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Review Article

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# Portable & Smartphone Spectroscopy for Food Adulteration

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## *ABSTRACT*

Ensuring food quality, safety, and authenticity has become increasingly critical due to the growing complexity of global food supply chains and the rising incidence of food adulteration. Rapid technological advancements have significantly enhanced the ability to authenticate food products and detect fraudulent practices. Traditional food authentication approaches primarily relied on the assessment of a limited number of indicators against predefined standards. In contrast, modern analytical strategies employ targeted profiling and untargeted fingerprinting techniques that integrate advanced spectroscopic methods with sophisticated statistical analyses, enabling more accurate and reliable detection of adulteration. Although several reviews have examined conventional spectroscopic techniques and general food authentication methods, limited attention has been given to the emerging field of portable and smartphone-based spectroscopy. The increasing availability of smartphone-integrated analytical platforms offers new opportunities for rapid, cost-effective, user-friendly, and on-site food analysis. Therefore, a comprehensive evaluation of these technologies is timely and necessary. This review explores the application of smartphone-assisted spectroscopic technologies for food adulteration detection. It discusses the integration of smartphones with spectroscopic systems, smartphone-based biosensors, fluorescence spectroscopy, and colorimetric approaches for food quality assessment. Recent smartphone spectroscopy platforms and their analytical performance are critically summarized, highlighting advances in portability, sensitivity, and real-time monitoring capabilities. Furthermore, the review also examines current challenges, technological limitations, and future market prospects for smartphone-enabled food analysis. By providing a focused and updated assessment of recent developments, this review addresses gaps in previous literature and highlights the potential of smartphone-based spectroscopy as an accessible and effective tool for food authentication and adulteration detection.

**Keywords:** Smartphone Spectroscopy, Food Adulteration Detection, Food Authentication, Portable Analytical Devices, Biosensors, Food Quality Assessment

## Introduction

Technology has improved rapidly, making it possible to more precisely, swiftly, and successfully check foods for integrity issues in order to guarantee the quality, safety, and authenticity of meals in supply chains [1]. Food authenticity is defined as "ensuring that the food offered for sale or sold is the type, substance, and quality that the consumer expects." Traditional approaches to food authenticity have been based on the evaluation of one or a small number of indicators and comparison with predefined thresholds [2]. Over the past 20 years, the number of analytical signature-based food authentication methods has increased. These methods use either unexplained traits (untargeted—fingerprint) or recognized substances (targeted—profiling). Most of these methods combine complex

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statistical methods with spectrometric or spectroscopic data. Analytical equipment is becoming easier to use outside of laboratory settings. This includes handheld, portable, and non-intrusive devices, some of which are built into or linked to phones. Spectroscopy has been a significant industrial and research tool. It is widely and successfully used in applications such as drug analytical testing, environmental sensing, diagnostics, and food quality assessment. The process is rapid and non-destructive by nature. New microtechnologies including micromirror arrays, microelectromechanical systems (MEMS), and microopto-electromechanical systems (MOEMS) can now be used in microspectrometers [3]. These developments result in reduced size and cost, good performance, and high volume manufacturability. Miniaturized systems must be a black-box that consistently generates the required data without the help of spectroscopy, in contrast to lab-based instruments. Mobile diagnostics is growing in popularity in the agri-food, health care, and environmental monitoring sectors because it enables rapid on-site analysis to collect crucial and preliminary data [4]. By minimizing the need for expensive and time-consuming instrumentation-based routine testing performed by qualified personnel, the goal is to reduce cost and time. Because cellphones are so widely used, accessibility can take many different forms. There are several situations where smartphones can be used, including isolated or undeveloped rural areas. Currently, routine, resource-intensive laboratory testing of chemicals and/or foodborne microbes is the main means of guaranteeing food safety [5]. Sending specimens to a lab for analysis may be difficult in isolated areas with few resources. Reflectance is used with smaller optical sensors in UV-VIS and IR spectroscopy. Larger and heavier laser-excitation sensors include Raman spectroscopy and LIBS [6]. Imaging devices are often larger, much like the latter. Sensor arrays can be used in machines of any scale. While certain gadgets come in both huge, heavy versions and smaller, lighter versions, there are some differences in size and weight based on the sort of technology. Therefore, the size is determined by the characteristics of the technology in use. To ensure food integrity, each portable equipment must have a database containing reference values and/or calibration curves. Because color is such an important factor in food evaluation, efforts are being undertaken to create analytical procedures based on optical principles [7]. The consumer's visual perception of the objects under examination is most strongly associated with visible light procedures, which are easy to implement. The color grade of the samples reflected off the samples appear on the phone's screen, depending on the colorant concentration but evaluating non-colored items, such as milk, is more difficult.

