



Advancements in Soil Nutrient Sensing for Real Time Nutrient Management based Recommendation System

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Abstract: Rapid soil testing and site specific nutrient management are the keys to improve agricultural production sustainably to feed the growing global population, which is projected to cross 9 billion by the end of 2050. A number of soil nutrient sensors are being developed to meet the demand. This paper is focused on the various recent developments in the field of soil nutrient sensors and their sensitivity for particular nutrients. The incorporation of these sensors to develop agriculture decision support systems is also been discussed. It may be concluded that it is better to integrate a number of sensors (optical and electrochemical) to obtain real time data on nutrient level in soil for a particular cropping season to provide the farmers with a real time report and support. Technologies to convert the results into farmer friendly reports and databases to store the real-time data are also very much essential. The entire study is summarized to have an idea of the development in the field of soil nutrient sensors globally in order to gain insights for the sustainable agricultural production in developing countries, such as India, where cost and population are the governing factors.

Keywords: Nutrient management, soil nutrient sensors, Electro-chemical sensors, sustainable agricultural production, crop specific decision support system

1. Introduction

The global population is projected to cross 9 billion by the end of 2050 (FAO, 2020) requiring the food production to increase 70% as compared to the base period in order to feed the global population. Research and development to eradicate global hunger and achieve food security has been extensively discussed and incorporated in the 17 Sustainable Development Goals (UN, 2015). The increased food demand is producing immense pressure on the available land and water resources, which is further exaggerated because of the climate change impacts. Declining the health of soil will affect the overall production in a long run. In addition to this, for the developing and underdeveloped countries, where most of the 850 million people continue to face hunger (FAO, 2020). Laboratory-based soil assessment becomes an expensive task. Farmers, therefore, practice blanket recommendations of fertilizer, mostly based on large-scale soil survey based agro-ecological zoning, rather than site specific and crop specific recommendations based on soil testing. The Imbalanced fertilizer use is one of the primary



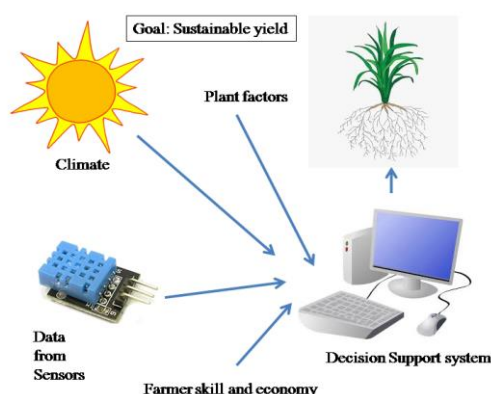
causes of soil degradation and adversely influences the environment, human health, and farm profitability.

India, being a developing country with the projection for population to cross China by the year 2025 (UN, 2015), is also facing a similar challenge to meet the food demand through sustainable agriculture. In order to boost site-specific nutrient management under the umbrella of precision farming with the long-term goal to improve soil health, the Government of India had initiated the Soil Health Card (SHC) Scheme in February 2015. SHC is a field specific detailed report of soil fertility status and other important soil parameters that affect crop productivity. It is similar to a physician's prescription, where the health status of the soil is provided and recommendations are made to the farmers accordingly (Trivedi and Dutta, 2020). Details in a SHC includes 12 important parameters such as pH, electrical conductivity (EC), organic carbon, collectively known as soil physical parameters, macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), secondary nutrients such as sulfur (S) and micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B). However, the main drawback in the preparation of SHC is soil sampling by the farmers, which is also a very crucial step for soil testing. Improper soil sampling may not represent the nutrient status of the whole field resulting in faulty recommendations and management, encouraging the farmers to revert to the cultural practices. In addition, the farmers have to waste significant amount of their cultivatable period waiting for the laboratory test results, which most of the time is incomprehensible to them. High demand and limited resources are causing delay and non-uniformity in SHC report generation in India. In order to expedite the process of soil testing, Indian Agricultural Research Institute (ICAR), New Delhi has developed a portable soil kit known as PUSA-STFR (soil test fertilizer recommendation) meter. This kit helps the farmers in testing the 12 important soil parameters mentioned in the SHC in a relatively shorter period and recommends fertilizer dose for 100 crops. Maintaining such kits in Village Community Centers can help in the periodical analysis of soil to achieve the goals of a sustainable agricultural production.

