the sensitivity of ALS has been enhanced by a diffuser cap combined with an optical band-pass filter for the measurement of maize canopy. A comparative study with a commercial instrument has also been carried out and found a convincing performance in terms of accuracy and stability. Figure 1.7 shows the development of smartphone ALS based sensing systems useful for agricultural based applications.

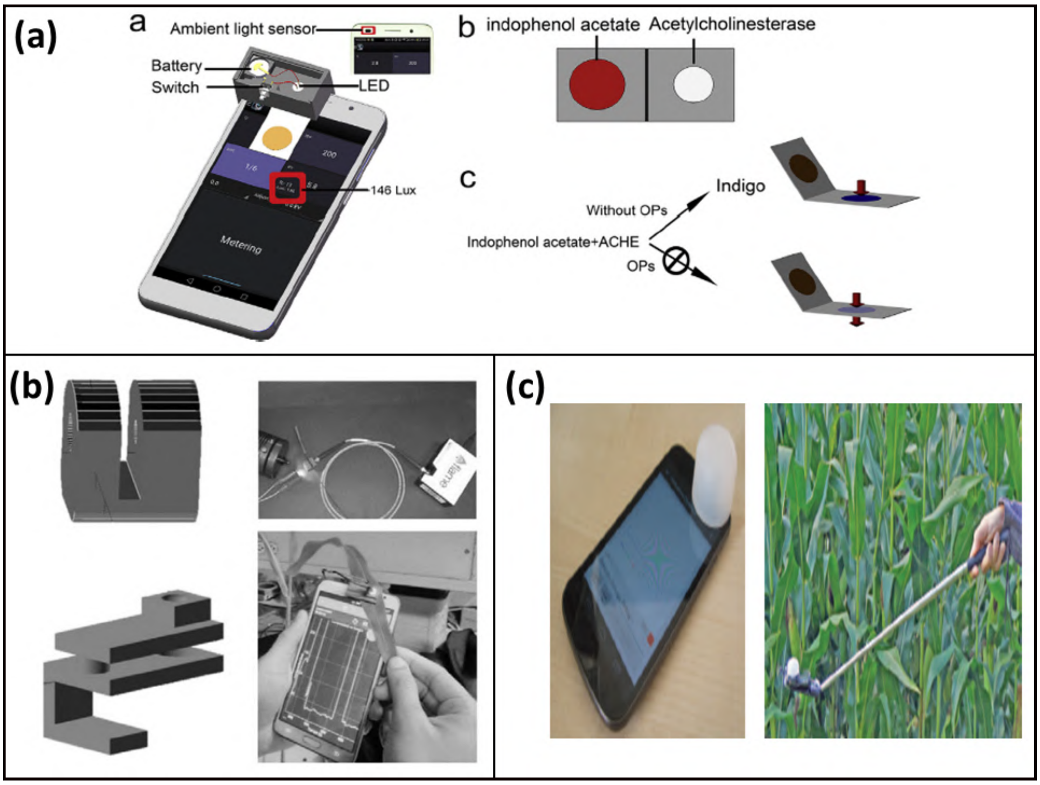

Figure 1.7: The development of different smartphone ALS based sensing systems useful for agricultural based applications; (a) working of a smartphone ALS based pesticide detection system [71] with permission from Elsevier, (b) demonstration of smartphone ALS based plant chlorophyll measurement system, reproduced from [72] with permission from Dyna and (c) demonstration of smartphone ALS based Leaf Area Index measurement system, reproduced [73] with permission from IEEE.

1.6.3 Smartphone accelerator and audio-jack based sensing platforms

Modern day smartphones come with built-in accelerometer sensor by which the processor of a smartphone senses its orientation in 3D space and takes actions accordingly. Accelerometers based smartphone sensing systems has been used heavily as activity recognition sensor in many areas of research [74]. Habib, M. A et al. [75] have reviewed various smartphone based sensing system using in-built accelerator for monitoring of fall detection and prevention. A limited number of smartphone's inbuilt accelerator based sensing platform has been developed for agricultural applications. Confalonieri, R. et al. [76] have developed a smartphone application "PocketPlant3D", which measures the leaf insertion angle using the device's accelerometer and magnetometer. A 3D distribution of the angles of photosynthetic tissues have been created by using the leaf angles from the insertion to the tip. The developed app measures the mean leaf tilt angle (MTA), the Campbell and leaf angle distributions (LAD), as well as a new leaf curvature indicator from these angles.

