

# Sensors for Agriculture and the Food Industry

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Modern agricultural management relies strongly on many different sensing methodologies to provide accurate information on crop, soil, climate, and environmental conditions. Almost every sensing technique may find an application in agriculture and the food industry. This paper briefly reviews some of the applications of sensors in agriculture and the food industry.

## Remote Spectral Sensing

Remote spectral sensing of crops has been intensively investigated and proven to be an important tool in modern agricultural management. Agricultural remote spectral sensing typically refers to imagery taken from above a field where the incident electromagnetic radiation is generally sunlight.<sup>1</sup> When sunlight hits the surface of the crop or soil, the light will be reflected, absorbed, or transmitted, depending on the wavelength of the light and the characteristics of the contacted body. The differences in the physical and chemical properties of the contacted body, such as leaf color, texture, and shape, determine the amount of the reflected, absorbed, and transmitted energy of a specific wavelength. The most common remote sensing technique used in agriculture is spectral reflectance measurements, in which the spectral reflectance (the ratio of reflected energy to incident energy) is measured as a function of wavelength.<sup>2,3</sup> The images of the wavelength-dependent reflectance

curves, which are known as a spectral signature, are unique to plant species and conditions.

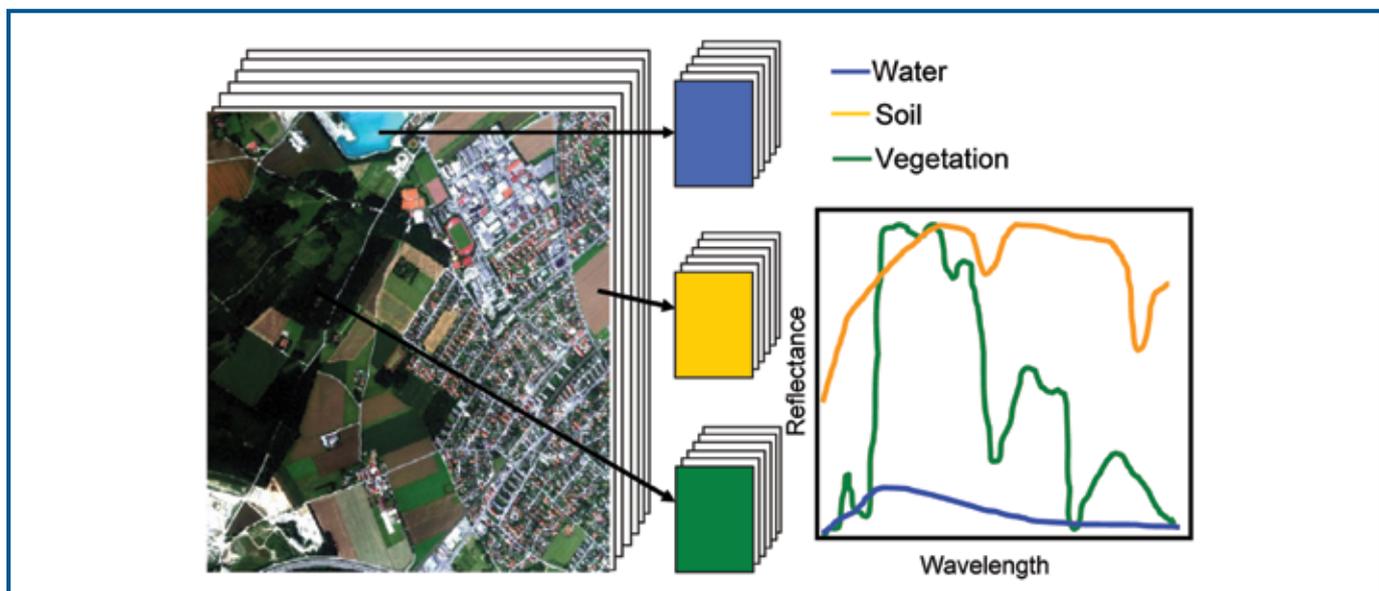
The wavelengths measured in most agricultural applications cover the visible (400-700 nm) to near infrared (700-2500 nm) regions of the electromagnetic spectrum.<sup>1</sup> Research has shown that spectral signatures in this region offer a wealth of information regarding physiological and biological properties of crops and soil.<sup>1,4,5</sup> Special vegetation and crop indices have been derived from the measured spectral reflectance values for studying different agricultural properties.<sup>1,6</sup>

