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Applications of Smartphone Cameras in Agriculture, Environment, and Food: A review

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Abstract

Purpose: The smartphone is actively being used in many research fields, primarily in medical and diagnostic applications. However, there are cases in which smartphone-based systems have been developed for agriculture, environment, and food applications. The purpose of this review is to summarize the research cases using smartphone cameras in agriculture, environment, and food. **Methods:** This review introduces seventeen research cases which used smartphone cameras in agriculture, food, water, and soil applications. These were classified as systems involving "smartphone-camera-alone" and "smartphone camera with optical accessories". **Results:** Detecting food-borne pathogens, analyzing the quality of foods, monitoring water quality and safety, gathering information regarding plant growth or damage, identifying weeds, and measuring soil loss after rain were presented for the smartphone-camera-alone system. Measuring food and water quality and safety, phenotyping seeds, and soil classifications were presented for the smartphone camera with optical accessories. **Conclusions:** Smartphone cameras were applied in various areas for several purposes. The use of smartphone cameras has advantages regarding high-resolution imaging, manual or auto exposure and focus control, ease of use, portability, image storage, and most importantly, programmability. The studies discussed were achieved by sensitivity improvements of CCDs (charge-coupled devices) and CMOS (complementary metal-oxide-semiconductor) on smartphone cameras and improved computing power of the smartphone, respectively. A smartphone camera-based system can be used with ease, low cost, in near-real-time, and on-site. This review article presents the applications and potential of the smartphone and the smartphone camera used for various purposes in agriculture, environment, and food.

Keywords: Agriculture, Environment, Food, Smartphone, Smartphone camera

Introduction

The smartphone penetration rate is very high in the Republic of Korea (over 87%) while the rates in the USA, France, Japan are less than 80, 50, and 40%, respectively (Poushter, 2016). The smartphone penetration rate for age 60 and above increased from 6.8% to 32.1% over three years from 2012 to 2015 (Jeong, 2016). Smartphone use even in farming areas increased to 52.2% in 2015 (Statistics Korea, 2015). The smartphone is widely used because of its ease of use, portability, and variety of functionalities.

The computing power of smartphones has grown to similar levels as desktop computers. As with desktop computers, the mobile processor on the smartphone has a central processing unit (CPU) and a graphics processing unit (GPU). Comparing the operating frequency and the number of cores, which are the most important criteria for estimating the performance of the CPU, operating frequencies are 2.2 GHz to 2.3 GHz, and the numbers of cores are 4 to 8. In other words, although the smartphone environment differs fundamentally from the desktop environment owing to the characteristics of mobile devices, there is not much difference in computing ability between the mobile processor and the desktop processor. In addition to the computing power of the smartphone, it

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offers other features with various integrated sensors. Most smartphones have built-in image sensors, proximity/ambient light sensors, gravity sensors, acceleration sensors, geomagnetic sensors, gyroscopes, microphone (acoustic) sensors, and GPS (global positioning system) sensors. There are also models equipped with newly developed sensors such as a fingerprint recognition sensor module, barometer, thermometer, hygrometer, heart-rate sensor, and retina recognition modules.

The smartphone is actively being used in many research fields, primarily in medical and diagnostic applications. Smartphones can provide health information (Oncescu et al., 2013; Oresko et al., 2010), a true point-of-care diagnostic system for pathogen detection (You et al., 2013; Mudanyali et al., 2012; Coskun et al., 2013; Zhu et al., 2012; Zhu et al., 2013), caregiving assistance (Abbate et al., 2012), and so on.

However, smartphone-based systems have been developed not only for diagnostics but also for agriculture, environment, and food applications. This review introduces systems which have used smartphone cameras in agriculture, food, water, and soil (Table 1). Seventeen cases were published from 2012 to the present, which used smartphones for sensing or detecting subjects of interest. Most studies developed their own smartphone application software (App.). These studies were classified as systems of "smartphone- camera-alone" and "smartphone camera with optical accessories" developed with or without an App.