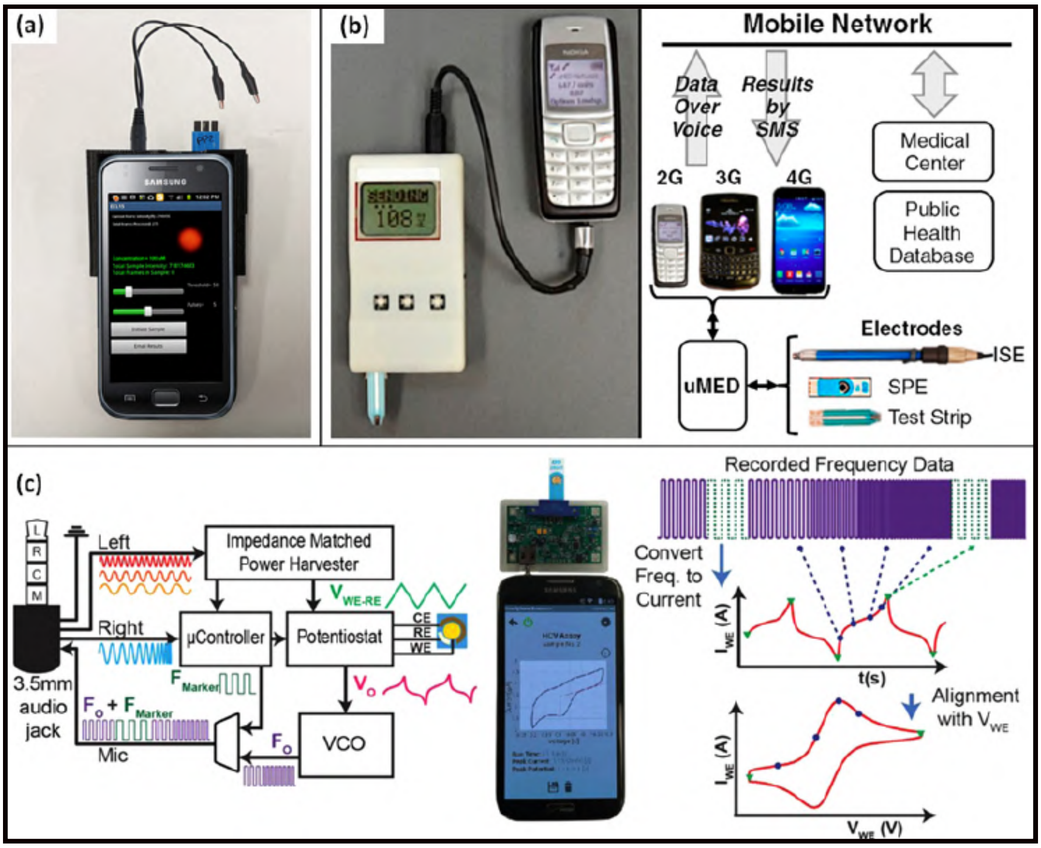

Figure 1.8: The development of smartphone audio jack based sensing platforms; (a) Demonstration of embedded audio jack of the smartphone as a potentiostatic control for ECL based applications, reproduced from [76] with permission from Elsevier, (b) audio jack based universal mobile electrochemical detector for POC applications in resource poor settings, reproduced from [77] with permission from American Association for the Advancement of Science, and (c) audio jack based potentiostat for cyclic voltametric applications in a smartphone platform, reproduced from [78] with permission from Elsevier.

The smartphone can be connected to external devices using the built-in audio port. The audio jack serves as a means of data transfer between devices. The ability of audio jacks to produce audio signals makes it useful in a variety of sensing applications. Delaney et al. [77] have demonstrated that a smartphone audio jack may be used to regulate and polarise an external electrode in order to create an electrochemiluminescence (ECL) signal from an electrochemical reaction. The smartphone camera has been used to capture the emitted ECL signal to measure the analyte content. Nemiroski et al. [78] have developed uMED, a universal smartphone-based electrochemical sensing platform, employing the common audio wire. With the use of commercially available electrodes, the uMED platform may be connected to several mobile phone generations to carry out various electrochemical sensing operations. Although less number of work has been published there are still various scope for development of smartphone audio jack based sensing platforms for monitoring of agricultural parameters. Figure 1.8 shows the examples of different smartphone based electrochemical sensing platforms developed by using the embedded audio jack.