With these emerging technologies, India, despite being a large and populous country, has not only secured self-sufficiency and food security but also positioned itself as an important exporter of agriculture commodities. India is presently leading the world in the production of pulses, jute, and milk. It is also the second-largest producer of rice, wheat, sugarcane, cotton, fruits, and vegetables. However, productivity is low, with yields of all major crops lagging far behind global averages (Padmaja and Reddy, 2018). Undertaking projects that include rapid soil analysis and developing a decision support system (cloud-based using internet of things platform) which could help farmer with field level analysis of nutrient and crop is a need of the hour. With these challenges in mind, the present review consist an overall knowledge on the technologies that have been applied for nutrient analysis globally. The study might act as a guideline to check the feasibility of these techniques under Indian scenario for specific crops, keeping in mind the farm income and limitations. For example,



remote sensors for time-series data collection, drones and satellites with high-quality cameras for spatial image collection and smart phone apps for real-time control and recommendations are being adapted in developed countries to analyze data and extracted knowledge for a next-generation smart farming (Mirkouei, 2020). The entire review paper is divided into sections describing the current technologies available globally for analyzing the status of nutrient analysis from which we can gain inputs to design a decision support system for sustainable agriculture.



2. Soil Nutrient Sensors

Sensors are developed to avoid the classical procedure of time consuming and invasive wet chemistry for soil nutrient detection and to allow for quantification with minimum or no sample preparation (Tavares et al., 2021). Use of sensors in agriculture has begun long back with the measurement of transpiration rates (Briggs and Shantz, 1917). However, advancement in the precision farming and real time nutrient management started with the advancement in technology and communications to develop and transmit sensor data worldwide in a cost effective manner. The sensors are single hand-held devices, mobile (Adamchuk et al., 2004) or autonomous (Manderson and Hunt, 2013) using solar energy. Soil nutrient sensing are mostly carried out using optical, electrochemical, and/or colorimetric sensors. In addition, acoustic sensors, pneumatic sensors, electrical and electromagnetic sensors, photoelectron meters, machine vision, satellite imagery, and machine olfaction system to name a few, are suggested to detect the micro nutrient levels in soil. Elaborate reviews of various types of sensors to measure soil properties, including soil nutrients, are available in the literature (Sudduth et al., 1997; Adamchuk et al., 2004; Kim et al., 2009; Burton et al., 2020). In the following sections, we briefly discussed the recent developments in the field of soil-nutrient sensors.

2.1 Optical sensors:

Optical sensors uses reflectance spectroscopy to identify the magnitude of reflected and absorbed energy by soil nutrient ions (Burton et al. 2020) and is mostly reported for the three major nutrients,



N, P, and K in soil. There are a number of inventions using spectroscopy to detect nutrient embodied as a portable soil sensor. Bogrekci and Lee (2007) invented a portable Raman sensor for soil P detection in dry as well as wet soil. A 600 mW laser light source at 785 nm with a full width at half maximum of about 0.2 nm and a spectrometer that covers 340 and 3640 cm^{-1} was used. The program was written in Visual C++ and partial least squares analysis was used to calibrate the model. Rogovska *et al.* (2019) utilized the potential of diamond-attenuated total internal reflectance (D-ATR) Fourier Transform Infrared (FTIR) spectroscopy as a soil NO_3 sensor for rapid field-mobile determination of soil NO_3 concentrations. Zhou *et al.* (2019) developed an optical sensor for in-situ soil total nitrogen and soil moisture detection. The unit is composed of eight single band Near-infrared (NIR) laser sources at 1260, 1330, 1360, 1430, 1530, 1580, 1660 and 1450 nm. The software part of the program was written in the JN5139 microcontroller unit. Ma *et al.* (2019) also developed a multichannel, optoelectronic measurement system with automatically switching light sources that consists of peak emission wavelengths of 405 nm, 660 nm, and 515 nm, a photodiode array, and a circuit board with a MCU. They used it for the detection of N, P, and K content in six soil samples. Mukherjee and Laskar (2019) reported the design of a portable soil nutrient detector for N, P, and K based on optical sensors and microcontroller. Based on experimentation and analysis, the researchers reported 850 nm for nitrogen, 620–630 nm for phosphorous, and 460–470 nm for potassium analysis for the design. Most of these sensor devices are equipped with farm vehicles to map the variability of soil parameters while traversing the farm terrain (Shibusawa, 2003). Although optical sensors using reflectance spectroscopy changes with the nutrient content in soil, the reflectance signatures varies with the soil type making it challenging to calibrate the model for quantification. Therefore, it is challenging to obtain consistently good estimates across range of soils (Thomasson *et al.*, 2001).

