Advancements in soil nutrient sensing for real time nutrient management based recommendation system

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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 realtime 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.

Key Words: Nutrient management; Soil nutrient sensors; Electrochemical sensors; Sustainable agricultural production; Crop specific decision support system

INTRODUCTION

The global population is projected to cross 9 billion by the end of 2050 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. 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. 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.

MATERIALS AND METHODS

India, being a developing country with the projection for population to cross China by the year 2025, 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 [1]. Details in a SHC includes 12 important parameters such as pH, Electrical Conductivity (EC), organic carbon, collectively known as soil physical parameters, macro-nutrients 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 cultivate 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 PUSASTER (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 [2]. 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 adopted in developed countries to analyze data and extracted knowledge for a next-generation smart farming (Figure 1) [3]. 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.

Figure 1) Gain inputs to design a decision support system for sustainable agriculture
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 [4]. Use of sensors in agriculture has begun long back with the measurement of transpiration rates [5]. 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 using solar energy. Soil nutrient sensing are mostly carried out using optical, electrochemical, and/or colorimetric sensors [6,7]. In addition, acoustic sensors, pneumatic sensors, electrical and electromagnetic sensors, photomultiplier tubes, 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 [8,9]. In the following sections, we briefly discussed the recent developments in the field of soil nutrient sensors.

Optical sensors

Optical sensors use reflectance spectroscopy to identify the magnitude of reflected and absorbed energy by soil nutrient ions 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. Bogorecki and Lee invented a portable Raman sensor for soil P detection in dry as well as wet soil [10]. 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 cm⁻¹ and 3640 cm⁻¹ was used. The program was written in Visual C++ and partial least squares analysis was used to calibrate the model. Ragoowsa utilized the potential of Diamond-Attenuated Total Internal Reflection (D-ATR) Fourier Transform Infrared (FTIR) spectroscopy as a soil NO₃ sensor for rapid field-mobile determination of soil NO₃ concentrations [11]. Zhou et al. developed an optical sensor for in situ soil total nitrogen and soil moisture detection [12]. The unit is composed of eight single band Near-Infrared (NIR) laser sources at 1260, 1330, 1360, 1430, 1530, 1580, 1660 and 1845 nm. The software part of the program was written in the JN513 microcontroller unit. TD et al. 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 [12,13]. They used it for the detection of N, P, and K content in six soil samples. Mukherjee and Laskar reported the design of a portable soil nutrient detector for N, P, and K based on optical sensors and microcontroller [14]. Based on experimentation and analysis, the researchers reported 850 nm for nitrogen, 620–630 nm for phosphorus, and 450–470 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 [15]. Although optical sensors using reflectance spectroscopy changes with the nutrient content in soil, the reflectance signatures vary 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 [16].