## Smart phones in spectroscopy

The rapid multicore CPU, digital camera, battery, visual display, and user-friendly interface of a smartphone are the components that can be measured and detected. Additionally, a number of wireless data transfer technologies found in smartphones, such as Bluetooth, Wi-Fi, and cellular data service, can transmit test results to cloud databases or visualized directly to the user [8]. However, cell phones cannot be utilized as independent laboratory apparatus. However, they require additional equipment. The upgraded devices show great potential as portable diagnostic instruments for food analysis. A variety of external sensor modules have been created and installed in recent years to enhance smartphones' capacity to collect more intricate diagnostic data. Routine testing now be completed rapidly at the point of care using portable, inexpensive technologies due to the widespread use of cellphones worldwide. These tests are currently administered by qualified personnel using lab apparatus. The smartphones can now discern physical numbers due to new embedded sensors, cable and wireless connection options, and advanced visual interfaces that allow them to receive measurements from a variety of external systems. The development of point-of-care systems for biomedical applications has been the subject of numerous studies, according to Xu et al. [9]

## Biosensors in smartphones

Biosensors are analytical tools that identify target analytes by using a bio-receptor and an appropriate transduction mechanism [10]. A quantitative signal highlighting the presence of the desired component is produced by the precise interaction between the target analyte and receptor. Because the target analyte is immediately detected, the method is highly selective. However, an invasive sample pre-treatment step is always required to induce transduction. In addition to their potential for portability and shrinkage, biosensors offer rapid, inexpensive analysis and produce data in minutes. Biosensor-based analytical systems are appealing instruments for on-site detection of analytes such pollution, medicines, pesticide residues, and foodborne pathogens, because they combine smartphones with customized biochemical assays [11]. Because biosensors and cellphones offer portable, rapid, sensitive, and user-friendly detection platforms, their combination is emerging as a promising trend in food analysis. Smartphone-assisted biosensing systems integrate sensing principles such as fluorescence detection, colorimetric assays, electrochemical sensing, immunoassays, and microfluidic technologies with advanced photo processing and computational capabilities. With detection thresholds of 5–10 CFU mL-1 and 0.50 μg mL-1, respectively, fluorescence-based methods have demonstrated remarkable sensitivity for the detection of microbiological contamination and residues, such as Escherichia coli in water and antibiotic residues in milk [12]. The detection of allergies, toxins, and pollutants such as peanut allergens, aflatoxin B1, okadaic acid, and saxitoxin has also made extensive use of immunological methods such as colorimetric ELISA, lateral flow immunoassays, and competitive immunochromatographic testing. Smartphone-enabled colorimetric platforms have been used to analyze glutamate, biogenic amines, fluoride levels, and food quality indicators. Faster testing, reduced sample sizes, more portability, cloud access, and remote data transfer are all made possible by the integration of cellphones with microfluidic equipment. The identification of E.coli has been made possible by the analytical performance of DNA-based biosensing techniques for pathogen detection. Salmonella enterica and E. Coli O157:H7 at incredibly low genomic copy numbers [13]. Investigations on food authenticity, such as honey characterization and red wine differentiation, have effectively employed electrochemical and chemometric assays that are supported by cellphones. Decentralized, real-time, and reasonably priced food monitoring apps could greatly benefit from smartphone-integrated biosensors.