2.2 Electrochemical sensors:

Electrochemical sensors use ion-selective electrodes (ISE) and ion-selective field effect transistors (ISFET) that generate a voltage or current output in response to the activity of selected ions. As the name suggests, the ion-selective field effect transistors combines the technologies ion-selective electrodes and field effect transistors. The use of ion-selective electrodes for the measurement of pH and electrical conductivity (EC) is well established and extensively used, electrochemistry is also being used for decades for the detection of other available soil nutrients for e.g. Orion nitrate ion electrode (model 92–07). Although, relatively large amount of variation are reported to present among multiple measurements of the same sample e.g. NO_3 with ion selective electrodes, these are very efficient because they have rapid response, are small and portable, and can perform on-site monitoring of a large number of soil samples (Carey and Riggan, 1994) and are being rapidly modified and developed. The electrodes are currently available for most of the important soil nutrients including NO_3 , K, sodium (Na), and calcium (Ca). However, the identification of a specific sensing material (i.e., ionophore) for the selection recognition of a specific nutrient is a challenging task, particularly



because of the interference of other similar ions present in the soil. A number of works are, therefore, dedicated towards selecting the appropriate ion-selective electrode for the particular nutrient. Kim *et al.* (2007) fabricated and validated the performance of three types of phosphate ISEs and investigated the sensitivity and selectivity responses of the electrodes when using the Kelowna soil extractant ($0.25 \text{ mol L}^{-1} \text{ CH}_3\text{COOH} + 0.015 \text{ mol L}^{-1} \text{ NH}_4\text{F}$). They observed that the cobalt rod-based electrodes exhibited the highest sensitive responses over a range of 10^{-5} to 10^{-1} mol/L (typically found in agricultural soil) of total phosphate concentration with a detection limit of 10^{-5} mol/L and a rapid response time of $<15 \text{ s}$ when tested in the Kelowna solution. In addition, the selectivity of the electrodes was satisfactory for measuring phosphates in the presence of each of six possible interfering ions, i.e., HCO_3^- , Cl^- , Br^- , NO_3^- , Ac^- , and F^- . Dam and Zevenbergen (2019) reported the development of a miniaturized sensor with a NO_3^- selective electrode for quick NO_3^- detection. It was made from a stack of AgCl electrode, screen printed on polyethylene terephthalate foil, internal electrolyte layer of cellulose gel loaded with NaNO_3 , and nitrate-selective membrane casted directly on the cellulose gel layer. The flexible electrode showed a sensitivity of $54 \text{ mV/p}[\text{NO}_3^-]$ in a nitrate concentration range from 0.1 to 100 mM showed low cross sensitivity to H_2PO_4^- , CO_3^{2-} and SO_4^{2-} (below 2.3 mV/dec). In addition to the individual ion detection, arrays of ion-selective electrodes have also been used to simultaneously detect a number of nutrients in soil solution. Kim *et al.* (2007) reported a sensor array of three different ion selective electrodes based on TDDA–NPOE and valinomycin–DOS membranes and Cobalt rod for the simultaneous determination of NO_3^- , phosphate, and K ions in soil for 37 different Missouri and Illinois soils extracted with the Kelowna extractant. Tregoning (2019) reported an elaborate study on the characterization of ion selective electrodes for on field nutrient analysis. After a number of experiments and analysis, he concluded that the N32.6 nitrate electrodes performed with reasonable selectivity for the interfering phosphate, sulfate, and carbonate ions. He also suggested that the manufacturing process needs to be updated to include conditioning the ion selective electrodes in strontium chloride to improve its stability. Choosang *et al.* (2018) reported the simultaneous detection of ammonium and nitrate in water and soil using an ion selective electrode and compared the results with colorimetric assays. They used a poly (methyl methacrylate)/poly(decyl methacrylate) copolymer as matrix materials and reported their functionality to detect NH_4^+ - and NO_3^- -selective electrodes by analyzing 8 water and 15 soil samples. The results showed excellent correlation with that obtained using colorimetric assay (Pearson's $R = 0.97$ and 0.99 for NH_4^+ - and NO_3^- ions, respectively). Smolka *et al.* (2017) developed microfluidic chip for the simultaneous detection of NO_3^- , NH_4^+ , K, and PO_4 in which the sample ions are separated in an electric field using capillary electrophoresis and the individual ion concentrations are detected by a conductivity measurement. Xu *et al.* (2016) reported a similar work. They developed an electrophoresis based microfluidic ion nutrient sensor for the detection of anions in soil solution samples using a polydimethylsiloxane-glass electrophoretic microchip. Recently, Chen *et al.* (2020) reported an all-solid-state ion selective electrode for the detection of nitrate with a