1.7 Scope of the present thesis work

Ensuring food security has been a top priority for human civilization [79]. To secure global food security, agriculture- the upstream food producing sector needs to be monitored carefully. Successful agriculture depends on healthy soil, which is the original source of nutrients that crops needs to grow. To produce good quality crops regular monitoring of soil quality is critical. Frequent sensing of the soil nutrients improves the efficiency of agricultural production and also boost the creation of innovative soil sensing methods [80]. Although various methods are available to monitor the quality soil as discussed in section 1.2, the conventional methods are usually expensive and time-consuming due to the involvement of extraction and pre-treatment procedures, and it requires specialised tools and trained personals to operate these tools. The majority of sensing protocol and detection techniques that are used for soil assessments includes laboratory based procedures that requires sophisticated instruments and are mostly laboratory confined [81]. Thus, immediate measures on controlling the nutrients of affected farmland cannot be taken. A farmer residing in the interior regions struggles a lot to get his soil quality checked in the soil sensing laboratories which are mostly located in the central places. Therefore, there is an urgent need for a suitable alternative soil quality parameter sensing tool. Due to the advanced technology of the smartphones, the usability of smartphone-based sensing systems has been emerged as promising substitute for lab-constrained devices [82, 83]. There are currently a lot of smart phone-based devices available for sensing of different environmental and agricultural parameters [84, 85]. The inbuilt sensors of the phone have been extensively utilized to develop smartphone based sensing systems that might serve as a substitute for laboratory-confined standards instruments. The smartphone's built-in camera is the most frequently used sensor to detect and sense a parameter of interest. The advanced features of present smartphone cameras have led to a variety of studies being conducted in the fields of agricultural and food items [58]. In low resource settings, smartphone camera-based optical platforms can significantly help by offering inexpensive, field-deployable equipment. Along with the camera sensor, the embedded ALS of the phone offers an option to use it as a detector for optical sensing. Numerous significant biological as well as agricultural sensing studies have made substantial use of the smartphone's ALS [65, 86]. The use of ALS in optical sensing related to agricultural applications has received comparatively little attention till date. Although a few bio-sensing applications have reported using ALS [87–90], however, no suitable optics design has been developed for sensing of agricultural parameters. Considering the urgent need of alternate soil quality sensing system and observing the popularity of the smartphone-based optical platforms in biochemical, and diagnostic applications, the present thesis work proposed to develop smartphone based sensing systems that can be used for environmental, and agricultural parameter monitoring purpose. Apart from the mostly used colorimetric technique in optical sensing of soil nutrients, other techniques like spectrometric, fluorescence based sensing can also be implemented on smartphone based soil sensing applications. This would open a new avenue for soil quality parameter sensing using smartphone. The development of smartphone-based technology in soil sensing would help to increase agricultural production to sustain the entire society. The continuous monitoring of soil quality would be possible with the development of low-cost smartphone based optical systems. Regular monitoring of soil quality would improve the soil fertility which would led to the less use of water and fertilizers, which, in turn, would reduce the cost of farming. Also the sensing tool would prevent the ecosystem from the damages due to over-application of the unsuitable fertilizer which would led to severe nutrient leaching and waste materials goes into water bodies thus, affecting the water resources.

1.8 Aim of the thesis and its contribution

The main objective of this thesis work is to develop smartphone-based optical sensing platforms by creating robust hardware and software platforms and to promote its applicability in agricultural monitoring purpose. The applicability of the designed smartphone sensors in this thesis work is largely illustrated through the measurement of important chemical parameters of soil considering the need of alternative soil quality monitoring system. The optical design and user interface of the smartphone application have been kept as simple as possible while developing these tools in order to make them adaptable by the people from these remote and resource-poor regions who may not have enough scientific expertise. The thesis work contributes to the development of low-cost user-friendly smartphone based sensing systems for detection and analysis of different environmental and agricultural parameters with reference to the resource-poor regions. The usability of in-built sensors of the phone has been explored for agriculture and environment monitoring purpose. The CMOS image sensor, Ambient Light Sensor (ALS) and USB port (for powering) of smartphone have been utilized to make a complete standalone smartphone based sensing system. Different compact cradles have been fabricated using the 3D-printing technology to assemble all the optical components which can be attached easily to a smartphone. Along with the optical setup, custom-coded smartphone applications have been developed to make the designed platform a truely standalone tool. The usability of the developed systems have been demonstrated for detection of soil parameters such as pH level, macronutrients (Phosphorus and Nitrogen), toxic metal ions (Arsenic and Lead), etc. and chlorophyll content in plant leaf. Below the contributions of the present thesis work in the development of the sensing platforms are outlined with the motivations:

