SOIL MACRONUTRIENT DETECTION BASED ON VISIBLE AND NEAR-INFRARED ABSORPTION SPECTROSCOPY

KHAIRUNNISA BINTI MOHD YUSOF

UNIVERSITI TEKNOLOGI MALAYSIA

SOIL MACRONUTRIENT DETECTION BASED ON VISIBLE AND NEAR-INFRARED ABSORPTION SPECTROSCOPY

KHAIRUNNISA BINTI MOHD YUSOF

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2018

Dedicated to my beloved father and mother

MOHD YUSOF BIN HASHIM

KURSIAH BINTI TAWI

and

my brothers and sisters

for their support and encouragement.

ACKNOWLEDGEMENT

Firstly, I would like to express my gratitude and appreciation to my parents for their encouragement and support. I would like to take this opportunity to express heartfelt gratitude to my supervisor, Dr Suhaila binti Isaak for her guidance, encouragement, constant support, suggestion, patience and help to complete my project. Not forgetting to thank my co-supervisor, Dr Nor Hafizah binti Ngajikin for sharing her knowledge, support and suggestion to me over the whole duration Master studies.

Gratefulness to my fellow mate, Nurfatihah binti Che Abd Rashid for sharing the knowledge, information and cooperation to complete this project. Last but not least, I would like to acknowledge with much appreciation to all those who gave me the possibility to complete this project. I also would like to thanks to all my friends who gave me motivation, encourage and help.

ABSTRACT

Precision agriculture using cost-effective soil fertility measurement is important to obtain adequate quality and quantity of crops. Modern agriculture uses soil spectroscopy, which is a fast, cost-effective, environmentally friendly and reusable method. Soil fertility is used in modern agriculture to sustain plant growth and optimize crop yield. However, most existing light sources and computerized photodetection modules in soil spectroscopy are bulky in size, consume high power and expensive such as tungsten-halogen lamps, deuterium lamps and commercial spectrometer. This thesis proposes an improved experimental module based on absorbance spectroscopy to determine the nitrogen (N), phosphorus (P) and potassium (K) in various soil samples which are extracted using colour-developing reagent. The experimental module consisting light-emitting diode (LED) in visible and near-infrared range, and integrated passively quenched silicon photodiode. The optical absorption of various soil samples, including agricultural and non-agricultural soils are experimentally investigated in absorbance mode using an optimal wavelength range of 467 nm until 741 nm. Beer-Lambert Law (BLL) is applied to identify the relationship between the nutrient concentration and the amount of absorbed light. At a wavelength (λ) of 467 nm, N gives a coefficient of determination (R^2) between 0.49 and 0.63 for agriculture soil samples. Meanwhile, R^2 of agricultural soils for K gives a value from 0.54 to 0.73. At λ = 741nm, P produces R^2 in the range of 0.47 to 0.82. Furthermore, research findings using LED and photodiode follow the BLL. BLL states that high concentration has many chemical absorbing species which will lower the transmitted light intensity and give low output voltage. This study has shown that absorbance spectroscopy with proposed LED and photodiode modules are able to distinguish the nutrient concentration in the soil.

ABSTRAK

Pertanian teliti menggunakan kaedah mengukur tahap kesuburan tanah dengan kos yang berkesan adalah penting bagi mendapatkan kualiti dan kuantiti tanaman yang mencukupi. Pertanian moden menggunakan spektroskopi tanah merupakan kaedah yang pantas, kos berkesan, mesra alam dan boleh diguna pakai semula. Kesuburan tanah digunakan dalam pertanian moden untuk mengekalkan kadar pertumbuhan dan mengoptimumkan hasil tanaman. Walau bagaimanapun, sebahagian besar sumber cahaya sedia ada dan modul pengesanan foto berkomputer dalam spektroskopi tanah mempunyai saiz yang besar, menggunakan tenaga yang tinggi dan mahal seperti lampu tungsten-halogen, lampu deuterium dan spektrometer komersial. Tesis ini mencadangkan satu modul eksperimen yang ditambah baik dengan menggunakan spektroskopi serapan untuk menentukan nitrogen (N), fosforus (P) dan kalium (K) dalam pelbagai sampel tanah yang diekstrak dengan menggunakan reagen warna. Modul eksperimen ini terdiri daripada diod pemancar cahaya (LED) dalam julat cahaya tampak dan inframerah dekat dan pelindap pasif silikon fotodiod bersepadu. Serapan optik bagi pelbagai sampel tanah, termasuk tanah pertanian dan tanah bukan pertanian diselidik secara eksperimen dalam mod serapan menggunakan jarak gelombang optimum di antara 467 nm dan 741 nm. Hukum *Beer-Lambert* (BLL) digunakan untuk mengenal pasti hubungan antara kepekatan nutrien dan jumlah cahaya yang diserap. Pada panjang gelombang (λ) 467 nm, N memberikan pekali penentuan (R^2) diantara 0.49 dan 0.63 bagi sampel tanah pertanian. Sementara itu, R^2 untuk tanah pertanian untuk K pula memberikan nilai dari 0.54 hingga 0.73 . Pada λ = 741 nm, P menghasilkan R^2 dalam julat dari 0.47 hingga 0.82. Tambahan lagi, dapatan kajian dengan menggunakan LED dan fotodiod mengikuti BLL. BLL menyatakan bahawa kepekatan yang tinggi mempunyai spesies penyerap kimia yang banyak dimana ia akan menurunkan tahap keamatan cahaya dan memberikan voltan keluaran yang rendah. Kajian ini menunjukkan bahawa spektroskopi serapan dengan modul LED dan fotodiod yang dicadangkan dapat membezakan kepekatan nutrien di dalam tanah.

TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

N	-	Nitrogen
P	-	Phosphorus
K	-	Potassium
PA	-	Precision Agriculture
NIR	-	Near-Infrared
OM	-	Organic Matter
BLL	-	Beer-Lambert Law
T	-	Transmittance of light
I_i	-	Intensity of light before it strikes the substance
I_t	-	Intensity of light after passed through the substance
P_i	-	Power of light before it strikes the substance
P_t	-	Power of light after passed through the substance
A	-	Absorbance
ε	-	Molar absorptivity of the sample
L	-	Path length of the cuvette
C	-	Concentration of the sample

NA	-	Numerical aperture
UTM	-	Universiti Teknologi Malaysia
R^2	-	Correlation of determination
EDX	-	Energy Dispersive X-Ray
SEM	-	Scanning Electron Microscope
R_L	-	Load resistance
Wt %	-	Weight percentage
cps/eV	-	Count per second per electrode volt
$\Re_\lambda$	-	Responsivity of photodiode
V_o	-	Output voltage

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter discusses the background of the study, including soil features for agricultural plant growth, soil macronutrient, soil nutrient testing, the nutrients needed by the plants and the impact of the fertilizer amount to the plant growth and the environment. In addition, this chapter has also discussed on several types of soil sensor for measuring various soil properties. Apart from that, the identified problem that leads to this research and the objectives of this study are highlighted.

1.2 Background of Study

The soil is a natural resource which covers the uppermost of the earth's surface and act as a medium for plant roots to grow. The soil consists of minerals, organic matter (OM), living organisms, air and water for life support to the plants. Furthermore, the plant roots absorb the required amount of water and necessary minerals for growth from the soil. Soil fertility measurement is important to determine the availability of nutrients and necessary solute in the soil to ensure better quality and quantity of the crops [1-3]. The fertility level of the soil can be obtained by measuring the soil nutrients such as nitrogen (N), phosphorus (P), potassium (K), soil moisture, soil minerals and soil OM which are the important elements needed for plant growth [3-8].

Soil nutrients are divided into three categories: primary macronutrients, secondary macronutrients and micronutrients. The primary macronutrients, the essential nutrients that highly required in large quantities for plant fertilizing are nitrogen (N), phosphorus (P) and potassium (K) [2, 4, 9-11]. Soils secondary macronutrients that are composed of calcium (Ca), magnesium (Mg) and sulphur (S) are required in small quantities for the plants. Micronutrients that are needed in trivial amounts for the plant to grow in a healthy way are iron (Fe), boron (B), molybdenum (Mo), copper (Cu), chlorine (Cl), nickel (Ni), zinc (Zn) and manganese (Mn) [2, 12]. Soil nutrients are important to specify the fertility of the soil and commonly used for nutritional deficiency detection, which can affect the production and/or quality of plants [13, 14].

The nutrient content must be monitored regularly by the farmers for stabilization of the soil fertility and to control the amount of the fertilizer applications [6, 15, 16]. Excessive use of fertilizer may lead to the contamination of land surface and groundwater, reduce the harvest rate, poor quality in fruit production, and vegetable underdeveloped in colour, size and quantity [1, 4, 6, 10]. Therefore, soil nutrient measurement is needed to accurately determine the presence of nutrients in the soil and used for fertilizer applications at various soil types [4]. This test can result in efficient fertilizer usage, increase crop production at low expenditure, environment protection and product quality enhancement [11, 16].