Applications of smartphone-camera-alone

The built-in camera is the most used device in the smartphone for sensing and identifying an object or substance of interest. The use of smartphone cameras has advantages of high-resolution imaging (over 12 mega-pixels), manual or auto exposure and focus control, ease of use, portability, and programmability. Because of these advantages, diverse research is being carried out in the field of agriculture and food products based on built-in smartphone cameras.

Park et al. (2013) and Park and Yoon (2015) developed a paper microfluidics device which is loaded with polystyrene particles conjugated with antibodies of *Salmonella Typhimurium* and *Escherichia coli*. The particles agglutinate and increase their effective diameter within the paper channel when a pathogen is introduced. A smartphone camera captures the difference in light scattering from the agglutinated particle and quantifies the foodborne pathogens present. However, as light scattering (Mie scatter) is highly dependent on the angle of measurement, images were taken at an optimized angle and distance. A smartphone App. was designed and programmed to

Table 1. List of research cases of smartphone cameras applied in agricultural engineering

	Purpose	Addition to smartphone-camera	Reference
Food	Detection of antibiotics in milk		Li et al., 2017
	Measurement of alkaline phosphates activity in milk		Yu et al., 2015
	Detection of methanol in sugar cane spirits	App.	Franco et al., 2017
	Detection of *Salmonella*	App.	Park et al., 2013
	Detection of *E. coli* in ground meat	Gyro sensor, App.	Liang et al., 2014
	Determination of fat in cured meat		Cruz-Fernández et al., 2017
Plants	Phenotyping crop seed	Bluetooth, App.	Zhihong et al, 2016
	Measuring foliar damage area	App.	Machado et al., 2016
	Measuring chlorophyll content in corn	App.	Vesali et al., 2015
	Weed identification	Web, App	Rahman et al., 2015
Water	Analysis on catechols	Web, App.	Wang et al., 2016
	Detection of biochemicals in sea water	App.	Fang et al., 2016
	Detection of water salinity	Web, App.	Hussain et al., 2017
	Measuring chlorine	App.	Sumriddetchkajorn et al., 2013
	Monitoring pH		Dutta et al., 2015
Soil	Soil type classification	App.	Han et al., 2016
	Soil water erosion analysis		Prosdocimi et al., 2017

guide the user to determine the optimum angle and distance between the paper microfluidics and the smartphone. The App. also guides the user to follow the measurement protocol and displays the measured amount of the target pathogen concentration (Fig. 1).

Liang et al. (2014) developed a smartphone-based sensor to detect *E. coli* in ground beef. The measurement system consists of a NIR-LED (near infrared light emitting diode), camera, and gyro sensor in a smartphone with a developed App. The 880nm NIR-LED is vertically irradiated on the surface of beef while the smartphone camera takes a series of pictures of the sample at 15°, 30°, 45°, and 60°. The gyro sensor in the smartphone allows the user to hold the smartphone at the designated angle when images are taken. The developed App. measures scatter intensity from the sample surface which varies depending on the amount of the *E. coli* colony and calculates and displays the amount of the pathogen on the meat sample (Fig. 2).

Related to meat quality, a smartphone camera was used for measuring fat content in cured meat products. The camera takes a color image using its own LED (light emitting diode) flashlight and the image is separated into red, green, and blue images. Those images are analyzed to investigate the fat content (Cruz-Fernández et al., 2017).

Alkaline phosphatase (ALP) is one enzyme which hydrolyzes phosphate groups to phosphoric acid. When phosphorus builds up in the body, it prevents calcium absorption and promotes calcium excretion through urine. ALP is primarily found in milk and should be