nanohybrid composite film of gold nanoparticles (AuNPs) and electrochemically reduced graphene oxide (ERGO), which illustrated a detection range from 10^{-1} to 10^{-5} M, a response time of about 10 s and a life time of about 65 days. The recent research towards the development of all-solid-state ion selective electrodes would further benefit in its miniaturization and automation as the need for an internal reference electrode will be eliminated. Zeng and Qin (2020) reported the development of a solid-contact calcium ion-selective electrode with a new inorganic redox buffer-Ag@AgCl/1-tetradecyl-3-methylimidazolium chloride (TMMCl) as the ion-to-electron transducer. An integrated all-solid-state, polymer membrane-based ion-selective-electrode was recently designed and fabricated (Chen *et al.*, 2020). The device includes an on-chip Pt pseudo-reference electrode and three independent Au working electrodes. Nitrate, potassium, and phosphate selective membranes are coated on the three electrodes independently. In addition to these three macronutrients, *i.e.*, NPK, sensors are also developed and deployed for the detection of micronutrients. Ayranci and Ak (2019) developed a pyrene-substituted poly (2,5-dithienylpyrrole)-based electrode for the sensing and detection of iron (III) ions with a detection limit of 1.73×10^{-7} M. The recent developments are a step towards achieving the required pace of nutrient detection for an improved sustainable agricultural production.

3. Soil pH based sensing of soil nutrients

The availability of various nutrients, particularly N, P, and K depends on the activity of hydronium ions in a solution. The pH electrodes were, therefore, extensively used for a rapid sensing of nutrient status in the soil and is been utilized for the development of real time soil fertility analyzers. The equivalent N, P, and K content of the soil is determined from the pH to NPK conversion chart (Reddy *et al.*, 2018) where the contents are displayed as High, Medium and Low. Although the pH to nutrient conversion chart gives the values for Sulphur (S), Calcium (Ca), Magnesium (Mg), Iron (Fe), Zinc(Zn), Iron(Fe), Manganese (Mn), Boron(B), Copper(Cu), and Molybdenum (Mo) as a function of optimal pH, however, the chart is used for the determination of the availability of N, P, K to a large extent in reported studies. On the basis of the pH values, Vadalia *et al.* (2017) proposed a system that would tests multiple soil samples and obtain an average value of nutrients for a particular field. The results would be displayed on a screen, which the farmer would enter in his mobile application to generate a soil e-fertility report. The pH based nutrient analysis was carried a step forward by devising an automated fertilization unit using analog pH sensor and Arduino. The working principle is quite simple. The difference between the ideal pH and the pH value of the soil sensed by the electrode is converted to a deficient amount of N, P, and K in soil. The exact deficient value of fertilizer is then calculated by the controller the solenoid valve is opened for the flow of the fertilizer to be pumped and sprinkled. Arduino monitors the switching operation of the solenoid valve at regular intervals to control the amount of fertilizer solution to be pumped with respect to the change in the pH. As the pH sensor



generates a voltage due to ionic reactions in millivolts, a driver circuit with an instrumentation amplifier is also used to amplify the voltage so that the controller can read it. Reddy *et al.* (2018) also developed an automatic irrigation and soil quality testing where the N, P, and K sensing was conducted using a TCS230 colour sensor. The colour ranges of the soil solution are defined using an arduino code, which runs on the output of the colour sensor to determine the pH of the soil. The equivalent NPK content of the soil is determined from the pH to NPK conversion chart.

4. Technologies to utilize the results of colorimeter for nutrient analysis

A number of studies focus on increasing the interpretation of already developed soil kits for nutrient analysis. Puno *et al.* (2017) utilized image processing and artificial neural network to determine the nutrient and pH level in soil based on the changes in the color of the chemical present in soil kits after reacting with the soil. They developed a program that will give soil pH, N, P, K, Zn, Ca, and Mg using image processing and artificial neural network using MATLAB programming environment. One of the future scopes of their work was mentioned as having a crop specific fertilizer recommendation system based on the result of the soil testing. A previous work reported by Regalado and Cruz (2016) utilized the soil test kit and used color sensors to measure the RGB values of the colors. The study also tried to eliminate the lighting and distance effect using a fixed distance from an origin. The device was composed of one digital color detector and a Light Dependent Resistor - Red Green Blue Light Emitting Diode color sensor for the color analysis of the soil. The system was microcontroller-based using Arduino and had data storage for future use. The stored data was processed using a program written in vb.net, which provided the analysis and the recommendations of fertilizer. The recommendations were given on the basis of Soil pH, Nitrogen, Phosphorus, and Potassium measured by the system. Recently, Golicz *et al.* (2019) showed that the smart phone app Akvo Caddisfly could replace the expensive reflectometers that are provided as a part of the test strips. The researchers used the app to replace the Quantofix Relax Reflectometer generally provided with Quantofix test strips and obtained satisfactory results particularly for the quantification of plant available nitrate. Moonrungssee *et al.* (2015) developed an "Android mobile phone" based colorimetric analyzer that is field deployable for faster and cheaper determination of P in soil. The classic reaction of the orthophosphate, ammonium molybdate, and potassium antimonyl tartrate to form phosphomolybdic acid that is reduced by ascorbic acid to produce the intense colored molybdenum blue was used. The picture of the solution was taken in a light tight box with LED source and a software program was written analyzing RGB color of the picture. A standard graph for P was used to quantify the P present in a particular soil solution. A recent development in the field of nutrient analysis is the development of a microfluidic environment by mixing the reagent with the sample in the micro-channels that enable the use of small volumes of reactant solutions, large surface-to-volume ratio, high efficiency, and repeatability. Dudala *et al.* (2020) mixed the Griess reagent (1% sulphanilamide and 0.1 % n-(1-