One of the tests is known as conventional soil test which required the farmers to send the soil samples to the soil analysis laboratory and usually it will takes about four to five weeks for the result of the soil test to be released. This test requires skilled operators in the chemical processes [11, 16]. Furthermore, the sample preparation and the sample treatment process are time-consuming [9, 11-13, 16-18]. Another limitation with this conventional soil test is the cost which limits the number of soil samples analyzed per field [4, 11, 13] and the variable affecting crop yield cannot be altered and optimized in real-time [12, 13]. Thus, a rapid, cost-effective and reliable analysis of soil nutrient test should be developed to provide quality information on soil fertility in real time [19].

One of the technologies used nowadays is called precision agriculture (PA). PA is a farming management approach used in many developed countries to increase the agricultural profit by applying the farm input at the right location and in the right quantity. PA is a useful technique to monitor the soil moisture, surface temperature, photosynthetic activity, and weed and pest infestations [20]. This technique helps to improve the quality and quantity of the products, increase the efficiency of resources used and give better crop management. In addition, PA also could improve the environmental quality and reduced the soil compaction, which limits the roots grow and leads to the insufficient amount of water and nutrient uptake by the plants [1, 12, 13, 17, 20-24]. However, this technique only applicable for large farms [23], time-consuming and costly [13], and the satellite imagery is limited to cloud-free days [21]. Furthermore, this approach is complex and requires expertise to analyze the informations [25-27]. Generally, the device of PA is mounted on the tractor or pulled by the agricultural vehicle. The required instruments and technologies typically for PA are satellite positioning system, control data and transfer system, sensing system and precision application systems [28, 29]. The focus of this research is the sensing part.

Currently, there are four types of sensors have been used in PA such as the mechanical sensor, the optical sensor, the electrochemical sensor, and the electrical and electromagnetic sensor. These soil sensors are utilized to measure various soil properties including soil moisture, soil pH, soil compaction, OM detection, irrigation detection, soil conductivity, soil macronutrient detection and soil mapping.

Figure 1.1 (a) shows the mechanical sensor which usually mounted on a tractor and only capable to measure the soil physical composition and soil compaction. Secondly, an optical sensor as shown in Figure 1.1 (b) uses visible and near-infrared (NIR) light wavelength range to measure the reflectance of soil, which is assembled to the motorcycle for collection of data in real-time. In general, the optical sensor is widely used for soil spectroscopy where the spectra of absorption, reflected or transmitted light (after interacting with the sample) is captured and analyzed by a spectrometer [10, 13]. Thirdly, the electrochemical sensor uses ion-selective electrode or ion-selective field effect transistor to detect the nutrients by interacting with the nutrient ion in the soil solution. The commercial of electrochemical sensor is given in Figure 1.1 (c) that measure the soil pH level [4]. Lastly, the electrical and electromagnetic sensor as in Figure 1.1 (d) is using the electrical circuits to detect the soil texture, salinity, OM, moisture content and other parameters [4, 11, 13, 24]. Prioritizing the implementation of the sensors for the PA, the laboratory analysis should be conducted to determine the correlation between the proposed systems with the tested soil properties.