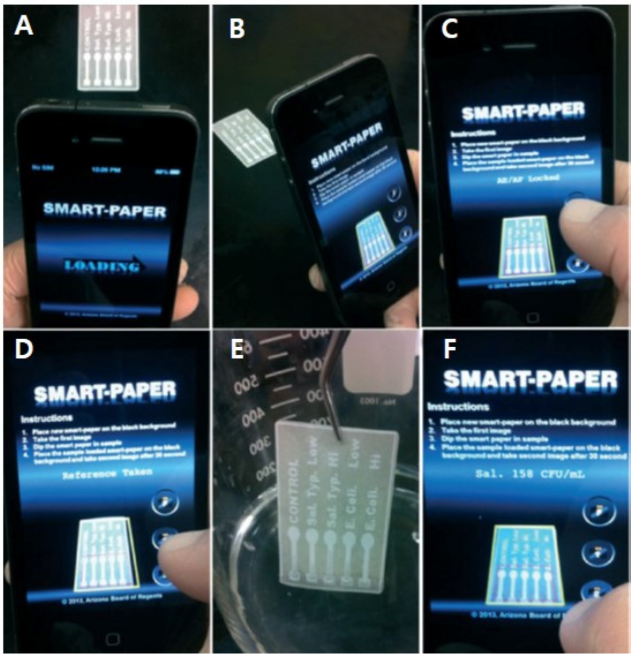


Figure 1. Images of smartphone application workflow to detect *Salmonella* on a multi-channel paper microfluidics device. Smartphone loads the developed App. (A), the App. guides the user to adjust angle and distance between camera and the device (B), locking auto-exposure and auto-focus of camera (C), taking reference image with dry Ab-PS loaded on the device (D), sample loading (E), and displaying the assay result after taking signal image of the loaded device (F) (Figure taken from Park et al., 2013 with permission, © 2013 Royal Society of Chemistry).

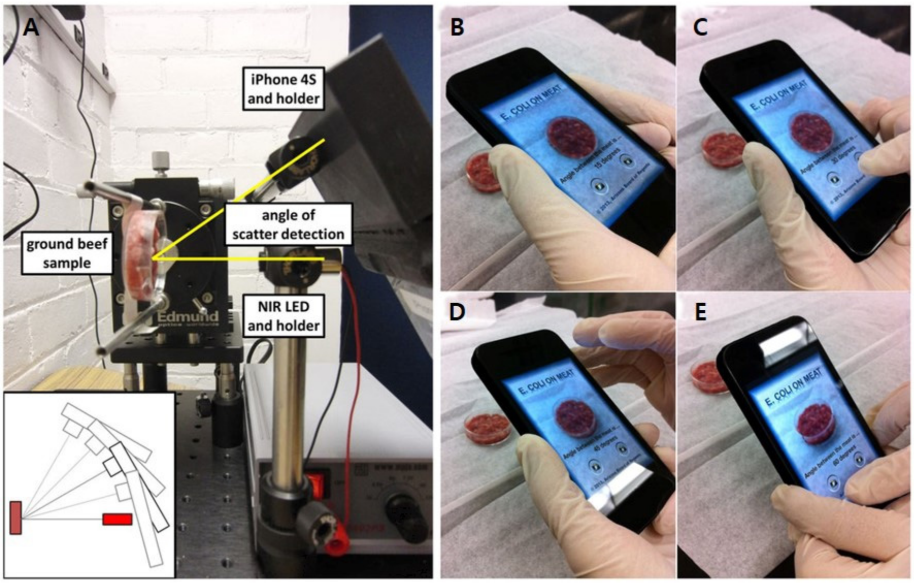


Figure 2. The configuration of the benchtop system taking images of ground beef to detect *E. coli* (A). Developed smartphone App. capturing images of ground beef at 15° (B), 30° (C), 45° (D), and 60° (E) guided by gyro sensor mounted in the smartphone (Figure taken from Liang et al., 2014 with permission, © 2014 Liang et al.).