Spectrometers, radiometers, or digital cameras can be mounted on a variety of platforms either ground (truck, tractor), aerial (aircraft), or space (satellite) to gather data. Sequential measurements of small areas are made as the sensor platform moves and subsequent processing assembles measurement results into an image.<sup>3</sup> The remote sensing is characterized by spatial resolution, spectral resolution, and temporal resolution.<sup>1,3</sup> Spatial resolution refers to the smallest area that can be distinguished in the image. Spatial resolution is directly related to the image pixel size. Spectral resolution refers to the number and width of the portions of the electromagnetic spectrum measured by the sensor. Temporal resolution refers to how often a remote sensing platform can provide measurements of an area. Agriculture and farm management applications typically require a spatial resolution of 2-5 m

with a 1 to 3-day temporal resolution, a 1 pixel geolocation accuracy, 24-hour product delivery time, and correction for atmospheric interference such as dust, CO, CO<sub>2</sub>, ozone, etc.<sup>6</sup>

Over the past decades, sensor development for agriculture has been driven largely by the stringent requirement of sensor resolution.<sup>6</sup> Spatial resolution is largely determined by the type of sensor platform. Ground or aerial based sensor platforms can easily meet the requirement of spatial resolution at the field scale, but they are costly and labor consuming. On the other hand, space-based platforms provide low spatial resolution and can be affected by weather conditions, such as clouds. The advantages and disadvantages of different sensor platforms have been summarized by Scotford *et al.*<sup>1</sup>

Remote spectral sensing has been applied to agriculture since the early 1960s. Conventional spectral sensors used a multispectral imaging system, in which parallel sensor arrays measured a small number (3-6) of spectral bands within the visible to middle infrared region of the electromagnetic spectrum.<sup>2,7</sup> Advances in hyperspectral imaging have led to improvements in spectral resolution over the past two decades. Today, hyperspectral imaging systems can measure numerous (several hundred) very narrow contiguous spectral bands throughout the visible, near-infrared, mid-infrared, and thermal infrared portions of the electromagnetic spectrum (Fig. 1).<sup>2,3,7,8</sup> The high spectral



**Fig. 1.** The concept of hyperspectral imagery. Reflectance spectra measurements are made at many narrow contiguous wavelength bands, resulting in a complete spectrum for each pixel.

resolution of the hyperspectral system produces detailed spectral data that can be used to obtain in-depth and accurate information of crop or field features. Hyperspectral imaging generates a very large volume of data. Interpreting the data requires an in-depth understanding of the hyperspectral sensor and the properties that are measured.<sup>2,3</sup> Current hyperspectral imaging research topics include data processing mechanisms, data assimilation schemes, and model development.<sup>9,10</sup>

Remote spectral sensing has been successfully used to measure crop nutrition, crop disease, water deficiency or surplus, weed infestations, insect damage, plant populations, flood management, and many other field conditions.<sup>1-3,11,12</sup>

The food industry has used remote spectral sensing to monitor food quality and detect possible food contaminants.<sup>13-16</sup> Typically in food processing plants an artificial light source is used to illuminate the food as it passes on a conveyor belt. A sensor system then measures induced fluorescence or scattered reflectance. The wavelengths used in food quality monitoring usually include the ultraviolet (10-400 nm), visible (400-750 nm), and near infrared (750-2500 nm).<sup>13</sup> Recently three-dimensional hyperspectral images have been generated for accurate detection.<sup>17-21</sup>

## The Electronic Nose

Plants and trees normally release volatile organic compounds (VOCs) as a byproduct of everyday physiological processes. The specific VOCs and the quantities released are indicative of both the crop and field conditions. Humidity, light, temperature, soil condition, fertilization, insects, and plant diseases all affect the release of VOCs. The most common applications of electronic noses in agriculture are to detect crop diseases, identify insect infestations, and monitor food quality. The electronic nose generally consists of an array of gas sensors with a broad and partly overlapping selectivity and an electronic pattern recognition system with multivariate statistical data processing tools. The electronic nose is typically trained by comparing the profile of VOCs released by healthy plants/fruits with diseased plants/fruit. Recent developments in this area have been reviewed by Sankaran *et al.*<sup>22</sup>