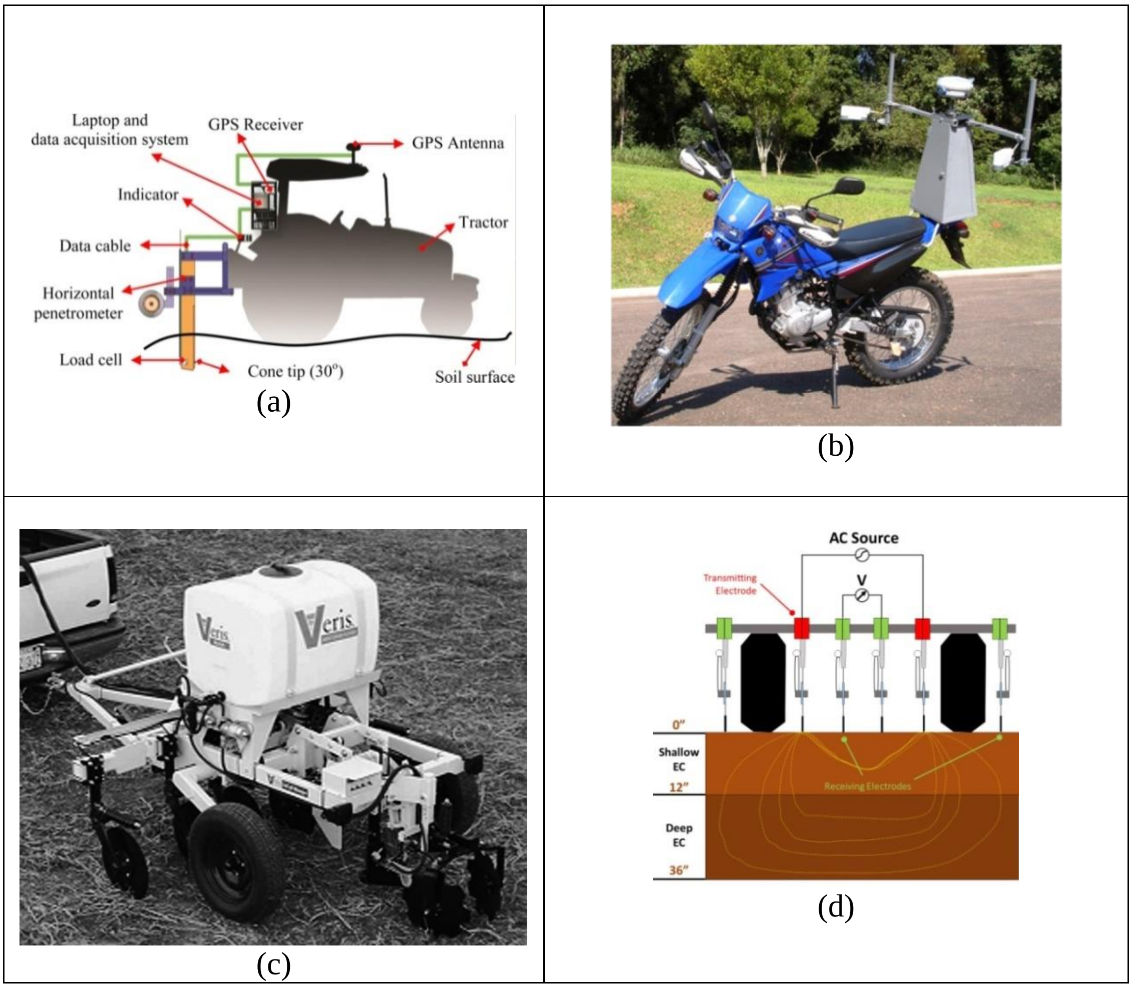

Figure 1.1: The configurations of soil sensors; (a) mechanical sensor [30], (b) optical sensor [31], (c) electrochemical sensor [4], (d) electrical and electromagnetic sensor [32]

Among the four soil sensors, the optical and electrochemical sensors are the most suitable methods to measure the soil macronutrients content [16, 22]. However, the electrochemical method is time-consuming, requires complex laboratory analysis and not suitable for in-situ evaluation due to the sensitivity towards the pressure and temperature, whereas the optical sensor is efficient, low power consumption and does not require dangerous chemical [3, 10, 13, 24]. Therefore, for this research, the optical sensor method has been chosen for soil macronutrients analysis.

Typically, the optical method usually involves the use of the spectrometer for soil spectra measurement. A spectrometer is a photometer which measures light intensity in a function of wavelength [33] and the spectroscopic technique uses an optical sensor to characterize the elements of materials according to its absorbance or reflectance at a specific wavelength. The characterization of the elements in the sample is achieved from the soil spectrum by illuminating the sample using a wide wavelength range light source and the reflected or transmitted light is sent to the spectrometer. The advantages of spectroscopic technique are rapid, convenient and non-destructive analytical technique. However, the size of commercial spectrometer (Ocean Optics spectrometer) has an approximate weight of 570 g with a dimension of 148.6 mm x 104.8 mm x 45.1 mm and costly (> RM10,000) [34]. Meanwhile, the commercial halogen light source (Ocean Optics DH-2000) is expensive (> RM5,000) with approximately 6 kg in weight and dimension of 150 mm x 135 mm x 319 mm [35]. These costs and sizes become the main limitations for in-situ measurement [36, 37].

Currently, LED is utilized extensively in instrumentations as a light source due to its compact size, low power consumption and much longer lifetime. As reported by [15], three LEDs are used which consists of green, red and infrared LEDs with wavelengths of 524 nm, 632 nm and 849 nm respectively of soil nutrient determination. Six soil nutrients that tested with various concentrations are conducted with ammonium-nitrate, nitrate-nitrogen, phosphorus, iron, manganese and calcium oxide. The nutrient extraction involves commercial soil extractions which produce coloured solution. Moreover, [1] also used three LEDs (green, red and infrared) for ammonium-nitrate, nitrate-nitrogen and phosphorus determination in ten soil samples. These nutrients are extracted chemically according to Olsen method. However, the concentration determination from colour-developed solution is completely human dependent and can lead to confusion. Besides that, the extraction process required complex chemical procedure. Apart from that, one research conducted by [6] utilized reflective method by placing a mirror at the back of the sample's cell for total internal reflection. The interest nutrients are N, P and K which have been extracted using a commercial soil kit and developed coloured-solution. Six high bright LEDs and one photodiode are constructed in concentric configuration and dipped into the chemical cell containing the extracted samples. The proposed sensor involves longer path length and using reflective mode, which causing more interaction of light with the samples and a portion of the reflected light is loss to the surrounding. In this thesis, an absorbance spectroscopy is utilized using LEDs and photodiode to develop a convenience, miniaturize and low-cost soil macronutrients sensor by employing commercial colour reagent which required simple extraction preparations.