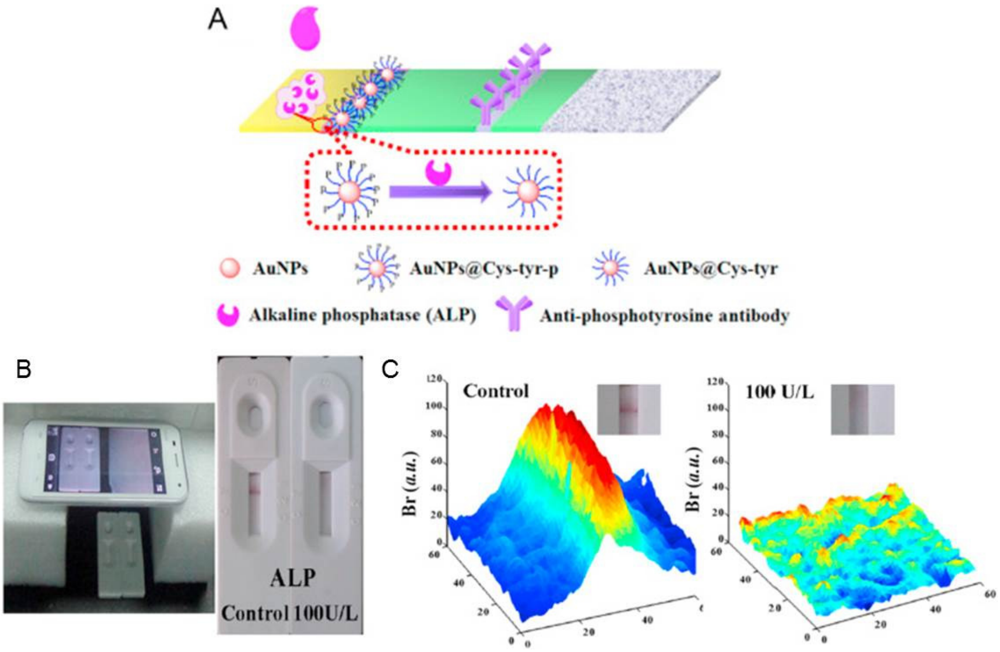


Figure 3. (A) Schematic illustration of the test strip and detection of ALP activity using AuNPs @ Cys-Tyr-p based lateral flow strip. (B) Smartphone-camera-recorded-photographs of lateral flow strip, (C) Photographs processed by customized MATLAB code (Figure taken from Yu et al., 2015 with permission, © 2015 Elsevier, B. V.).

inactivated by the pasteurization process. The level of ALP activity was measured to evaluate the degree of pasteurization in milk by Yu et al. (2015), who developed a disposable lateral flow assay strip which can rapidly detect the activity of ALP and a smartphone camera was used to measure the response on the strip (Fig. 3). The smartphone captures the image of a strip after the reaction has occurred and image analysis follows to quantify the alkaline phosphatase.

Chlorine concentration in water is a parameter for quality control in drinking or tap water. However, when chlorine flows into seawater, it causes a harmful effect on the ocean environment and eventually on human health. Conventional methods of quantifying the amount of chlorine in water typically require costly instruments (Belz et al., 1997). To overcome this drawback, Sumriddetchkajorn et al. (2013) proposed a self-referencing colorimeter that can measure the chlorine concentration in water using a smartphone camera. The configuration for measuring the amount of chlorine in water consists of a smartphone camera, a reference scene (background: white blank), and a transparent glass bottle filled with a water sample. The water is mixed with KI-starch solution to develop a blue color according to the concentration of chlorine present. A smartphone camera is used to capture the image and quantify the concentration of chlorine based on the blue color ratio of the reference scene versus the sample bottle. The algorithm for analysis and calculation of the image was implemented with a smartphone App (Fig. 4).