One of the major applications of the electronic nose in the food industry is to assess the freshness/spoilage of fruits and vegetables during the processing and packaging process.<sup>23,24</sup> Studies have been conducted to detect VOCs that indicate fruit ripeness and/or compounds that trigger fruit ripening, such as ammonia,<sup>25,26</sup> ethanol,<sup>26</sup> ethylene,<sup>26,27</sup> and trans-2-hexenal.<sup>28</sup> Electronic noses have been used to

monitor changes in the aroma profile during storage of apples,<sup>29</sup> to assess the postharvest quality of peaches, pears, bananas,<sup>29-31</sup> and nectarines,<sup>29,31</sup> and to detect spoilage in potatoes.<sup>32</sup> Most of these studies are still in the preliminary feasibility stage. Problems with sensor stability, longevity, calibration, selectivity, and standardization of gas array instruments currently limit commercial applications.<sup>33</sup>

Electronic noses and electro-antennogram sensors have also been used to determine the area of coverage of pheromone traps set to capture insect herbivores.<sup>34-36</sup> Recently, the ability of the electronic nose to identify early stages of insect infestations by detecting VOCs secreted by plants that have been attacked has been investigated.<sup>37-39</sup>

## Electrochemical Sensors

An important application of electrochemical sensors in agriculture is in the direct measurement of soil chemistry through tests such as pH or nutrient content. Soil testing results are important to obtain optimal crop production yields and produce quality, tasty food. The development of soil sensors has been recently reviewed by Adamchuk *et al.*<sup>40</sup> Two types of electrochemical sensors are commonly used to measure the activity of selected ions (H<sup>+</sup>, K<sup>+</sup>, NO<sup>3-</sup>, Na<sup>+</sup>, etc.) in the soil: (1.) ion selective electrode (ISE) sensors, and (2.) ion selective field effect

**Table I. Summary of literature on the use of phage as a bio-recognition element in various assays.**

Transduction	Assay Type and Mechanism	Target	Ref.
Amperometric electrode	Phage induced cell lysis causing release of components (such as $\beta$ -galactosidase, $\alpha$ -glucosidase and $\beta$ -glucosidase)	<i>E. coli</i> (K-12, MG 1655) <i>B. anthracis</i> <i>M. Smegmatis</i>	100-102
Impedimetric biosensors	Phage display technology to engineer display peptides specific to the target analyte	PSMA Antibody for P8	103-105
LAPS	Phage display technology to engineer display peptides specific to the target analyte	hPRL-3 MDAMB231	106
Bio-luminescence	Luciferase reporter phage	<i>M. tuberculosis</i> <i>L. monocytogenes</i>	107
Fluorescence	Fluorescently labeled phage in combination with immunomagnetic beads	<i>E. coli</i> O157:H7	108-110
Quantum Dots	Biotinylated phage and streptavidin conjugated quantum dot	<i>E. coli</i> BL-21	111
Au-phage network	Phage display technology to engineer display peptides specific to the target analyte	Melanoma cells	112
SPR	Affinity-selected phage-immobilized using physical adsorption/SAMs	<i>S. aureus</i> $\beta$ -galactosidase <i>L. monocytogenes</i>	113-115
Opto-fluidic ring resonator	Phage display technology to engineer display peptides specific to the target analyte	Streptavidin	116
QCM	Phage display technology to engineer display peptides specific to the target analyte Affinity-selected phage-immobilized using physical adsorption	<i>S. typhimurium</i>	67,117
Magnetoelastic cantilever	Phage display technology to engineer display peptides specific to the target analyte Affinity-selected phage-immobilized using physical adsorption	<i>B. anthracis</i> <i>S. typhimurium</i>	85,118
Magnetoelastic particle resonators	Phage display technology to engineer display peptides specific to the target analyte Affinity-selected phage-immobilized using physical adsorption	<i>B. anthracis</i> <i>S. typhimurium</i> <i>E. coli</i>	77-81,88-90

transistor (ISEFT) sensors. ISE and ISEFT sensors have also been used to monitor the uptake of ions by plants. The rate of nutrient uptake is determined by the demand of the plant, which is dependent on the growth rate and on the status of the plant's nutrient content. Most macronutrients (e.g., nitrogen, phosphorous, and potassium) are absorbed actively. Monitoring ion concentrations in plants or growing systems enables farmers to design fertilization strategies that optimize production.

Ion-selective sensors have been developed to detect a variety of ions. ISE sensors have been developed to monitor nitrogen ions in the soil and crops, such as potatoes,<sup>41,42</sup> and vegetables for fertilization management.<sup>43,44</sup> Concentrations of ions, such as iodide, fluoride, chloride, sodium, potassium, and cadmium, in plants or soils have been measured by ISE sensors to investigate plant metabolism, nutrition, and toxicological effects that heavy metals may have on plants.<sup>45-48</sup>

With the advent of ISE and ISEFT, the development of ion-specific nutrient supply systems for crops/plants in the greenhouse industry is now possible. Several investigators have developed systems that inject liquid fertilizers based upon ion-specific concentration measurements.<sup>49,50</sup> These systems automatically ensure that the nutrient demand of the plants is satisfied.