Absorption spectroscopy is a technique to measure the existing elements in the samples by measuring the absorbed radiation of the elements. Each atom absorbs UV, visible or NIR light and release the energy. The amount of energy is measured in the form of photons absorbed by the sample. Each element emits a specific spectral line and has a distinct pattern of the wavelength of the absorbed energy. This happens because of the unique configuration of electrons in its outer shell. The absorption spectroscopic technique is a reliable method to analyze any type of materials. However, the measurement of solid sample must be in liquid form for data analysis. Therefore, the soil samples must be liquefied by the extraction method [38].

1.3 Problem Statement

Nowadays, the soil fertility measurement is important before any cultivation or plantation takes place. One of the fertility measurements is known as soil nutrient analysis. The nutrients availability in the soil is identified at various locations. Precision agriculture (PA) is the technology used to determine various soil properties and only suited to be used in large farm areas. In the undeveloped country, the application of PA is costly and complex. Besides, the conventional method which required the farmers to send their soil samples across the field to the soil analysis laboratory can be expensive and time-consuming depending on the number of samples and nutrients [9, 13]. In order to overcome the drawbacks, the optical method which is rapid, simple and cost-effective soil analysis utilizing LEDs as excitation light and silicon (Si) photodiode as the detector is proposed.

Moreover, the soil is a complex and natural resource that consists of various organisms and elements. To analyze the nutrient contained in the soil, the nutrient extraction should be conducted prior to soil nutrients measurement. In this research, the extraction of nutrients is carried out using commercial colour-developing reagent where the reaction between the reagent and the sample will form a specific coloured solution according to the concentration of the nutrients in the samples. The evaluation of coloured solution or concentration level will fluctuate according to the human eyes [1, 15]. Therefore, an absorbance spectroscopy is proposed to overcome the problems in improving the accuracy of concentration level evaluation.

1.4 Research Objectives

The objectives of this research are:

1. To analyze the absorbance of various soil samples in visible and near-infrared (NIR) light range using colour-developing reagent.
2. To characterize the performance of Si photodiode in absorption spectroscopy (between 200 nm and 1100 nm) using light-emitting diode (LED) light source.

1.5 Scope of Research

This research is conducted to measure the concentration level of soil macronutrients on two types of samples consists of agricultural soils and non-agricultural soils. The interest soil macronutrients are nitrogen (N), phosphorus (P) and potassium (K) have been extracted using commercial colour-developing reagent. The reagent will react with the nutrients and produce specific coloured solution depending on the nutrient content in the samples.

Initially, the extracted nutrients are analyzed using commercial halogen light sources and commercial spectrometer for absorbance measurement. This system is measured in visible and NIR wavelength range between 400 nm and 1100 nm. Apart from that, the utilization of LED and Si photodiode in replacing the usage of commercial halogen light source and spectrometer is carried out. Four wavelengths of LEDs are used, including blue, green, red and NIR LEDs with a center wavelength of 467 nm, 530 nm, 634 nm and 741 nm respectively. The Si photodiode works in the wavelength range of 200 nm until 1100 nm. LED and the photodiode is chosen for soil macronutrients detection due to the compact size, easy to implement for a portable device, inexpensive and mechanically robust [15, 36, 39]. Furthermore, photodiode is one of the components in the spectrometer module.

Generally, the principle of this research followed Beer-Lambert law by illuminating the samples using halogen light or LED in a cuvette and the transmitted light (after interact with the samples) is detected by the photodiode. Simultaneously, the transmitted power is measured using an optical power meter. Besides that, the performance of current-voltage (IV) characteristics of the photodiode is analyzed for soil spectroscopy analysis.

1.6 Significance of the Study

In this study, two types of soil samples consist of agricultural soils and non-agricultural soils are used. The non-agriculture soil samples are chosen to identify the potential commercial soil for agricultural cultivation. To conduct the soil nutrient analysis, soil nutrient extraction should be executed, importantly because the soil is complex and with the natural resources that consist of many living organisms and minerals. The extraction of soil nutrients is conducted using colour-developing reagent to identify the concentration of nutrients in the soil samples. From the reagent, a specific colour solution is formed according to the nutrient contents. The wavelength of each nutrient in the Vis-NIR wavelength range (from 400 nm until 1100 nm) is identified for further data measurement. Moreover, the proposed method for soil macronutrients content measurements using LEDs and Si photodiode based on absorption spectroscopy is executed.