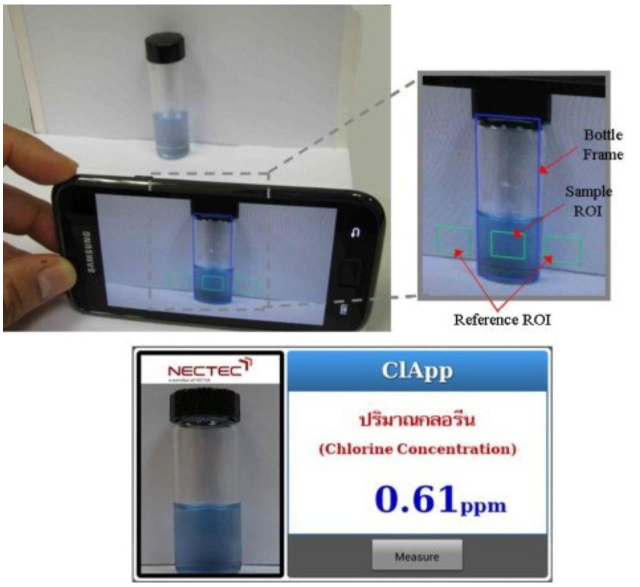


Figure 4. Snapshot of experimental demonstration for measuring chlorine in water (top) and the screenshot of the App. displaying the result (bottom) (Figure taken from Sumriddetchkajorn et al., 2013 with permission © 2013 Elsevier, B. V.).

Chlorophyll is a factor representing the growth characteristics of crops. Vesali et al. (2015) developed an

Android App. that quantifies the chlorophyll content in corn leaves by contact imaging using a smartphone. Contact imaging captures the penetrating light through plant leaves by contact with the camera lens of a smartphone. The distance between the leaf and the sensor is maintained continuously flat so that the leaf's morphology or lighting condition does not affect the measurement. The image acquired by the smartphone-camera using App. the amount of chlorophyll in the leaf is then converted to the SPAD (Soil Plant Analysis Development) value. Two different models (linear model and neural network model) were implemented in the App. to estimate the SPAD value based on the captured image (Fig. 5).

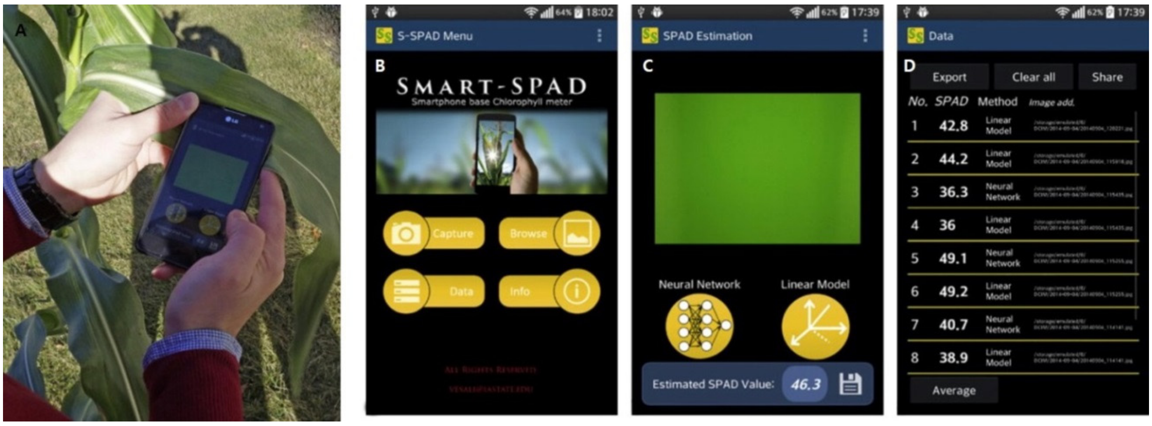
There were several other approaches to collect information on plants in the field using a smartphone. Machado et al. (2016) developed a smartphone system to analyze damaged areas on crop leaves. Images taken by a smartphone camera reconstruct the outline of damaged leaves and quantify the damaged area. Hernández-Hernández et al. (2017) were able to measure a number of plants to estimate their average growth and density using a smartphone camera. The developed App. captures an image of plants with soil background, trims plant area, segments between plant and soil, and counts the number of plants. The results are stored in a historical record on the Web. Rahman et. al. (2015) developed a crowdsourcing App. which connects farmers with experts to identify and discriminate weeds from plants. The farmers upload images of plants on their farms through the App., and the experts deliver supporting opinions.