RESULTS

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 sensors 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, and are being rapidly modified and developed [17]. The electrodes are currently available for most of the important soil nutrients including NO₃⁻, K⁺, SO₄²⁻, Cl⁻, and calcium (Ca²⁺). 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. 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 mol L⁻¹ CH₃COOH+0.15 mol L⁻¹ NH₄Cl) [18,19]. They observed that the cobalt red-based electrodes exhibited the highest sensitivity responses over a range of 10⁻³ to 10⁻¹ mol/L (typically found in agricultural soil) of total phosphate concentration with a detection limit of 10⁻⁴ mol/L and a rapid response time of <15 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., HCO₃⁻, Cl⁻, Br⁻, NO₃⁻, PO₄³⁻, and F⁻. Dam and Zevenbergen reported the development of a miniaturized sensor with a NO₃⁻-selective electrode for quick NO₂⁻ detection. It was made from a stack of AgCl electrode, screen printed on polyethylene terephthalate foil, internal electrolyte layer of cellulose gel loaded with strontium chloride to improve its stability [18,19]. Choosang et al. reported the simultaneous detection of ammonium and nitrate in water and soil using an ion selective electrode and compared the results with colorimetric assays [20]. They used a poly (methyl methacrylate)/poly (acryl methyl methacrylate) copolymer as matrix materials and reported their functionality to detect NH₄⁺ and NO₃⁻ selective electrodes by analyzing 9 water and 15 soil samples. The results showed excellent correlation with the method that obtained using colorimetric assay (Pearson’s R=0.97 and 0.99 for NH₄⁺ and NO₃⁻, respectively). Smolka et al. developed a photonic chip for the simultaneous detection of NO₃⁻, NH₄⁺, K⁺, and PO₄³⁻ in which the sensor contents are separated in an electric field using capillary electrophoresis and the individual ion concentrations are detected by a conductivity measurement [21]. Xu et al. reported a similar work [22]. They developed an electrochemical base microfluidic ion sensor nutrient sensor for the detection of anions in soil solution samples using a poly di-methylsiloxane-glass electrophoretic microchip. Recently, Chen et al. reported an all-solidstate ion selective electrode for the detection of nitrate with a Nano hybrid composite film of gold nanoparticles (AuNP) and electrochemically reduced graphene oxide (ERGO), which illustrated a detection range from 10⁻³ to 10⁻⁴ M, a response time about of 10 s and a life time of about 65 days [23]. The current research towards the development of all-solidstate ion selective electrodes would further benefit its miniaturization and automation as is needed for an internal reference electrode will be elaborated. Zeng and Qin reported the development of a solid-state calcium ion selective electrode with a new inorganic redox buffer Ag₃AgCl/I-Tetracyclid-Methylimidazolium Chloride (TMMCl) as the ion-electrode transducer [24]. An integrated all-solid-state, polymer membrane-based ion-selective electrode was recently designed and fabricated. 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 main nutrients, i.e., NPK, sensors are also developed for NO₂⁻, phosphate-selective membrane casted directly on the cellulose gel membrane. Ayranci and Ak developed a pyrene-substituted poly (2, 5-dithienylpyrrole)-based electrode for the sensing of N, P, and K content of the soil is determined from the pH to NPK conversion chart [25]. 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, needed to be updated to include conditioning the ion selective electrodes in simulated soil conditions i.e., HCO₃⁻, Cl⁻, Br⁻, NO₃⁻, PO₄³⁻, and F⁻. 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

Soil pH based sensing of soil nutrients

The availability of various nutrients, particularly N, P, and K is a function of optimal

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pH, however, the chart is used for the determination of the availability of N, P, K to a large extent in reported studies [2]. On the basis of the pH values, Vadalia proposed a system that would test 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 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 the liquid, a driver circuit with an instrumentation amplifier is also used to amplify the voltage so that the controller can read it. Reddy et al. also developed an automatic irrigation and soil quality testing where the N, P, and K sensing was conducted using a TCS230 color sensor. The color ranges of the soil solution are defined using an arduino code, which runs on the output of the color sensor to determine the pH of the soil. The equivalent NPK content of the soil is determined from the pH to NPK conversion chart.

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. Punio et al. 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 [26]. 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 Regal ado and Cruz utilized the soil test kit and used color sensors to measure the RGB values of the colors [27]. 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 colour 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. showed that the smart phone app Alovso Caddisfly could replace the expensive reflectometers that are provided as a part of the test strips [28]. The researchers used the app to replace the Quantofox Relax Reflectometer generally provided with Quantofox test strips and obtained satisfactory results particularly for the quantification of plant available nitrate. Moorunyee et al. developed an "Android mobile phone" based colorimetric analyzer that is field deployable for faster and cheaper determination of P in soil [29]. 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 microchannels that enable the use of small volumes of reactant solutions, large surface-to-volume ratio, high efficiency, and repeatability. Dadala et al. mixed the Griess reagent (1 ± sulfanilamide and 0.1% n-(1-naphthyl) ethylenediamine dihydrochloride in 5% polyphosphoric acid) with filtered soil solution to detect nitrite in microchannels using LED and photodiode [30]. The flow control was achieved using a low-cost 3D printed syringe pump. In addition, Atmega 328 P (onboard Arduino Uno) was used to integrate the subsystems and a smartphone application was built to control the system and store geo-tagged 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.

DISCUSSION

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. 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 [19]. Recently, Ban et al. 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 [31,32]. 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 of N, P, K and Ca. A similar system that is called "N-Sensor 2017" is available in Germany. Zhang and Wei developed an Internet of Things (IoT) based system for the moisture and nutrient monitoring of a citrus orchard in China [31]. 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 uses several real-time soil moisture, humidity, and nutrient sensors to create a database [32]. According to soil moisture and nutrient status, fruit growers obtain the citrus fertilization irrigation support decision based on decision support models [33]. 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[34,35].

CONCLUSION

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 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.

DECLARATION OF COMPETING INTEREST

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.

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