1.7 Overview of the Thesis

This thesis has five main chapters, each of them dealing with a different aspect. Chapter one discusses the background of the research study, the research objectives and the motivation to achieve the research objective. In this chapter, the organization of the thesis is also given.

Chapter two is the literature review of the theory used for this research. It focuses the information about the soil physical characteristics and the importance of soil macronutrients for plant growth. In addition, the soil sensors for various soil parameters are explained. Besides that, the spectroscopic technique used for soil spectroscopy is discussed.

Chapter three describes the methodology to carry out the research. This chapter is divided into three parts. Part one is the preliminary test using the commercial Vis-NIR light sources to measure and identify the absorbance level and wavelength of nutrients across the wide wavelength range. Part two is the absorbance measurement of soil samples using LEDs and a spectrometer. Finally, part three consists of measurements with LEDs and Si photodiode.

The fourth chapter is discussing regarding the results and discussion obtained from the conducted experiments. All relevant figures, graphs and tabulated data are highlighted in this chapter.

Chapter five is briefly summarized about the research achievement. In addition, several recommendations are provided for further improvement and continuation for future development.

REFERENCE

1. Adhikary, T., et al., *Test Implementation of a Sensor Device for Measuring Soil Macronutrients*, in *IEEE*. 2015, IEEE: International Conference on Networking System and Security (NSysS) 2015.
2. Mussa, S.A.B., et al., *Determination of Available Nitrate, Phosphate and Sulfate in Soil Samples.* International Journal of PharmTech Research, 2009. **1**(3): p. 598-604.
3. Du, C. and J. Zhou, *Evaluation of Soil Fertility Using Infrared Spectroscopy: A Review.* Environmental Chemistry Letter, 2009. **7**(2): p. 97-113.
4. Kim, H.-J., K.A. Sudduth, and J.W. Hummel, *Soil Macronutrient Sensing for Precision Agriculture.* Journal of Environmental Monitoring, 2009. **11**: p. 1810-1824.
5. Lu, C., et al., *Analysis of Total Nitrogen and Total Phosphorus in Soil using Laser-Induced Breakdown Spectroscopy.* Chinese Optics Letters, 2013. **11**(5): p. 053004.
6. Ramane, D.V., S.S. Patil, and A.D. Shaligram, *Detection of NPK Nutrients of Soil using Fiber Optic Sensor*, in *International Journal of Research in Advent technology Special Issue National Conference "ACGT 2015"*. 2015. p. 66-70.
7. Askari, M.S., et al., *Evaluation of Soil Structural Quality using VIS-NIR Spectra.* Soil & Tillage Research, 2014. **146**: p. 108-117.
8. Troeh, F.R. and L.M. Thompson, *Soils and Soil Fertility*. Sixth Edition ed. 2005, Denver: Blackwell Publishing.
9. He, Y., et al., *Prediction of Soil Macronutrients Content Using Near-Infrared Spectroscopy*. Computers and Electronics in Agriculture, 2007. **58**: p. 144-153.
10. Sankpal, A. and K.K. Warhade, *Review of Optoelectronic Detection Methods for The Analysis of Soil Nutrients.* International Journal of Advanced Computing and Electronics Technology, 2015. **2**(2): p. 26-31.
11. Bansod, S.J. and S. Thakre, *Near-Infrared Spectroscopy based Soil Nitrogen Measurement - A Review.* International Journal of Current Engineering and Technology, 2014. **4**(1): p. 268-272.