Rain is the most important means of irrigating in agriculture; however, hard rain causes soil erosion which affects productivity losses, especially in vineyards. Prosdocimi et al. (2017) captured a digital image of soil before and after rainfall to evaluate the amount of soil erosion. A high-resolution structure-from-motion technology was applied to construct 3-D soil elevation model using smartphone cameras. The soil loss estimated by the digital elevation model successfully measured the amount of soil erosion.

Applications of smartphone camera with optical accessory

The built-in camera on the smartphone has been used for various applications. However, the measurement can be affected by surrounding lighting conditions, especially when the developed system must be operated outdoors. There have been some cases using optical accessories attached in front of smartphone cameras to control optical conditions or adding optical tools when collecting image data.

Methanol was detected in sugar cane spirits using a smartphone camera with accessory. The smartphone took an image of a chemical sensor which carried the spirit sample and underwent several steps of chemical reaction (methanol oxidation, mixing with chromotropic acid, and heating). The image was analyzed and the amount of methanol was measured as R^2=0.998 after 20 minutes of pre-treatment, smartphone image acquisition, and analysis. Thus, a simple, portable, accurate, and low-cost analytical procedure for methanol was presented (Franco et al., 2017).



No.	SPAD	Method	Image add.
1	42.8	Linear Model	[illegible]
2	44.2	Linear Model	[illegible]
3	36.3	Neural Network	[illegible]
4	36	Linear Model	[illegible]
5	49.1	Neural Network	[illegible]
6	49.2	Linear Model	[illegible]
7	40.7	Neural Network	[illegible]
8	38.9	Linear Model	[illegible]

Figure 5. Measuring chlorophyll in a corn leaf by contact imaging using a smartphone (A), Smart-SPAD App. developed on an Android smartphone (B), presenting the result of chlorophyll measured (C), and history of the measured values (D) (Figure taken from Vesali et al., 2015 with permission, © 2015 Elsevier, B. V.).

Antibiotics are used on animals to cure and prevent diseases. However, antibiotic residues in food cause allergic reactions or reduce the efficacy of antibiotics in the human body. The problem is that antibiotics are often detected in foods such as milk or other dairy products. Li et al. (2017) developed a smartphone-based immunoassay microarray to analyze and quantify tetracyclines and quinolones in milk. A 3-D printed smartphone accessory device was fabricated to keep the ELISA (Enzyme-Linked Immunosorbent Assay) test kits under dark conditions. A smartphone camera captured and analyzed the image of the test kit showing the limit of detection of 1.51 ng/mL and 1.74 ng/mL for tetracyclines and quinolones, respectively.

Toxic substances in aquatic products such as okadaic acid and saxitoxin were investigated using a smartphone and accessory. Okadaic acid causes diarrhea and abdominal pain. Saxitoxin, which is similar to tetrodotoxin, may lead to human death by respiratory paralysis. Fang et al. (2016) presented a smartphone-based aqua-toxin analysis system which consists of a smartphone camera, test strip, a 3-D printer-made smartphone adapter, and test strip adapter (Fig. 6). Smartphone accessories provide a controlled environment for optical detection, and the results of immunoassay strips are captured by the smartphone camera and are quantitated by an internal arithmetic system and stored on a smartphone by the developed App.

Monitoring water quality using smartphone cameras with accessories was reported to analyze catechols and pH. A 2x2 colorimetric sensor array was developed to quantify 14 different catechols in water. Four different pH indicator solutions were mixed with water samples separately and the color difference before and after sample mix was analyzed by images taken using a smartphone camera. The image acquisition was accomplished using a white LED under a light-tight box to prevent the effects of ambient light (Wang et al., 2016).

A smartphone camera-based spectrometer was developed to measure pH in water. The system consisted of a light source, collimator, cuvette, cylindrical-lens, plane transmission grating, and housing to align the optical components to the smartphone camera lens. The transmission image of the sample cuvette carrying a water sample with pH indicator was converted to intensity versus wavelength and measured changes in the optical absorption wavelength (450-650 nm). The captured image can be transferred to a computer via Bluetooth or mobile network for further processing (Dutta et al., 2015) (Fig. 7).