**Table 1.** Typical Smartphone-Based Biosensing Systems for Environmental and Food Monitoring

| Analyte/Target | Sensing Principle | Key Components | Analytical Performance | Smartphone Functionality | Ref. |
|---|---|---|---|---|---|
| *Escherichia coli* in water | Fluorescence-based detection | Antibodies, quantum dots, UV illumination | Detection limit: 5–10 CFU mL$^{-1}$ | Image capture through camera adaptor | [14] |
| rbST antibodies in milk | Fluorescent microsphere immunoassay | Antibodies, quantum dots, UV and white LEDs | 80% sensitivity and 95% specificity | Smartphone-assisted image acquisition | [15] |
| Lactose and galactose in food matrices | Bacterial fluorescence biosensing | Engineered bacterial cells, blue-light excitation, optical filter | Quantification range: 1–1000 mM | Fluorescence image analysis | [16] |
| Peanut allergen contamination | Colorimetric ELISA | Commercial ELISA kit, dual-LED accessory | ~1 ppm; assay completed within 20 min | Camera-based signal recording | [17] |
| Aflatoxin B1 in maize | Lateral flow immunoassay | Paper strip, LED source, magnifying lens | Detection limit: 5 μg kg$^{-1}$ | Smartphone LFIA reader interface | [18] |
| BDE-47 in food products | Microfluidic competitive ELISA | PCB circuit, Arduino Nano, microfluidic chip | Reduced assay time (15 min) and sample volume | Power supply, imaging and cloud connectivity | [19] |
| Red wine characterization | Paper microfluidic colorimetry with PCA | Chemical indicator dyes | Successful discrimination of wine varieties and oxidation status | Digital image acquisition | [20] |
| Biogenic amines in meat | Membrane-based colorimetric sensing | Dye-coated membrane system | Detectable at concentrations as low as 1 ppm | Camera-enabled monitoring | [21] |
| Antibiotic residues in milk | Fluorescence spectroscopy | Fluorescent lightbox system | LoD: 0.50 μg mL$^{-1}$; LoQ: 1.50 μg mL$^{-1}$ | Smartphone functioning as portable spectrometer | [22] |
| Glutamate in soups and wines | Enzyme-mediated colorimetric assay | Glutamate-specific enzyme | Detection limit: 0.028 mmol L$^{-1}$ | Image processing and quantification | [23] |
| Alkaline phosphatase (ALP) in milk | Lateral flow-through assay | Disposable strip and sample pad | Detection range: 0.1–150 U L$^{-1}$; assay time <10 min | Image capture with software analysis | [24] |

| Analyte/Target | Sensing Principle | Key Components | Analytical Performance | Smartphone Functionality | Ref. |
|---|---|---|---|---|---|
| Okadaic acid (OA) and saxitoxin (STX) | Competitive immunochromatographic assay | 3D-printed strip holder | LoD: 2.8 ng $mL^{-1}$ (OA), 9.8 ng $mL^{-1}$ (STX) | Adapter-assisted image analysis | [25] |
| Fluoride in drinking water | Smartphone colorimetry | Compact sample chamber attachment | Linear response between 0–2 mg $L^{-1}$ | Portable colorimetric measurement | [26] |
| Catechol compounds in water | Sensor-array colorimetric imaging | 96-well array, LED illumination box | Qualitative and quantitative discrimination using chemometric tools | Smartphone-linked remote analysis | [27] |
| *Vibrio parahaemolyticus* in fish | Colorimetric immunoassay | Biosensor cartridge, CMOS sensor, Wi-Fi module | Detection limit: $1.4 \times 10^4$ CFU $mL^{-1}$ | Dedicated mobile application and cloud upload | [28] |
| *E. coli* O157:H7 and *Salmonella enterica* | DNA-based microfluidic detection | Magnetic bead-assisted transduction system | Detection down to 20 genomic copies | Mobile application for image interpretation | [29] |
| Clenbuterol | Electric field-enhanced immunoreaction | Functionalized electrode biochip | Detection limit: 0.076 ng $mL^{-1}$ in 6 min | USB-connected smartphone reader | [30] |
| Brazilian honey authentication | Cyclic voltammetric fingerprinting | Gold electrode and portable potentiostat | Accurate generation of electrochemical fingerprints | Smartphone-based chemometric analysis | [31] |