1. In the first step of the thesis, a cost-effective, portable and user-friendly smartphone-based sensing system has been developed and demonstrated its usability for monitoring of pH value in soil. To convert the phone into a pH sensing tool, the smartphone has been converted into a spectrometer. In this work, a piece of DVD has been used as a grating element that disperses the focused broadband line source into its component colors. The use of DVD in this work reduces the overall cost of the tool. A 3D printed compact set-up has been developed that houses the required optical components for the present set-up. The performance of the designed smartphone sensor has been compared with a laboratory-grade spectrometer. The designed tool has been successfully implemented for accurate and reliable estimation of the pH value of different field-collected soil samples. Further, the designed sensor has been utilized for Localized Surface Plasmon Resonance (LSPR) based sensing of metal ions present in soil. In the present sensing setup the DVD grating element has been replaced by a commercial grating element for better sensitivity. The designed tool has been implemented to Arsenic(III) and Lead(II) ions using synthesized gold nanoparticles (AuNP). The LSPR peak of the AuNPs shifts to the longer wavelength region upon reaction with As(III) and Pb(II) which is used for sensing of these two particular ions. The change in the absorbance for each ion at the LSPR peak have been used for quantification of the two ions. An android based application “Soil Quality Monitoring” (SoQM) has been developed so that onsite detection and analysis can be performed. The performance of the device has been checked with field-collected soil samples and compared the results with standard UV-Vis spectrometer data for validation.

2. Monitoring of phosphorous levels in water and agricultural soil is critical for maintaining the water quality and soil fertility. Although, several methods to estimate phosphorous concentration are available, the existing approaches are laboratory-confined and involve costly equipment that are not suitable for autonomous operation in the field. To overcome these limitations, in the second step, a compact, portable, and cost-effective smartphone-based colorimetric analyzer has been designed for the quantification of phosphate levels in water and soil. The integrated CMOS camera of the smartphone is used as an image detector that captures the images of the samples to be analyzed. The designed

sensor converts the modulated signal in the form of color information which subsequently has been used to quantify the phosphate concentration present in the sample. A 3D printed cradle has been developed to hold the optical components which can be attached easily to the camera of the phone. By using two freely available android applications, the experimental data of the sensor have been analyzed within the phone itself thus, making the designed tool a truly standalone platform. The applicability of the proposed sensor has been evaluated by estimating the phosphate concentrations of different field-collected water and soil samples.

3. In the third step of the thesis work, the design of a portable smartphone-based dual mode sensing tool for the onsite detection of trace nitrite concentration has been demonstrated. For this purpose, Carbon Nanodot-Neutral Red sensing medium has been synthesized where C-dots acts as donors and NR as acceptors. In presence of trace nitrite, the C-dot-NR sample shows colorimetric and fluorescence emission which has been used as the basis for dual model sensing of nitrite concentration using a smartphone. The ALS and CMOS image sensor of the smartphone have been explicitly used for photometric and fluorescence-based study for the present sensor, respectively. Two freely available android applications have been used for nitrite level measurement and analysis in the samples. The performance of the designed smartphone sensor in both the sensing schemes have been compared with the standard method. The designed tool has been successfully implemented to monitor nitrite level concentration in different field-collected water and soil samples, thus, offering a feasible method for determining nitrite residues on-site.

4. Chlorophyll content estimation in leaf is often required for monitoring stress level, nitrogen content and overall health condition of the plants. Spectrophotometric and reflectance-based sensors are generally used for such purposes; however, the detection methods require relatively expensive, bulky and sophisticated instruments, thus hindering their use in resource-limited settings. Considering the need for an alternative platform, the last part of the thesis work attempted to design a low-cost, robust, user-friendly fluorescence-based sensor using a smartphone for estimation of chlorophyll content in plant leaves. This device has been developed using the inbuilt ambient light sensor of the smartphone as detector with an arrangement of simple optical components. The extracted plant chlorophyll sample is excited with an optical source (475 nm), and the corresponding emitted fluorescence signal at 679 nm has been recorded by the phone's ambient light sensor (ALS). A 3D printed compact optical set-up has been designed to couple it with the phone to record the emitted fluorescence

signal intensity from the sample. With the designed sensing platform, chlorophyll concentrations in fresh tea leaves have been accurately estimated and the results have been compared with the commercial-grade chlorophyll meter.

References

[1] Andrews, S. S., Karlen, D., and Mitchell, J. A comparison of soil quality indexing methods for vegetable production systems in northern california. *Agriculture, ecosystems & environment*, 90(1):25–45, 2002.

[2] Carter, M. R., Gregorich, E., Anderson, D., Doran, J., Janzen, H., and Pierce, F. Concepts of soil quality and their significance, 1997.

[3] Doran, J. W. and Parkin, T. B. Defining and assessing soil quality. *Defining soil quality for a sustainable environment*, 35:1–21, 1994.

[4] Yokota, M., Okada, T., and Yamaguchi, I. An optical sensor for analysis of soil nutrients by using led light sources. *Measurement Science and Technology*, 18 (7):2197, 2007.

[5] Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., et al. Soil quality–a critical review. *Soil Biology and Biochemistry*, 120:105–125, 2018.

[6] Pansu, M., Gautheyrou, J., and Loyer, J. Soil analysis. *Sampling, Instrumentation and Duality Control. AA Balkema, Abington*, 2001.

