Chapter 8

CONCLUSION, LIMITATIONS AND FUTURE PROSPECTS OF THE PRESENT THESIS WORK

The final chapter of the present thesis summarizes the works conducted during the PhD period. The limitations of the designed smartphone-based analytical platforms have been discussed in this chapter. At the end, the chapter highlights the potential applications and future prospects of the developed analytical platforms in the field of sensing and imaging studies.

8.1 Summary of the thesis work

Present thesis work discusses the working of several smartphone-based analytical platforms that have been developed primarily for the assessment of water quality parameters and sensing of microbial particles in laboratory environment. The designed platforms are based on colorimetric, fluorescence, nephelometric and photometric principles. Different quality parameters of water such as dissolved chemicals, heavy metals and biological contaminants have been estimated by the designed platforms. Custom developed Android applications have been used to analyse the data recorded by the phone's inbuilt sensors. Amongst the various embedded sensors in the phone, the ALS and the rear camera have been utilised as photo-detectors to design different analytical platforms. By utilising the developed platforms, estimation of mercury, zinc, sulphate and chloride ions in water have been detected reliably. The thesis work further demonstrates the multi-model sensing scheme to determine multiple analyte on a single sensing platform. The present study further demonstrates the simultaneous measurement of two different optical parameters of a test sample. Finally, a universal smartphone holder compatible with all variant smartphones has been designed for various sensing and imaging purposes. The designed smartphone-based analytical platforms are compact, cost-effective and easy to use. Summary of each smartphone-based analytical platform that have been developed during the PhD period are described below:

1. A smartphone-based fluorescence sensing system has been designed to estimate mercury (II) ion concentration in water. The system measures the fluorescence signal emitted by the test sample inserted in the setup. The sensing principle is based on the quantitative analysis of fluorescence quenching of rhodamine 6g (R6G) in presence of mercury ions. Upon increasing the mercury ions concentration, the fluorescence intensity of the test sample decreases proportionately. The modulated signal has been captured by the rear camera of the phone at an angle 90° to the excitation source. A diode laser of peak emission wavelength 532 nm has been utilised as an excitation source in the present sensing setup. Upon capturing the images, the V channel values have been extracted by a custom-developed Android application and established a relationship between the colour channel values and mercury concentrations. The detection limit of the platform was estimated to be 32 ppb while measuring the concentration of mercury in water samples.

2. The growth kinetics of different bacteria samples have been monitored using a smartphone-based nephelometer. The bacterial inoculum was allowed to grow in an incubator where, the process of bio-fission increases the turbidity of the medium which could be detected by the designed setup. The designed system records the scattered intensity coming from the bacterial sample using the ambient light sensor (ALS) of a phone and subsequently measures the turbidity of the sample. ALS of the phone has been positioned at an angle 90° to the incident light signal. The system evaluates turibidity of the bacterial sample at different time points within the growing period of 24 hrs. All the responses recorded at different time points are stored in a custom developed Android application and finally, the acquired data were used to plot the growth curve for the considered bacteria sample. The designed system has been used

to evaluate the growth kinetics of *E. Coli* and *B. Subtilis* bacteria samples in laboratory environment.

3. The working of a dual-mode photometric and nephelometric sensing platform has been demonstrated by successfully measuring the OD and turbidity of a given sample. The ALS of the phone has been used to record the transmitted and scattered light intensities for respective OD and turbidity measurements. Both the modes of sensing can be used interchangeably through plug-and-play mode of a 3D printed sensing holder and with the help of a custom developed Android application. As proof-of-concept, sulphate and chloride concentrations in water samples which were collected from various locations in Assam, India have been examined by the designed platform. The system can estimate the sulphate and chloride concentrations as low as 0.5 ppm and 0.4 ppm respectively. It is envisioned that the designed sensor can be used for monitoring of other chemicals (both organic and inorganic) in water and could emerge as an alternative platform in those regions where access to laboratory-grade tools is very limited.

4. The development of a smartphone-based analytical platform has been discussed which has the ability to measure the absorbance and fluorescence emission of a fluorophore at the same time. The system has been designed using two different embedded optical sensors, namely, the ALS and the rear camera of a smartphone. A single light source (LED) has been used for both absorbance and fluorescence measurements. In the designed system, ALS of the phone records the transmitted light signal to measure the absorbance of the test sample. On the other hand, the fluorescence spectrum of the sample has been evaluated by using the rear camera of the phone. As a proof-of-concept, the designed platform has been used to measure the zinc concentration in water samples with an estimated detection limit of 0.1 ppm.

5. The working of a universal phone holder used for multiple sensing and imaging studies has been demonstrated. The holder has been designed to couple with any smartphones regardless the dimension and position of the rear camera positions. The holder is compatible with phones of different physical dimensions ranging from 65 mm to 95 mm in width. The photometric, fluorescence and microscopic based studies have been successfully demonstrated utilising the universal smartphone holder. In this study, transmitted and emitted light signals coming from rhodamine 6g (R6G) solutions with varying concentra-

tion have been measured by the proposed system. Moreover, a microscopic setup has also been developed and coupled with the holder to capture high quality images of micro-particles. As a proof-of-concept, red blood cells of human have been imaged by the designed smartphone-based microscopic imaging tool. The system has been developed as a universal analytical platform where a smartphone of any brand can be used for conducting multiple sensing and imaging studies.

8.2 Limitations

Although the present thesis work deals with some of the problems related to the smartphone-based analysis still the designed systems may have some possible limitations. It has been observed that the responses of these compact analytical platforms fluctuate upon changing the smartphone attributed to the use of different sensor modules by different smartphone manufacturers. It poses a significant challenge in developing a universal analytical platform which can be coupled to all varieties of smartphone with negligible deviation in the final results. Again, in case of multi-modal sensing, each sensing mode needs to be optimised simultaneously so that the system can operate reliably with the designed setup. It has been found that, the optimisation results narrowing down the dynamic range of the analytical platform. The single mode sensing platforms exhibit larger dynamic range compared to the multi-modal sensing platforms. This may be a noteworthy concern regarding the development of multi-purpose analytical platforms.

8.3 Future prospects

The thesis works open a new possibility towards the development of low-cost, field-portable and user-friendly sensing systems that can be used by all citizens irrespective of the requirement of technical knowledge. Although several sensing investigations have been performed regarding water quality assessment using the proposed systems, it has been envisioned that the study can be extended to various other domains such as air and soil quality monitoring, point-of-care diagnostics, clinical application and many more. The fluorescence-based platform can be used to detect different other heavy metal ions such as arsenic, lead and cadmium in water. Along with the monitoring of bacterial growth kinetics, the smartphone-based nephelometer can be utilised to measure turbidity and total suspended solute of water.

Similarly, the multi-modal sensing platforms can be used to monitor other chemicals and minerals such as fluoride, iron, phosphate and chlorine in water. Apart from these, the designed platforms can also be employed in monitoring of various soil-quality parameters such as micro/macro nutrients, NPK values and many more. Estimation of particulate matters and gaseous pollutants in air can also be investigated by the designed smartphone-based analytical platforms. The usability of the proposed tools in point-of-care diagnostic can also be explored in future course of time.