## Florescence spectroscopy in smart phones

Fluorescent dyes are used in fluorescence imaging to identify biological or chemical targets of interest. The locations of gene and protein expression, and molecular interactions in cells and tissues are possible using this fluorescence spectroscopy. A fluorescent marker capable of binding the target molecule must be added in order to label a biological molecule of interest. Similar to this, advanced fluorescence imaging systems use a monochromatic light source typically a UV LED to excite the dye and a smartphone camera as the detector to record and track the fluorescence intensity [32]. The employment of various molecular dyes to target multiple targets of interest is beneficial for a specific detection application. Zhu et al. [33] created a portable Escherichia coli detection technique for food and water sample screening. A particular use of the smartphone-based fluorescence imaging technique for the measurement of bacteria in a water sample enclosed in glass capillaries have been suitably functionalized with an antibody against E. coli. When the secondary antibodies were coupled with quantum dots, the fluorescence signal spread throughout every capillary. UV-LEDs were used to provide the excitation signal. The emission from the quantum dots was collected by the phone camera unit using a different lens . Each capillary tube's fluorescent light output and the relevant quantity of E.coli were measured. Ludwig et al. [34] detected anti-recombinant bovine somatotropin (rbST) antibodies in milk naturally produced after dairy calves were administered rbST, a milk production enhancer that is prohibited in the EU and considered harmful to public health in the US. Using a set of immunoassay microspheres, each designed to identify a specific antibody, the study simultaneously monitored the presence of this biomarker in a small volume of a single sample. Extracts of milk samples from cows treated and untreated with rbST were successfully subjected to the cell phone-based diagnostic technique. The true negative rate was 95%, whereas the true positive rate was 80%. In order to determine the content of lactose or galactose in undiluted food samples and to reveal its diffusion behavior, Mora et al. [35] created a biosensor based on genetically engineered bacteria (E. coli) that fluoresces in reaction to the analyte.

## Colorimetry in smartphones

In biochemistry, the colorimetric assay has been widely used to identify the presence of many analytes of interest, including peptides, enzymes, and antibodies. The method's fundamentals is the measurement of a chromogenic reagent's or reaction product's absorption of light for a specific amount of time. It has a different wavelength than the reagent being tested. To identify allergens in food samples with high sensitivity and specificity, Coskun et al. developed a cellphone-based technique for tube-based colorimetric testing [36]. Two tubes for the test and control solutions and two LEDs with wavelengths that match the absorbance of the active reagent in the test tube were used to create the cellphone attachment (Fig 1) .

