CHAPTER 7

CONCLUSIONS AND FUTURE PROSPECT OF THE THESIS WORK

The concluding chapter summarizes the overall works being carried out during the PhD work. The limitations of the developed smartphone sensing systems have also been highlighted in this chapter. Furthermore, the future prospect of the current thesis work and the potential uses of the designed smartphone sensing tools in other fields and possible future developments of the ongoing phone based sensing tools have been discussed.

7.1 Conclusions

Present thesis work covers the design of various smartphone-based sensing systems with a goal of achieving simple, compact and cost-effective sensing tools for monitoring of agricultural and environmental parameters useful in resource-constrained environments. The inbuilt sensors of the phone namely the CMOS camera and ALS have been exploited as optical signal detectors and USB-OTG port has been used to power the optical sources for the development of various sensing systems. Furthermore, advanced analytical tools or intelligent android applications have been developed so that detection, data analysis and communication of the experimental finding can be done within the phone itself. The key outcomes from the present thesis work are outlined as follows:

1. The design of a cost-effective spectrometric sensing system has been demonstrated on a smartphone platform by utilizing the embedded CMOS camera sensor as the detector. The experimental setup has been developed by arranging the optical components like lenses, grating and optical source in a custom

designed 3D printed cradle that can be attached to the rear camera of the smartphone. Using this developed sensing tool the pH value of soil has been accurately estimated. The proposed sensor responses for standard pH samples within the pH range 4 to 10 are observed to be linear yet yield a sensitivity of 0.129 per pH unit. The designed sensor's performance has been evaluated by comparing the experimental data with the commercial-grade pH sensing tool. In the second part of the chapter, LSPR based sensing of toxic metal ions (arsenic and lead) using the developed smartphone based sensor has been demonstrated. The detection approach is based on the red shift of the LSPR absorption band of the synthesized glucose functionalized gold nanoparticles (AuNPs/Glu) in the range of 200-800 nm caused by the addition of As(III) and Pb(II). The transmitted modulated signal intensity has been recorded by the rear camera of the phone and estimated the analyte's concentration within the phone itself by using custom designed android application. The quantifications of toxic metal ions, As(III) and Pb(II) present in agricultural soil have been done using the proposed sensor. It is envisioned that the developed smartphone based spectrometric tool would be feasible alternative for detection of various parameters of soil due to its benefits of being inexpensive, field portable, and user-efficient.

2. In chapter 4, the design of a low-cost, field-deployable smartphone-based sensing system for accurate estimation of phosphorus (in phosphate form) in water and agricultural soil has been demonstrated. A 3D printed cradle that houses optical source and other optical components of the sensor has been coupled to the rear camera of the phone and subsequently, converted it into compact colorimetric sensor. Two freely available android applications have been used for the detection and analysis of phosphate concentration. The HSV (Hue-Saturation-Value) color model's V-channel values of the captured images has been used to correlate with the phosphate concentrations of the samples. The reliability of the proposed sensor has been evaluated by comparing the results with the laboratory-grade spectrophotometer data. The sensing device offers advantages in terms of user-friendliness, low-cost, and has the ability to share the in-field data with the central laboratory instantly. With the proposed sensing system, it is envisioned that any common citizen without special laboratory equipment will be able to measure the phosphate content of water or soil media.

3. Nitrite level estimation in soil and water bodies is critical to monitor the ecosystem of our environment and agricultural yield. Considering the need for a compact and cost-effective nitrite sensing system, chapter 5 enables the design of a handheld compact dual mode sensing platform developed on a smartphone.

The sensing principle is based on frequency resonance energy transfer (FRET), where a mixture of Carbon-dots (C-dots) and Neutral Red (NR) act as donors and acceptors, respectively. The presence of nitrite in the C-dot−NR mixture affects the FRET process which causes the variation in colorimetric and fluorescence response. These variations in the emission process have been correlated to quantify the concentration of the nitrite level in the medium. The designed sensor has been implemented to estimate the nitrite level of infield water and soil samples, and the experimental results were compared with the laboratory standard tools. With the advantages of being low-cost, field portable, and relatively convenient to handle, it is anticipated that the proposed smartphone sensor could emerge as a potential avenue for onsite assessment of other parameters of water and soil as well.

4. Chlorophyll content estimation in leaf is often required for monitoring of stress level, nitrogen content and overall health condition of plants. Realizing the importance of chlorophyll and the lack of user-friendly, cost-effective chlorophyll detection devices, chapter 6 narrates a low-cost, robust, fluorescence-based sensor to estimate the chlorophyll content in plant leaves. The design of the sensing tool, smartphone's ambient light sensor (ALS) has been utilized to record the emitted fluorescence signal from the extracted plant chlorophyll sample when excited by an optical source of specific wavelength. With the designed sensing platform, chlorophyll concentrations in the range of 1-12 mg/g acquired from fresh tea leaves have been accurately estimated and its performance has been evaluated by comparing the data with the commercial-grade chlorophyll meter.

7.2 Limitations

Several challenges still remains to develop the proposed sensing tools to be compatible in all varient smartphones. The change in the smartphone models is a limiting factor in the field of smartphone sensing. Most of the attachments in the developed sensing setup are used for a specific model of smartphone only. The same attachment is not compatible with a different variant of smartphone. Therefore, a user needs to carry the specific phone to perform any sample analyses on the considered sensing system. The design and dimensions of the smartphone vary from model to model, which may affect the position of the ALS, LED flash, and rear camera in the device. The developed sensing platform cannot be applied to other phones due to the variation in design and dimension. Thus, the design of a universal holder which can be coupled to all variant phones would be challenging. The challenge in utilizing the developed sensing tools for soil quality monitoring is that soil extraction procedure involves filtration process that may require laboratory facilities. Onsite assessment may not be possible as the soil sample needs to be properly treated prior to the estimation of some soil quality parameters. Moreover, soil nutrients that are not suitable for spectrophotometric and colorimetric detection cannot be estimated by the designed sensing tools. Despite the fact that the developed sensing systems offer several important benefits in the form of affordability and user-friendliness.

7.3 Future prospects

Although only several soil quality parameters have been monitored with the smartphone's sensors, it is believed that the present work has immense scope to monitor other parameters of soil and water. In the future course of work, the developed smartphone based spectrophotometric and colorimetric sensing platforms will be utilized for estimation of other soil parameters such as soil micronutrients like zinc, manganese, aluminium etc. Machine learning-based smart applications are in demand with the ever improving software performance of the smartphones. The sensing platforms can be further transformed for the automatic on-board detection and analysis with the help of these effective smart applications. This may reduce potential errors arises due to a variety of circumstances and improve the accuracy, functionality and sensitivity of the sensing systems. Furthermore, the sensing systems can be upgraded to electro-optical sensing platforms to perform electrochemical sensing investigations. Due to the frequent variety in phone models, developed imaging system's capacity to be universally adaptable is limited. To mitigate this limitation a universal holder can be designed and fabricated with 3D printing technology. By using a universal holder which is compatible with different variants smartphones regardless of their dimensions and the position of the inbuilt sensors can solve the aforementioned limitations. In the future, this challenge would be resolved by offering a revolutionary design approach that would work with any smartphone, regardless of the manufacturer and sensor placement in the device. Thus, the developed sensing platforms would be improved in line with this, and find their applicability in areas beyond the scope of the present thesis work.