[7] Zewide, I. and Reta, Y. Review on the role of soil macronutrient (npk) on the improvement and yield and quality of agronomic crops. *Direct Res J Agric food Sci*, 9:7–11, 2021.

[8] Kim, H.-J., Sudduth, K. A., and Hummel, J. W. Soil macronutrient sensing for precision agriculture. *Journal of Environmental Monitoring*, 11(10):1810–1824, 2009.

[9] Alloway, B. J. Micronutrients and crop production: An introduction. In *Micronutrient deficiencies in global crop production*, pages 1–39. Springer, 2008.

[10] Graham, R. D. Micronutrient deficiencies in crops and their global significance. In *Micronutrient deficiencies in global crop production*, pages 41–61. Springer, 2008.

[11] Fageria, N., Baligar, V., and Clark, R. Micronutrients in crop production. *Advances in agronomy*, 77:185–268, 2002.

[12] Peverill, K., Sparrow, L., and Reuter, D. *Soil analysis: an interpretation manual*. CSIRO publishing, 1999.

[13] Kuang, B., Mahmood, H. S., Quraishi, M. Z., Hoogmoed, W. B., Mouazen, A. M., and van Henten, E. J. Sensing soil properties in the laboratory, in situ, and on-line: a review. *Advances in agronomy*, 114:155–223, 2012.

[14] Ge, Y., Thomasson, J. A., and Sui, R. Remote sensing of soil properties in precision agriculture: A review. *Frontiers of Earth Science*, 5(3):229–238, 2011.

[15] Tkachenko, N. V. *Optical spectroscopy: methods and instrumentations*. Elsevier, 2006.

[16] Levy, J. S. and Johnson, J. T. Remote soil moisture measurement from drone-borne reflectance spectroscopy: applications to hydroperiod measurement in desert playas. *Remote Sensing*, 13(5):1035, 2021.

[17] Zhou, P., Zhang, Y., Yang, W., Li, M., Liu, Z., and Liu, X. Development and performance test of an in-situ soil total nitrogen-soil moisture detector based on near-infrared spectroscopy. *Computers and Electronics in Agriculture*, 160: 51–58, 2019.

[18] Shi, Z., Ji, W., Viscarra Rossel, R., Chen, S., and Zhou, Y. Prediction of soil organic matter using a spatially constrained local partial least squares regression and the c hinese vis–nir spectral library. *European Journal of Soil Science*, 66 (4):679–687, 2015.

[19] Potdar, R. P., Shirolkar, M. M., Verma, A. J., More, P. S., and Kulkarni, A. Determination of soil nutrients (npk) using optical methods: a mini review. *Journal of Plant Nutrition*, 44(12):1826–1839, 2021.

[20] Burton, L., Jayachandran, K., and Bhansali, S. The “real-time” revolution for in situ soil nutrient sensing. *Journal of The Electrochemical Society*, 167(3):037569, 2020.

[21] Guerrero, A., De Neve, S., and Mouazen, A. M. Current sensor technologies for in situ and on-line measurement of soil nitrogen for variable rate fertilization: A review. *Advances in Agronomy*, 168:1–38, 2021.

[22] Wang, Y., Huang, T., Liu, J., Lin, Z., Li, S., Wang, R., and Ge, Y. Soil ph value, organic matter and macronutrients contents prediction using optical diffuse reflectance spectroscopy. *Computers and Electronics in Agriculture*, 111: 69–77, 2015.

[23] Rossel, R. V., Walvoort, D., McBratney, A., Janik, L. J., and Skjemstad, J. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. *Geoderma*, 131(1-2):59–75, 2006.

[24] Qin, R., Zhang, Y., Ren, S., and Nie, P. Rapid detection of available nitrogen in soil by surface-enhanced raman spectroscopy. *International Journal of Molecular Sciences*, 23(18):10404, 2022.

[25] Ribeiro-Soares, J., Cançado, L. G., Falcão, N. P., Martins Ferreira, E., Achete, C. A., and Jório, A. The use of raman spectroscopy to characterize the carbon materials found in amazonian anthrosoils. *Journal of Raman Spectroscopy*, 44 (2):283–289, 2013.

[26] Sousa, D. V. Pedoarqueologia de sítios pré-históricos na bacia do rio são francisco: Abrigo de santana do riacho e bibocas ii. 2016.

[27] Sankpal, A. and Warhade, K. K. Review of optoelectronic detection methods for the analysis of soil nutrients. *International Journal of Advanced Computing and Electronics Technology (IJACET)*, 2(2):26–31, 2015.

[28] Ali, M. A., Dong, L., Dhau, J., Khosla, A., and Kaushik, A. Perspective—electrochemical sensors for soil quality assessment. *Journal of The Electrochemical Society*, 167(3):037550, 2020.