Salinity levels in water were measured using a smartphone camera system. Hussain et al. (2017) proposed two approaches (Beer-Lambert absorption and evanescent field absorption) to measure salinity levels in water using a smartphone. Both systems used a smartphone holder, optical diffuser, lens, optical fiber, cuvette or coin cell as liquid sample holders, and smartphone LED for the light source. Both methods were successful in measuring salinity level variation as low as 0.1 parts per thousand with guidance from a developed App.

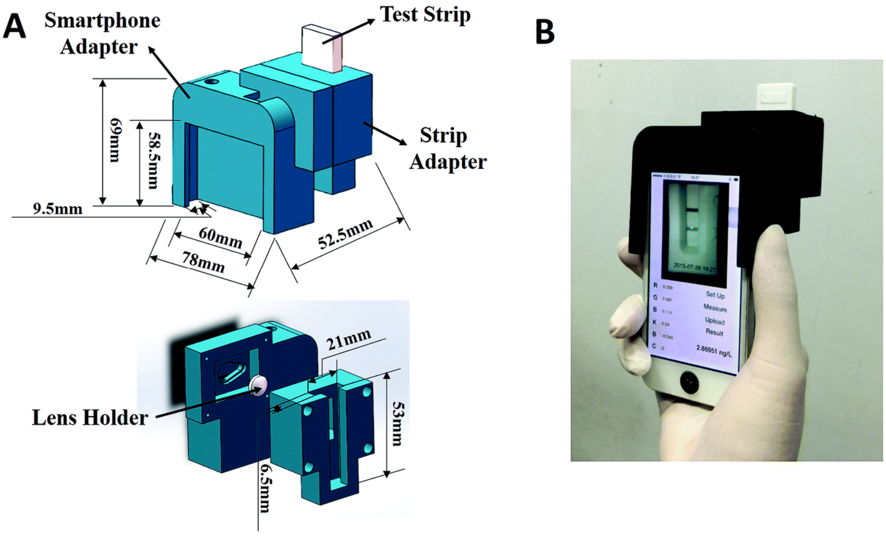


Figure 6. The composition of the toxin analysis system and its size (A) and the smartphone App. analyzing the test strip (B) (Figure taken from Fang et al., 2016 with permission, © 2016 Royal Society of Chemistry).

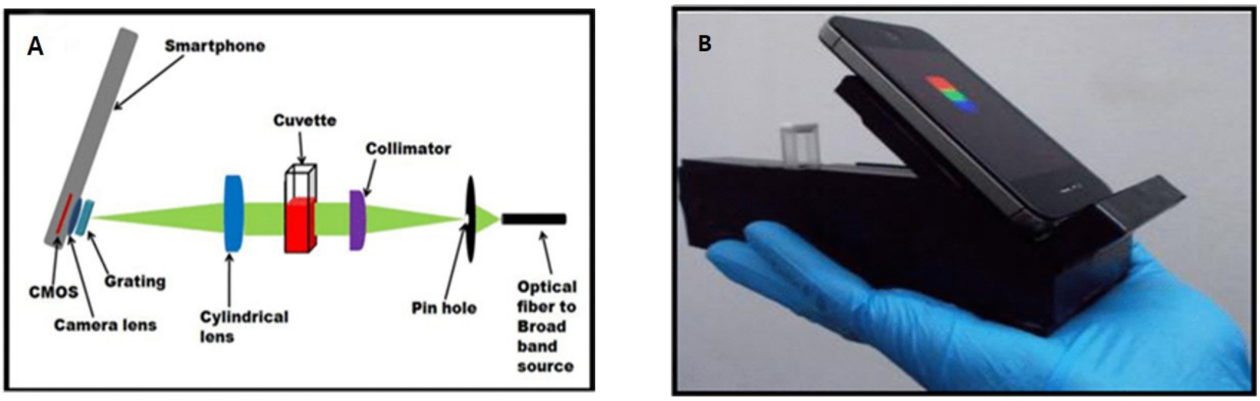


Figure 7. Schematic of aligned optical components (A) and a snapshot of the handheld smartphone-based pH sensor (B) (Figure taken from Dutta et al., 2015 with permission, © 2015 Dutta et al.).