## Biosensors

Biosensors have been widely investigated for detecting chemical contaminants and food-borne pathogens. Food-borne illnesses pose an imminent threat to the public health and result in an estimated loss of \$30 billion USD per year.<sup>51</sup> Current bacteria

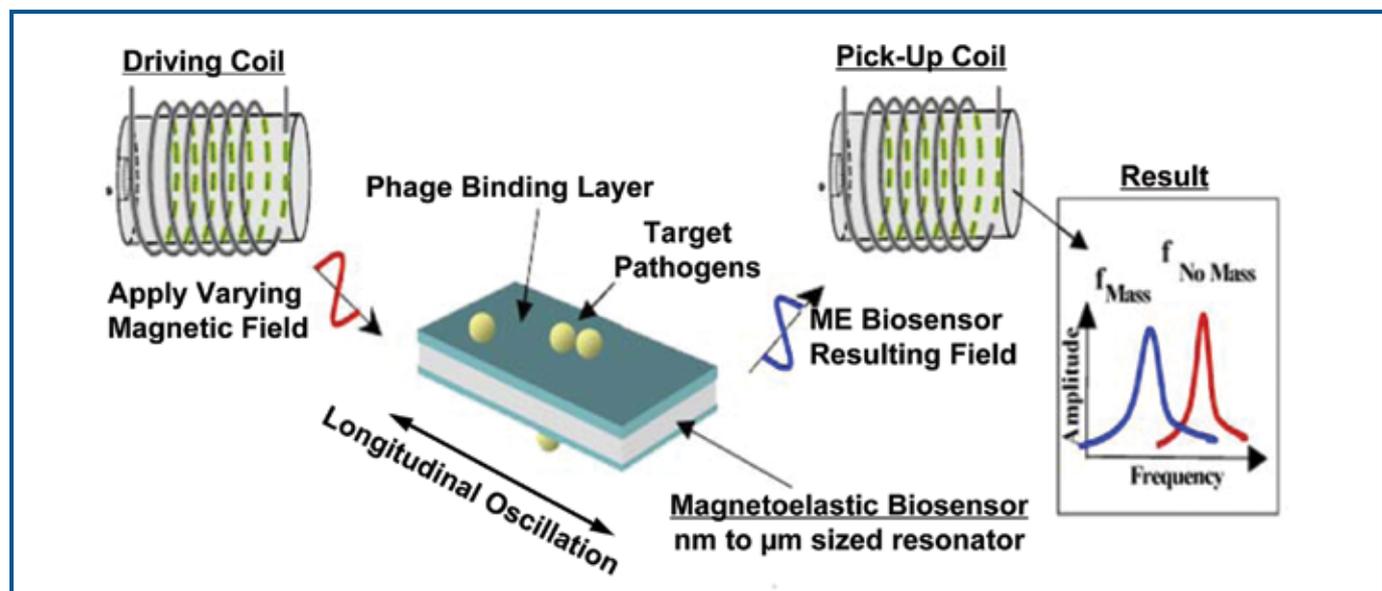
detection methods, such as culture and colony counting, polymerase chain reaction (PCR),<sup>52</sup> and antibody-based enzyme-linked immunosorbent assay (ELISA)<sup>53</sup> techniques, require the collection of many samples followed by sample preparation and analysis of the sample solutions in the lab, which are tedious and time consuming. Intensive research has been focused on developing biosensors that are capable of rapid detection of target chemicals or pathogens in the field by minimally skilled personnel.<sup>54-56</sup>

A biosensor is composed of (1.) a bio-molecular recognition element (bio-probe) that recognizes and reacts with the target pathogen, and (2.) a transducer that produces a measurable signal in response to the interaction of the bio-probe and target analyte. Bio-probes and transducers that have been explored in biosensor development have been recently well reviewed in several articles.<sup>57-60</sup> Currently, the major bioprobes are nucleic acid (DNA/RNA), proteins, enzymes, antibodies, and phages.<sup>61-63</sup> There are four main types of transducers mostly used in biosensors, namely, electrochemical transducers, optical transducers, thermal transducers, and acoustic wave (AW) devices. While the bio-molecular recognition element and its appropriate immobilization onto the sensor interface determine the specificity of a biosensor, the transducer determines the sensitivity of the biosensor. The need for high-performance biosensors have been and are still driving the investigation and development of different kinds of transducers.