[29] Lin, J., Wang, M., Zhang, M., Zhang, Y., and Chen, L. Electrochemical sensors for soil nutrient detection: Opportunity and challenge. In *International conference on computer and computing technologies in agriculture*, pages 1349–1353. Springer, 2007.

[30] Lobsey, C. R., Rossel, R., and Mcbratney, A. B. Proximal soil nutrient sensing using electrochemical sensors. *Proximal soil sensing*, pages 77–88, 2010.

[31] Lobsey, C., Rossel, R. V., McBratney, A., et al. An automated system for rapid in-field soil nutrient testing. In *19th World Congress of Soil Science, Soil Solutions for a Changing World*, volume 1, 2010.

[32] Kim, H. J. *Ion-selective electrodes for simultaneous real-time analysis for soil macronutrients.* PhD thesis, University of Missouri–Columbia, 2006.

[33] Price, R. R., Hummel, J. W., Birrell, S. J., and Ahmad, I. S. Rapid nitrate analysis of soil cores using isfets. *Transactions of the ASAE*, 46(3):601, 2003.

[34] Artigas, J., Beltran, A., Jimenez, C., Baldi, A., Mas, R., Domınguez, C., and Alonso, J. Application of ion sensitive field effect transistor based sensors to soil analysis. *Computers and electronics in agriculture*, 31(3):281–293, 2001.

[35] Kim, H.-J., Hummel, J. W., Sudduth, K. A., and Motavalli, P. P. Simultaneous analysis of soil macronutrients using ion-selective electrodes. *Soil Science Society of America Journal*, 71(6):1867–1877, 2007.

[36] Jones Jr, J. B. Soil test methods: past, present, and future use of soil extractants. *Communications in Soil Science and Plant Analysis*, 29(11-14):1543–1552, 1998.

[37] Sims, J. Environmental soil testing for phosphorus. *Journal of Production Agriculture*, 6(4):501–507, 1993.

[38] Sims, J., Edwards, A., Schoumans, O., and Simard, R. Integrating soil phosphorus testing into environmentally based agricultural management practices. *Journal of Environmental Quality*, 29(1):60–71, 2000.

[39] Nadporozhskaya, M., Kovsh, N., Paolesse, R., and Lvova, L. Recent advances in chemical sensors for soil analysis: a review. *Chemosensors*, 10(1):35, 2022.

[40] Chen, A., Jacob, M., Shoshani, G., Dafny-Yelin, M., Degani, O., and Rabinovitz, O. Early detection of soil-borne diseases in field crops via remote sensing. In *Precision agriculture'21*, pages 37–44. Wageningen Academic Publishers, 2021.

[41] Khanal, S., Kc, K., Fulton, J. P., Shearer, S., and Ozkan, E. Remote sensing in agriculture—accomplishments, limitations, and opportunities. *Remote Sensing*, 12(22):3783, 2020.

[42] Shanmugapriya, P., Rathika, S., Ramesh, T., and Janaki, P. Applications of remote sensing in agriculture-a review. *International Journal of Current Microbiology and Applied Sciences*, 8(1):2270–2283, 2019.

[43] Yuan, Q., Shen, H., Li, T., Li, Z., Li, S., Jiang, Y., Xu, H., Tan, W., Yang, Q., Wang, J., et al. Deep learning in environmental remote sensing: Achievements and challenges. *Remote Sensing of Environment*, 241:111716, 2020.

[44] Raich, J. Review of sensors to monitor water quality. *European reference network for critical infrastructure protection (ERNCIP) project*, 2013.

[45] BankMyCell. How many smartphones are in the world?, 2022. URL `https://www.bankmycell.com/blog/how-many-phones-are-in-the-world`. Accessed on: 2022-09-22.

[46] Wikipedia contributors. List of countries by smartphone penetration — Wikipedia, the free encyclopedia, 2022. URL `https://en.wikipedia.org/w/index.php?title=List_of_countries_by_smartphone_penetration&oldid=1114396871`. [Online; accessed 8-October-2022].

[47] Hutchings, M. T., Dev, A., Palaniappan, M., Srinivasan, V., Ramanathan, N., Taylor, J., Ross, N., and Luu, P. mwash: mobile phone applications for the water, sanitation, and hygiene sector. *Report for Nexleaf Analytics & the Pacific Institute*, pages 1–115, 2012.

[48] Wang, H., Heintzmann, R., and Diederich, B. The power in your pocket–uncover smartphones for use as cutting-edge microscopic instruments in science and research. *Advanced Optical Technologies*, 10(2):89–108, 2021.