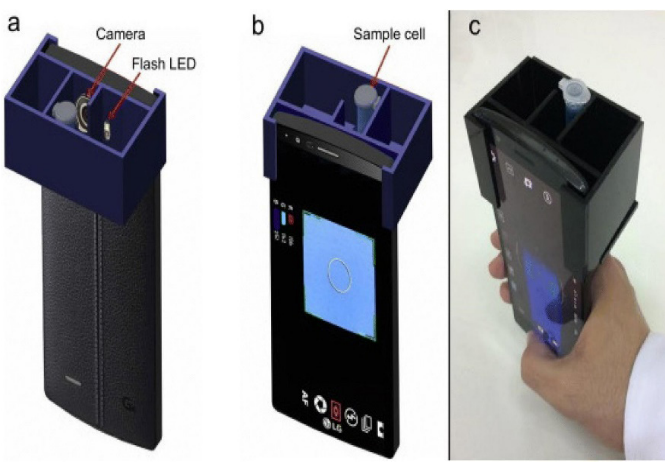


**Fig: 1. Smartphone Colorimeter**

For the purpose of identifying aflatoxin-B1 in maize, Lee et al. created a straightforward, rapid, and precise smartphone-based lateral flow immunoassay (LFIA) reader. One kind of maize mold produces dangerous secondary metabolites called aflatoxins. Analytes can be identified and quantified using a paper strip-based technique called lateral flow immunoassay (LFIA). To increase the LFIA sensitivity and detection limit for AFB1 in maize and lower the amount of read-out errors by visual inspection, a Samsung Galaxy S2 smartphone with a close-up lens and white LED as the LFIA reader was employed. The operator's subjective interpretation had no bearing on the outcome. By combining microfluidics and competitive ELISA, Chen et al. developed a portable smartphone-based system for the mobile detection of BDE-47, a frequent environmental contaminant, in food samples [37]. The smartphone's USB port served as the power supply, and an Arduino Nano microcontroller connected to a PCB handled power management. The designed microfluidic-based ELISA device was powered by the microcontroller to start the analyte-mediated reaction. The smartphone's camera then collected the colorimetric read-out and wirelessly sent it to a computer server for additional processing. Conventional ELISAs typically take at least two hours, however our lab on a chip test showed a significantly shorter reading time of fifteen minutes. Using paper microfluidic channels and chemical dyes in a colorimetric test, Park et al. developed a portable quality-control tool to evaluate the characteristics of red wine. Six different red wines were included in the "model sample set," and four were included in the "evaluation sample set." The smartphone measured and processed the colorimetric data, and PCA analysis was used to interpret the results. The red wines and grape varieties' oxidation was effectively detected [38]. PC2 was described as the body (light or heavy) of red wine, and PC1 as the sweetness (sweet or dry). To improve repeatability with less error and decrease sample-to-sample variance, the single red wine sample (i.e., undiluted) was split into eight distinct wells. Particle components were filtered using paper. As a result, the PCA plot became more segregated. PCA and image processing are used in cloud computing or as stand-alone smartphone apps. In endemic regions of India, where fluorosis—a chronic condition brought on by high fluoride consumption—occurs, Levin et al. created a colorimeter for field use to screen groundwater for fluoride.

## Recent smartphone spectroscopy system

Kumar et al. [39] used a smartphone-based visual diagnostic technique to detect beef microbiological deterioration (Figure 2). After exposing a near-infrared (NIR) LED at 880 nm perpendicular to the ground beef's surface, the scatter signal was recorded using a smartphone digital camera at angles of 15°, 30°, 40°, and 60° from the incoming light. A software application used the Gyrosensor included into the iPhone to control the angle of incidence between the camera and the NIR LED light source. The E. Coli concentrations ranged from 101 to 108 CFU/mL[40]. The Ecoli was calculated using the "pattern" of these scatter intensities along the angles.

**Table 2**. Recent Smartphone-Assisted Spectroscopic Platforms for Food Safety and Quality Assessment

| Analyte/Application | Spectroscopic Approach | Core Components | Analytical Performance | Key Findings/ Applications | Smartphone Integration | Reference |
|---|---|---|---|---|---|---|
| Microbial spoilage in beef | Mie scattering spectroscopy | Positioning stages, 880 nm NIR LED | Detection range: $10^1$–$10^8$ CFU mL$^{-1}$ | Enabled rapid assessment of microbial growth in meat products | Built-in camera and gyroscope used for spectral acquisition | [39] |