naphthyl) ethylenediamine dihydrochloride in 5% polyphosphoric acid) with filtered soil solution to detect nitrite in micro-channels using LED and photodiode. The flow control was achieved using a low-cost 3D printed syringe pump. In addition, Atmega 328P (onboard Arduino Uno) was used to integrate the subsystems and a smartphone application was built to control the system and store geotagged data.

In the above section, particulars of various sensors are given that are being developed recently with the aim of site selective nutrient management. The next step towards achieving a sustainable smart agriculture would be to incorporate the sensors into a nutrient management system.

5. Site specific nutrient management systems

Precision nutrient management and use of ion-selective electrodes to deliver exact quantity of deficient fertilizers are being practiced in hydroponics. Kim *et al.* (2013) developed a nutrient management system using ion selective electrodes to measure the concentration of N, K and Ca ion in hydroponics system and supplied the deficient nutrients. Recently, Ban *et al.* (2020) reported an improved hydroponic nutrient management system that performs fully automated 3-point calibration 24 times a day to ensure the sensitivity of the sensors. In addition, a machine learning algorithm is applied on the sensory parts to remove ion interference effect in the system. Similar site specific nutrient management strategies using calibrated sensors are required for land crop production, however, the automation would be a difficult task. In addition, a number of factors such as climate, soil characteristics, field infrastructure, and crop characteristics are required to be considered. Therefore, a proper nutrient management for a sustainable crop growth would require a complete decision support system which monitors the nutrient level regularly using sensors and incorporates the local climatic condition and crop characteristics as well. The Leibniz Institute of Vegetable and Ornamental Crops (IGZ) in accordance with the Fertilizer Ordinance 2017 published a program named "N-Expert – Fertilization Advice and Nutrient Balancing in Field Vegetable Farming" that supports growers to calculate fertilizer demand of vegetable crops and compiles nutrient balances for vegetables. It also includes an up-to-date database for information on nutrient requirements (N, P, K, and Mg) for important vegetable species. Zhang and Wen (2017) developed an internet of things (IoT) based system for the moisture and nutrient monitoring of a citrus orchard in China. The entire real-time monitoring system is divided into perception layer, network transmission layer, information service layer and application layer and the IoT platform design is applied for the system. Among these, the perception layer is mainly the data acquisition layer, which used several real time soil moisture, humidity, and nutrient sensors to create a database. According to soil moisture and nutrient status, fruit growers obtain the citrus fertilization irrigation support decision based on decision support models. The researchers are further working to reduce the cost of the entire system. Similar systems which integrates data acquisition using various state-of-the-art sensors along with the terrain, climate,



and crop properties is required to be developed in a cost effective manner, particularly for developing agriculture based countries, to achieve sustainable crop production.

6. Conclusion and remarks

This review is dedicated towards compiling the recently developed soil nutrient measurement devices and the various technologies that uses the output of these devices. It can observe that different sensors are sensitive to the measurement of different parameters in soil. For example, pH and EC are best measured using ion selective sensors. Whereas, quintoflix test strips with an android based mobile application is providing satisfactory measurement of soil NO₃ level at a low cost. Colorimeter based soil kits results are being analyzed to obtain exact quantification of many nutrients, such as P. Therefore, it is best to integrate a number of sensors to obtain real time data on nutrient level in soil for a particular cropping season to provide the farmers with a real time report and support. Bramley and Ouzman (2018) reported a very interesting study towards the attitude of growers towards the various decision support systems for nutrient recommendation in Australia. Similar surveys are quite necessary and fruitful for the proper implementation of site specific nutrient management in India as farmers are the driver force of the whole system and where cost is a major constraint.

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