[49] Blahnik, V. and Schindelbeck, O. Smartphone imaging technology and its applications. *Advanced Optical Technologies*, 10(3):145–232, 2021.

[50] Chan, H. N., Tan, M. J. A., and Wu, H. Point-of-care testing: applications of 3d printing. *Lab on a Chip*, 17(16):2713–2739, 2017.

[51] Ramya, A. and Vanapalli, S. L. 3d printing technologies in various applications. *International Journal of Mechanical Engineering and Technology*, 7(3):396–409, 2016.

[52] Placone, J. K. and Engler, A. J. Recent advances in extrusion-based 3d printing for biomedical applications. *Advanced healthcare materials*, 7(8):1701161, 2018.

[53] Xu, Y., Wu, X., Guo, X., Kong, B., Zhang, M., Qian, X., Mi, S., and Sun, W. The boom in 3d-printed sensor technology. *Sensors*, 17(5):1166, 2017.

[54] Lane, N. D., Miluzzo, E., Lu, H., Peebles, D., Choudhury, T., and Campbell, A. T. A survey of mobile phone sensing. *IEEE Communications magazine*, 48 (9):140–150, 2010.

[55] Li, F., Bao, Y., Wang, D., Wang, W., and Niu, L. Smartphones for sensing. *Science bulletin*, 61(3):190–201, 2016.

[56] Aram, S., Troiano, A., and Pasero, E. Environment sensing using smartphone. In *2012 IEEE Sensors applications symposium proceedings*, pages 1–4. IEEE, 2012.

[57] Pongnumkul, S., Chaovalit, P., and Surasvadi, N. Applications of smartphone-based sensors in agriculture: a systematic review of research. *Journal of Sensors*, 2015, 2015.

[58] Kwon, O. and Park, T. Applications of smartphone cameras in agriculture, environment, and food: A review. *Journal of Biosystems Engineering*, 42(4): 330–338, 2017.

[59] Moonrungsee, N., Pencharee, S., and Jakmunee, J. Colorimetric analyzer based on mobile phone camera for determination of available phosphorus in soil. *Talanta*, 136:204–209, 2015.

[60] Han, P., Dong, D., Zhao, X., Jiao, L., and Lang, Y. A smartphone-based soil color sensor: For soil type classification. *Computers and Electronics in Agriculture*, 123:232–241, 2016.

[61] Siddiqui, M. F., Kim, S., Jeon, H., Kim, T., Joo, C., and Park, S. Miniaturized sample preparation and rapid detection of arsenite in contaminated soil using a smartphone. *Sensors*, 18(3):777, 2018.

[62] Vesali, F., Omid, M., Kaleita, A., and Mobli, H. Development of an android app to estimate chlorophyll content of corn leaves based on contact imaging. *Computers and Electronics in Agriculture*, 116:211–220, 2015.

[63] Li, Z., Paul, R., Ba Tis, T., Saville, A. C., Hansel, J. C., Yu, T., Ristaino, J. B., and Wei, Q. Non-invasive plant disease diagnostics enabled by smartphone-based fingerprinting of leaf volatiles. *Nature plants*, 5(8):856–866, 2019.

[64] Prasad, S., Peddoju, S. K., and Ghosh, D. Energy efficient mobile vision system for plant leaf disease identification. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 3314–3319. IEEE, 2014.

[65] Dutta, S. Point of care sensing and biosensing using ambient light sensor of smartphone: Critical review. *TrAC Trends in Analytical Chemistry*, 110:393–400, 2019.

[66] Ayers, R. S., Westcot, D. W., et al. *Water quality for agriculture*, volume 29. Food and Agriculture Organization of the United Nations Rome, 1985.

[67] Hussain, I., Ahamad, K., and Nath, P. Water turbidity sensing using a smartphone. *Rsc Advances*, 6(27):22374–22382, 2016.

[68] Hussain, I., Das, M., Ahamad, K. U., and Nath, P. Water salinity detection using a smartphone. *Sensors and Actuators B: Chemical*, 239:1042–1050, 2017.

[69] Choudhary, S., Rani, M., Devika, O. S., Patra, A., Singh, R. K., and Prasad, S. K. Impact of fluoride on agriculture: A review on it's sources, toxicity in plants and mitigation strategies. *Int J Chem Stud*, 7(2):1675–1680, 2019.

[70] Hussain, I., Ahamad, K. U., and Nath, P. Low-cost, robust, and field portable smartphone platform photometric sensor for fluoride level detection in drinking water. *Analytical chemistry*, 89(1):767–775, 2017.

[71] Fu, Q., Zhang, C., Xie, J., Li, Z., Qu, L., Cai, X., Ouyang, H., Song, Y., Du, D., Lin, Y., et al. Ambient light sensor based colorimetric dipstick reader for rapid monitoring organophosphate pesticides on a smart phone. *Analytica Chimica Acta*, 1092:126–131, 2019.