| Analyte/Application | Spectroscopic Approach | Core Components | Analytical Performance | Key Findings/ Applications | Smartphone Integration | Reference |
|---|---|---|---|---|---|---|
| General spectroscopic analysis | Spectroscopic colorimetry | 3D-printed enclosure, LED array, VIS spectrometer, Phidgets board | Spectral deviation (dE/E) between 0.5–1.5% | Produced spectra closely matching certified reference standards | Connected as an IoT-enabled smartphone accessory | [40] |
| Glucose and ethanol quantification in beverages | FTIR spectroscopy with independent component analysis | Graphite light source, ATR prisms, 2D detector array | Spectral resolution of 0.057 μm | Demonstrated simultaneous determination of beverage constituents | Miniaturized spectroscopic module designed for smartphone attachment | [41] |
| Chlorophyll fluorescence (ChlF) monitoring in apples | UV fluorescence spectroscopy | UV LED, VIS spectrometer, Arduino Pro Mini, Bluetooth module | Strong correlation between fruit ripeness and fluorescence intensity | Effective evaluation of fruit maturity and freshness | Dedicated mobile application for data visualization and analysis | [42] |
| *Escherichia coli* contamination on meat surfaces | Fluorescence imaging spectroscopy | High-power LEDs, CCD camera, optical filter, Wi-Fi transmitter | Successfully identified most contamination sites | Facilitated rapid localization of fecal contamination | Real-time wireless transmission to smartphone devices | [43] |
| Food quality monitoring | Hyperspectral imaging | MEMS Fabry–Pérot interferometer (FPI), Bluetooth connectivity | Spectral range: 450–550 nm; resolution: 8–15 nm (FWHM) | Enabled portable hyperspectral food analysis | Smartphone-compatible imaging platform | [44] |
| Food quality evaluation | Diffractive interference refractometry | Semiconductor laser, Si detectors, PDMS chip | Detection limit: $4 \times 10^{-4}$ RIU | Accurate refractive index measurement for food characterization | Smartphone-based transmission-mode interface | [45] |
| Sugar content estimation in pears | Near-infrared (NIR) spectroscopy with PLS regression | Tungsten lamps, LVF filter, CMOS detector array | $R^2 = 0.96$; SEC = 0.29 °Bx; SEP = 0.46 °Bx | Reliable prediction of fruit sweetness and quality attributes | Wireless smartphone control and monitoring | [46] |

The proof-of-concept for SpiderSpec, a compact colorimeter with a potential use in food management is built on a 3D printed cylindrical shell that contains a tiny spectrometer for detection and an array of LEDs for lighting. As is customary for reflectance measurements, the optical head's 12 visible LEDs were positioned in a circle at a 45° angle from the center detecting axis. The chosen spectrometer works in the 350–800 nm wavelength range [41]. A proprietary Labview software interface was used to control both the spectrometer and the LEDs. For on-site research in food or beverage production plants, Fourier transform infrared (FTIR) spectrometers with attenuated total reflection (ATR) are expensive and heavy. A small FTIR spectroscopic imager that uses independent component analysis to assess ethanol and glucose in alcoholic beverages simultaneously were used. A portable instrument forassessing Using a prototype portable spectrometer, the authors investigated the UV fluorescence of chlorophyll (ChlF) in fruits. This technique makes it possible to assess fruit ripeness without causing injury. Using ChlF emission upon UV light activation, the smartphone spectrometer assembly has been employed to rapidly assess the maturity of several apple varieties. The spectrometer had a range of 340–780 nm, and the excitation source was a UV LED with a wavelength of 360–380 nm [43]. Meat fecal contamination is one facet of food safety and quality. In slaughterhouses, human inspectors physically evaluate and in order