12. Diaz, D., D.W. Hahn, and A. Molina, *Evaluation of Laser-Induced Breakdown Spectroscopy (LIBS) as a Measurement Technique for Evaluation of Total Elemental Concentration in Soils.* Applied Spectroscopy, 2012. **66**(1): p. 99-106.
13. Bah, A., S.K. Balasundram, and M.H.A. Husni, *Sensor Technologies for Precision Soil Nutrient Management and Monitoring.* American Journal of Agricultural and Biological Sciences, 2012. **7**(1): p. 43-49.
14. Jr., D.S., et al., *Laser-induced Breakdown Spectroscopy for Analysis of Plant Materials: A Review.* Spectrochimica Acta Part B, Elsevier, 2012. **71-72**: p. 3-13.
15. Yokota, M., T. Okada, and I. Yamaguchi, *An Optical Sensor for Analysis of Soil Nutrients by Using LED Light Source.* Measurement Science and Technology, 2007. **18**: p. 2197-2201.
16. Bansod, S.J. and S.S. Thakare, *Near-Infrared Spectroscopy Based a Portable Soil Nitrogen Detector Design.* International Journal of Computer Science and Information Technologies, 2014. **5**(3): p. 3953-3956.
17. Song, H., Y. he, and Annia. *A New Approach to Detect Soil Nutrient Content Based on NIR Spectroscopy Technique*. in *Engineering in Medicine and Biology*. 2005. Shanghai, China: IEEE.
18. Wang, Y., et al., *Soil pH Value, Organic Matter and Macronutrients Contents Prediction Using Optical Diffuse Reflectance Spectroscopy.* Computers and Electronics in Agriculture, 2014(111): p. 69-77.
19. Maleki, M., et al., *Phosphorus sensing for fresh soils using visible and near-infrared spectroscopy.* Biosystems Engineering, 2006. **95**(3): p. 425-436.
20. Herring, D., *Precision Farming*, R. Simmon, Editor. 2001, Earth Observatory
21. Mulla, D.J., *Twenty Five Years of Remote Sensing in Precision Agriculture: Key Advances and Remaining Knowledge Gaps.* Biosystems Engineering, 2013. **114**: p. 358-371.
22. Kulkarni, Y., K.K. Warhade, and S. Bahekar, *Primary Nutrients Determination in the Soil Using UV Spectroscopy.* International Journal of Emerging Engineering Research and Technology, 2014. **2**(2): p. 198-204.
23. Liaghat, S. and S.K. Balasundram, *A Review: The Role of Remote Sensing in Precision Agriculture.* American Journal of Agricultural and Biological Sciences, 2010. **5**(1): p. 50-55.

24. Adamchuk, V.I., et al., *On-the-go Soil Sensors for Precision Agriculture.* Computers and Electronics in Agriculture, 2004. **44**: p. 71-91.
25. Reuter, H.I. and K.C. Kersebaum, *Applications in Precision Agriculture*, in *Geomorphometry Concepts, Software, Applications*, T. Hengl and H.I. Reuter, Editors. 2009, Elsevier: Hungary. p. 623-636.
26. Maia, R.F., I. Netto, and A.L.H. Tran, *Precision Agriculture Using Remote Monitoring Systems in Brazil*, in *Global Humanitarian Technology Conference (GHTC)*. 2017: San Jose, USA.
27. Wachowiak, M.P., et al., *Visual Analytics and Remote Sensing Imagery to Support Community-Based Research for Precision Agriculture in Emerging Areas.* Computers and Electronics in Agriculture, 2017. **143**: p. 149-164.
28. Comparetti, A., *Precision Agriculture: Past, Present and Future*, in *International scientific conference "Agricultural Engineering and Environment - 2011"*. 2011: Akademija, Kaunas district, Lithuania.
29. Stafford, J.V., *The Role of Technology in the Emergence and Current Status of Precision Agriculture*, in *Handbook of Precision Agriculture: Principles and Applications*, A. Srinivasan, Editor. 2006, Food Products Press: United States of America. p. 19-56.
30. Topakci, M., et al., *Design of a Horizontal Penetrometer for Measuring On-The-Go Soil Resistance.* Sensors, 2010. **10**: p. 9337-9348.
31. Povh, F.P. and W.d.P.G.d. Anjos, *Optical Sensors Applied in Agricultural Crops*, in *Optical Sensors - New Developments and Practical Applications*, M. Yasin, S.W. Harun, and H. Arof, Editors. 2014, InTech. p. 141-163.
32. Hawkins, E., J. Fulton, and K. Port, *Using Soil Electrical Conductivity (EC) To Delineate Field Variation*, in *Agriculture and Natural Resources*. 2017: Ohio State University.
33. Hamzah, H.H., et al., *Spectrophotometric Determination of Uric Acid in Urine Based-Enzymatic Method Uricase with 4-Aminodiphenylamine Diazonium Sulfate (Variamine Blue RT Salt).* Journal of Analytical & Bioanalytical Techniques, 2013. **S7**(011).
34. Optics, O. *HR4000CG-UV-NIR.* Available from: https://oceanoptics.com/product/hr4000cg-uv-nir/.
35. Optics, O., *DH-2000 Deuterium-Halogen Light Source Installation and Operation Manual*. 2017, A Halma Company.