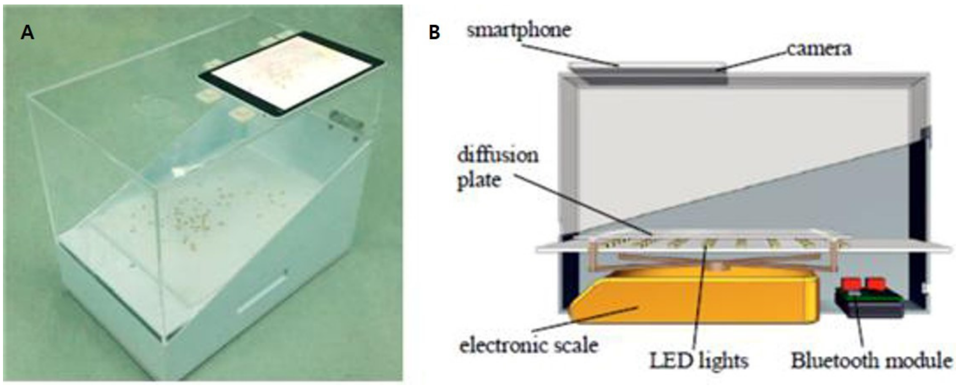


Figure 8. The smartphone camera-based seed phenotyping system (A) and the side view (B) (Figure taken from Zhihong et al., 2016 with permission, © 2016 International Federation of Automatic Control. Reproduced with permission from the original publication in IFAC-PapersOnline).

Zhihong et al. (2016) presented a smartphone camera-based portable seed phenotyping system. The instrument consisted of the smartphone camera, Bluetooth module, light diffuser, LED lighting, and electronic balance. A microprogram control unit (MCU) connected to the Bluetooth module is fixed at the bottom of the instrument to control LED lighting and transmit weight data from the electronic balance to the smartphone via the Bluetooth module. Seeds are sprayed on the light diffuser plate and the smartphone camera captures the image. Once the smartphone camera captures the image, it is converted into a binary image, and an outline of the seeds is detected. The length, width, and aspect ratio of the total seeds are measured and calculated. Furthermore, the weight data of seeds are transferred from the electronic scale to the smartphone via the Bluetooth module for data storage. This process is carried out through an App. (Fig. 8).

In addition to the above studies, soils were classified using a smartphone camera, optical accessories, and an App. Han et al. (2016) developed a smartphone-based soil classification system which successfully classified 10 different soil types based on the colorimetric method.

Conclusions

The purpose of this review was to summarize the research cases using smartphone cameras in agriculture, environment, and food. The reviewed articles highlighted the use and potential use of the smartphone and its camera for various purposes. Smartphone cameras and related Apps. were developed and applied in foods, plants, water, and soil to determine, measure, and classify various properties or characteristics of interest. The systems were classified as “smartphone-camera-alone” and “smartphone camera with optical accessories”. Detecting food-borne pathogens, analyzing the quality of foods, monitoring water quality and safety, gathering information regarding plant growth or damage, identifying weeds, and measuring soil loss after rain were presented for the smartphone-camera-alone system. Measuring food and water quality and safety, phenotyping seeds, and soil classifications were presented for the smartphone camera with optical accessories. These accomplishments were possible owing to the sensitivity improvement of CCDs (charge-coupled devices) and CMOS (complementary metal-oxide-semiconductor) for smartphone cameras and computing power enhancement of modern smartphones. The Apps. developed in the applications discussed in this paper enabled simple, cost-effective on-site use of smartphone camera-based systems in near-real-time.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

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