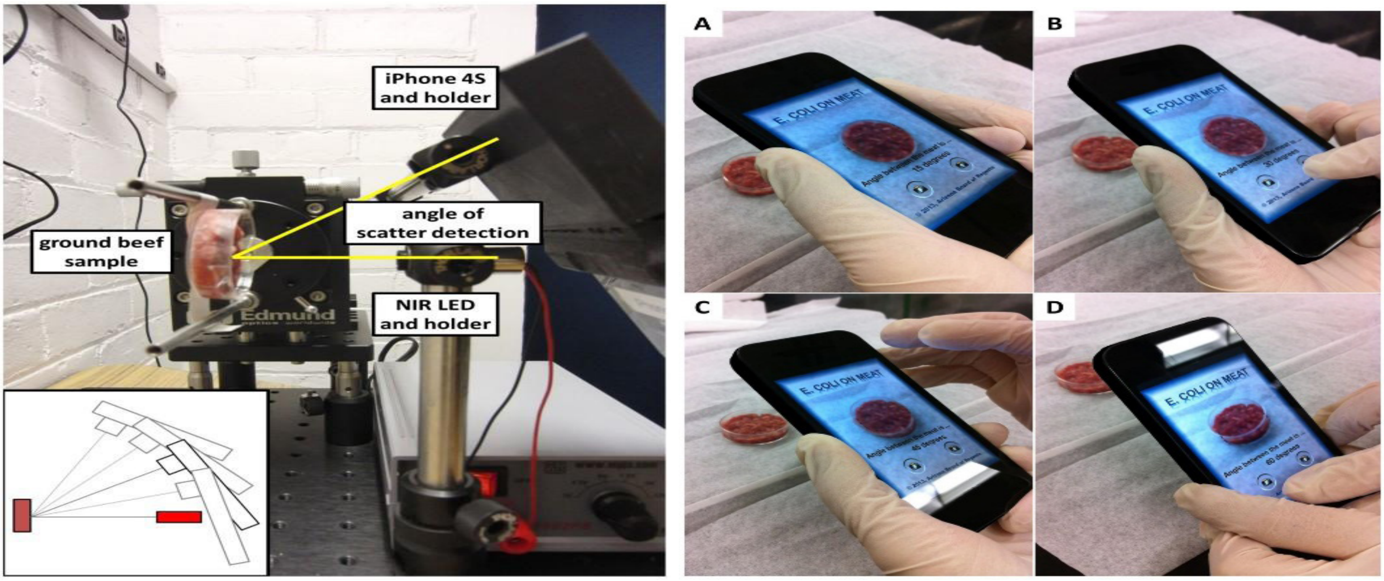


**Figure 2: Schematic representation of smartphone-based near-infrared light scattering system for microbial spoilage detection in beef samples.**

to enable human inspectors to more accurately detect fecal contamination on the red meat, fat, and bone surfaces of cattle under varying light intensities, Bui et al [44]. created a portable fluorescence-based imaging device. In order to accomplish hyper-spectral imaging in the vis-NIR band of 450–550 nm, the researchers built a MEMS Fabry-Perot interferometer (FPI) with tunable optical filters connected to an iPhone 5s camera. Bluetooth was used to connect the MEMS FPI module to the iPhone 5 [45]. The device included a charge-coupled device (CCD) camera, an optical filter at 670 nm, four 405 nm 10 W LEDs for fluorescence excitation, and a Wi-Fi transmitter for real-time data transfer to a tablet or smartphone. The majority of fecal contamination on beef surfaces can be detected at about 670 nm. Rissanen et al. presented a mobile phone-compatible hyper-spectral imager based on a tunable MEMS Fabry-Perot interferometer for identification and counterfeit detection, as well as future food sensing and health/wellness applications [46].

## Future market for food analysis smart phones

Many start-ups have suggested using mobile devices to evaluate food quality and identify its ingredients due to the growing popularity of crowdfunding. These gadgets are compact, portable labs with a single target detection capability. These are specialized smartphone applications that provide easy-to-use interfaces for controlling and presenting Bluetooth Low Energy (BLE) link test results. Professor Aydogan Ozcan launched Cellmic LLC (previously Holomic LLC), which created a number of quick diagnostic test readers for sophisticated mobile diagnostics [47]. Using an ELISA kit and a test tube module that connects to a smartphone camera, UCLA researchers have created a device that detects allergies. The enterprise ARS Lab and Kaunas University of Technology have collaborated to develop the patented smart electronic nose FOODsniffer (previously PERES). It is based on gas sensors and seeks to identify gases that signify fish and meat deterioration. Near-infrared spectroscopy-based sensors, a novel and promising method, are being offered by several new companies. After years of study at the VTT Technical Study Center in Finland, Spectral Engine OY has developed a variety of high-tech devices, all of which include a highly unique component: a changeable optical filter. Subsequently, a number of patent applications were submitted [48]. The Wireless NIR sensor device platform can be used with a PC, tablet, or smartphone and is intended for the creation of portable applications. In order to accurately determine the fat, protein, sugar, and overall calorie content of food products, the Food Scanner solution concept relies on a wireless NIR sensor with complex algorithms, cloud connectivity, and a sizable material library.