In biosensor development, antibodies and peptides have long been used as biological recognition structures.<sup>64,65</sup> However, both monoclonal and polyclonal antibodies have their

limitations, such as high costs, low availability, fragility, and the need for laborious immobilization procedures. Filamentous and lytic phages as the bio-molecular recognition elements have recently attracted the attention of investigators.<sup>66-68</sup> Filamentous phages have several key advantages over antibodies. The phage structures are very robust and have strong resistance to heat (up to 80°C) and chemicals such as acid, alkali, and organic solvents.<sup>69</sup> The three-dimensional recognition surface of phage can provide multiple binding sites and hence a strong binding to target pathogens. Furthermore, phage can be produced in large quantities at a relatively low cost.<sup>70</sup> Phage-based biosensors that have been used to detect food-borne pathogens are summarized in Table I.

AW devices form an important family of highly sensitive transducers. They offer many advantages, such as a high sensitivity, low cost, ease of use, remote measurement, miniaturization, and *in situ* testing capabilities.<sup>62,71-74</sup> Recently, AW devices made of amorphous magnetostrictive materials have been investigated and explored for the development of high performance biosensors. Two types of AW devices have been developed based on magnetostrictive materials: (1.) magnetoelastic (ME) resonators,<sup>75-82</sup> and (2.) magnetostrictive microcantilevers (MSMC).<sup>83-85</sup> Figure 2 shows the principle of operation of ME biosensors. Researchers have microfabricated free-standing, phage-based ME biosensors composed of a ME resonator that is coated with genetically engineered phage that binds specifically with target pathogens (Fig. 3).<sup>86,87</sup> The ME biosensor oscillates with a characteristic resonance frequency under an applied alternating magnetic field. Once the



**Fig. 2.** Principle of operation of a magnetoelastic (ME) biosensor. A driving coil generates a modulated magnetic field that drives the ME resonator into vibrational resonance. Binding of the target bacteria to the resonator increases the mass of the resonator resulting in a decrease in resonance frequency.

biosensor comes into contact with the target pathogen, binding occurs. This binding causes an increase in the mass of the resonator resulting in a decrease of the biosensor's resonance frequency. The ME biosensors are wireless sensors and require no on-board power. The ME biosensor is inexpensive (cost of fabrication of a single microfabricated sensor is less than 1/1000 of a cent) and disposable. The ME biosensors have been successfully shown to detect various pathogens, such as *S. typhimurium*, *B. anthracis* spores, and *E. Coli*.<sup>77-81,88,89</sup> Very recently, it has been demonstrated that ME biosensors were able to directly detect bacteria on a fresh food surface without the use of a sampling process (water rinse/stomaching).<sup>90</sup>

Enzyme-based biosensors have emerged in the past decades as very promising tools for highly sensitive and discriminative detection of many chemical threat agents and food contaminants. Since highly toxic organophosphate neurotoxins (OPs) have been used extensively in the form of agricultural insecticides and chemical warfare agents, discriminative detection of OPs in agriculture products and food is very important. The main two approaches in the development of biosensors for OPs are (1.) inhibition of particular enzymes such as acetyl or butyryl cholinesterases (AChE and BChE),<sup>91-94</sup> and (2.) OPs direct hydrolysis using different hydrolases.<sup>95-99</sup>

### Wireless Sensor Networks

Due to advances in wireless technologies, wireless sensor networks have been developed, which will enable new precision in agricultural practice. Wireless sensor networks composed of radio frequency (RF) transceivers; global positioning sensors; soil, water, ion and VOC sensors; microcontrollers; and power sources have been designed and are undergoing field trials.<sup>119</sup> The development of this technology is envisioned to provide revolutionary means for observing, assessing and controlling agricultural practices. Wireless sensor network technology is still in its earliest development stage. Recent developments and future trends in wireless sensor networks have been discussed and reviewed by several authors.<sup>119-122</sup>



**Fig. 3.** Scanning electron micrograph comparing the size of a ME biosensor with the Y in "LIBERTY" on a penny. The biosensors are microelectronically fabricated and are smaller than a particle of dust. The biosensors require no on-board power and their cost is less than 1/1000 of a cent each when fabricated in large numbers.

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