[72] Gaviria-Palacio, D., Guáqueta-Restrepo, J. J., Pineda-Tobón, D. M., and Pérez, J. C. Fast estimation of chlorophyll content on plant leaves using the light sensor of a smartphone. *Dyna*, 84(203):234–239, 2017.

[73] Bauer, J., Siegmann, B., Jarmer, T., and Aschenbruck, N. Smart flair: A smartphone application for fast lai retrieval using ambient light sensors. In *2016 IEEE sensors applications symposium (SAS)*, pages 1–6. IEEE, 2016.

[74] Incel, O. D., Kose, M., and Ersoy, C. A review and taxonomy of activity recognition on mobile phones. *BioNanoScience*, 3(2):145–171, 2013.

[75] Habib, M. A., Mohktar, M. S., Kamaruzzaman, S. B., Lim, K. S., Pin, T. M., and Ibrahim, F. Smartphone-based solutions for fall detection and prevention: challenges and open issues. *Sensors*, 14(4):7181–7208, 2014.

[76] Confalonieri, R., Paleari, L., Foi, M., Movedi, E., Vesely, F. M., Thoelke, W., Agape, C., Borlini, G., Ferri, I., Massara, F., et al. Pocketplant3d: Analysing canopy structure using a smartphone. *Biosystems Engineering*, 164:1–12, 2017.

[77] Delaney, J. L., Doeven, E. H., Harsant, A. J., and Hogan, C. F. Use of a mobile phone for potentiostatic control with low cost paper-based microfluidic sensors. *Analytica chimica acta*, 790:56–60, 2013.

[78] Nemiroski, A., Christodouleas, D. C., Hennek, J. W., Kumar, A. A., Maxwell, E. J., Fernández-Abedul, M. T., and Whitesides, G. M. Universal mobile electrochemical detector designed for use in resource-limited applications. *Proceedings of the National Academy of Sciences*, 111(33):11984–11989, 2014.

[79] Sasson, A. Food security for africa: an urgent global challenge. *Agriculture & Food Security*, 1(1):1–16, 2012.

[80] Rossel, R. A. V. and Bouma, J. Soil sensing: A new paradigm for agriculture. *Agricultural Systems*, 148:71–74, 2016.

[81] Karlen, D. L., Andrews, S. S., Wienhold, B. J., and Zobeck, T. M. Soil quality assessment: past, present and future. 2008.

[82] McCracken, K. E. and Yoon, J.-Y. Recent approaches for optical smartphone sensing in resource-limited settings: a brief review. *Analytical Methods*, 8(36): 6591–6601, 2016.

[83] Geng, Z., Zhang, X., Fan, Z., Lv, X., Su, Y., and Chen, H. Recent progress in optical biosensors based on smartphone platforms. *Sensors*, 17(11):2449, 2017.

[84] Sivakumar, R. and Lee, N. Y. Recent progress in smartphone-based techniques for food safety and the detection of heavy metal ions in environmental water. *Chemosphere*, 275:130096, 2021.

[85] Laport-López, F., Serrano, E., Bajo, J., and Campbell, A. T. A review of mobile sensing systems, applications, and opportunities. *Knowledge and Information Systems*, 62(1):145–174, 2020.

[86] Nelis, J., Tsagkaris, A., Dillon, M., Hajslova, J., and Elliott, C. Smartphone-based optical assays in the food safety field. *TrAC Trends in Analytical Chemistry*, 129:115934, 2020.

[87] Park, Y. M., Han, Y. D., Kim, K. R., Zhang, C., and Yoon, H. C. An immunoblot-based optical biosensor for screening of osteoarthritis using a smartphone-embedded illuminometer. *Analytical Methods*, 7(15):6437–6442, 2015.

[88] Park, Y. M., Han, Y. D., Chun, H. J., and Yoon, H. C. Ambient light-based optical biosensing platform with smartphone-embedded illumination sensor. *Biosensors and Bioelectronics*, 93:205–211, 2017.

[89] Fu, Q., Wu, Z., Xu, F., Li, X., Yao, C., Xu, M., Sheng, L., Yu, S., and Tang, Y. A portable smart phone-based plasmonic nanosensor readout platform that measures transmitted light intensities of nanosubstrates using an ambient light sensor. *Lab on a Chip*, 16(10):1927–1933, 2016.

[90] Fu, Q., Wu, Z., Li, X., Yao, C., Yu, S., Xiao, W., and Tang, Y. Novel versatile smart phone based microplate readers for on-site diagnoses. *Biosensors and Bioelectronics*, 81:524–531, 2016.