## Challenges

Each phone has a slightly varied color profile due to hardware variances. It is necessary to calibrate every phone. There might be actual variations in the lamps' spectral emittance, the digitizer's parts, and the cameras' spectrum responsiveness [49]. Because JPEGs are compressed, information is lost when taken. It is processed by the camera to create a JPEG. The image is then given a preset color space and white balance. This integrated processing's reliance on the camera is a drawback. Since all sensor data is recorded in RAW, post-processing options such as adjusting the white balance and choosing the appropriate color space to export the image in are always available. For mobile food diagnostics, which seeks to reduce the need for expensive and time-consuming instrumentation-based assays by qualified specialists, sample preparation represents a bottleneck. Measurements taken by non-expert users may be compromised by inadvertent contamination. For instance, if the solutes in the sample buffers have a positive or negative impact on light absorption, a colorimetric assay produce false positives or false negatives [50]. Sampling is an essential initial step, and this fundamental constraint primarily affects detection systems. By comparing the measured intensity of an unknown with the certified values, dye and glass standards are used to calibrate the relative intensity of fluorescence emission. The colorimetric test's software module must first be calibrated using a set of images produced from the reference concentrations in order to accurately identify unknown chemicals.

### Future Research and Regulatory Considerations

Future research should focus on improving the analytical sensitivity, specificity, robustness, and reproducibility of smartphone-based spectroscopic systems across diverse food matrices and adulterants. The integration of artificial intelligence, machine learning algorithms, cloud-based analytics, and Internet of Things (IoT) platforms may enhance predictive accuracy and facilitate real-time decision-making. Large-scale multicenter validation studies are required to establish standardized calibration models and assess performance under real-world conditions. In addition, efforts should be directed toward the development of universal protocols for sample preparation, data acquisition, and result interpretation to improve inter-device comparability.

From a regulatory perspective, widespread implementation of smartphone-assisted food analysis requires compliance with food safety and analytical validation standards established by regulatory agencies such as the Food and Drug Administration, European Food Safety Authority, and International Organization for Standardization. Standardized performance criteria, quality assurance procedures, and certification frameworks must be established before these devices can be routinely used for official food inspection and regulatory monitoring. Furthermore, issues related to data security, cloud-based data management, user training, and regulatory acceptance of smartphone-generated analytical results require careful consideration. Addressing these challenges will be essential for translating smartphone spectroscopy from laboratory prototypes into reliable, commercially viable tools for food authentication and adulteration surveillance.

## Conclusion

Smartphone-based spectroscopy has emerged as a promising platform for rapid, portable, and cost-effective food adulteration detection. The integration of spectroscopic techniques, biosensors, fluorescence analysis, and colorimetric approaches with smartphones has enhanced the accessibility and efficiency of food quality assessment. Recent smartphone spectroscopy systems demonstrate considerable potential for on-site, real-time monitoring, reducing reliance on laboratory-based analyses. Despite these advances, challenges related to standardization, sensitivity, calibration, and large-scale validation remain. Future developments in artificial intelligence, cloud computing, miniaturized sensors, and Internet of Things integration are expected to further improve analytical performance and expand commercial adoption. The growing market for smartphone-based food analysis highlights the increasing demand for user-friendly and decentralized testing solutions. This review provides a comprehensive overview of current technologies, applications, and limitations, serving as a valuable resource for researchers, industry stakeholders, and regulatory agencies working toward enhanced food authenticity, safety, and consumer protection.

## Conflict of interest

Conflict of interest declared none.

## Declarations

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## Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Author Contributions

All authors contributed to conceptualization, literature curation, critical appraisal, and manuscript preparation. All authors reviewed and approved the final submitted version.

## Data Availability

No new data were generated or analyzed for this review. All data sources are cited within the manuscript and are publicly available through the referenced databases.

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