36. Aenugu, H.P.R., et al., *Near Infra-Red Spectroscopy - An Overview*. International Journal of ChemTech Research, 2011. **3**(2): p. 825-836.
37. Rashid, N.C.A., et al., *Optical Fiber Loss Analysis for an Application of Spectrophotometer System*. Jurnal Teknologi, 2017. **79**(5): p. 63-68.
38. Garcia, R. and A.P. Baez, *Atomic Absorption Spectrometry (AAS)* in *Atomic Absorption Spectroscopy*, D.M.A. Farrukh, Editor. 2012, In Tech: Croatia.
39. Yeh, T.-S. and S.-S. Tseng, *A Low Cost LED-Based Spectrometer*. Chinese Chemical Society Taipei, 2006. **53**(5): p. 1067-1072.
40. Sen, I., *Spectroscopic Determination of Major Nutrients (N, P, K) of Soil*, in *Food Engineering Department*. 2003, Izmir Institute of Technology Turkey. p. 116.
41. Pearson, C.J., D.W. Norman, and J. Dixon, *Physical Aspects of Crop Productivity*, in *Sustainable Dryland Cropping in Relation to Soil Productivity*. 1995, Food and Agriculture Organization.
42. McMullen, B., *Features of Soil*, in *SOILpak for Vegetable Growers*, A. Munroe, Editor. 2000, NSW Agriculture: New South Wales.
43. Chaudhari, A.I. and A.D. Shaligram, *Development of Fiber Optic pH Meter Based on Colorimetric Principle*. Indian Journal of Pure & Applied Physics, 2002. **40**: p. 132-136.
44. Jones, C. and K. Olson-Rutz, *Plant Nutrition and Soil Fertility*. 2016: Montana State University.
45. Yost, R.S. and R. Uchida, *Interpreting Oil Nutrient Analysis Data*, in *Plant Nutrition Management in Hawaii's Soil, Approaches for tropical and Subtropical Agriculture*, J.A. Silva and R. Uchida, Editors. 2000, University of Hawaii, Manoa. p. 87-89.
46. Pearson, C.J., D.W. Norman, and J. Dixon, *Biological and Chemical Aspects of soil productivity*, in *Sustainable Dryland Cropping in Relation to Soil Productivity*. 1995, Food and Agriculture Organization.
47. *Spectrophotometry Absorption Measurement & Their Application to Quantitative Analysis*. 2005.
48. Hussain, T., et al., *Measurement of Nutrients in Green House Soil with Laser Induced Breakdown Spectroscopy*. Environmental Monitoring Assessment, 2007. **124**: p. 131-139.

49. Uchida, R., *Essential Nutrients for Plant Growth: Nutrient Functions and Deficiency Symptoms*, in *Plant Nutrient Management in Hawaii's Soil, Approaches for Tropical and Subtropical Agriculture*, J.A. Silva and R. Uchida, Editors. 2000: University of Hawaii, Manoa. p. 31-55.
50. Matias, F.A.A., M.M.D.C. Vila, and M. Tubino, *A Simple Device for Quantitative Colorimetric Diffuse Reflectance Measurement.* Sensors and Actuators B: Chemical, 2003. **88**(1): p. 60-66.
51. Dimkpa, C., et al., *Methods for Rapid Testing of Plant and Soil Nutrients*, in *Sustainable Agriculture Reviews*. 2017, Springer.
52. Walker, D., *Chemical Reactions*, ed. H. Brown. 2007, China: Evans Brothers.
53. Keeler, J. and P. Wothers, *Why Chemical Reactions Happen*. 2005, Great Britain: Oxford University Press.
54. LaMotte. *NPK Soil Test Kit*. Available from: http://www.lamotte.com/en/education/soil-testing/3-5880.html.
55. Program, T.G.L.a.O.t.B.t.E.G.
56. Srinivasan, A., *Precision Agriculture: An Overview*, in *Handbook of Precision Agriculture: Principles and Applications*, A. Srinivasan, Editor. 2006, Food Products Press: United States of America. p. 3-18.
57. Kweon, G. and C. Maxton, *Soil Organic Matter Sensing with an On-The-Go Optical Sensor.* Biosystems Engineering, 2013. **115**: p. 66-81.
58. Svanberg, S., *Atomic and Molecular Spectroscopy: Basic Aspects and Practical Applications*, ed. P.D.G. Ecker, et al. 2012, Berlin: Springer-Verlag.
59. Nilapwar, S.M., et al., *Absorption Spectroscopy*, in *Methods in Enzymology*. 2011, Elsevier: United State of America. p. 59-75.
60. Dasgupta, P.K., et al., *Light Emitting Diode Based Flow-Through Optical Absorption Detectors* Talanta, 1993. **40**(1): p. 53-74.
61. Harvey, D., *Spectroscopic Method*, in *Analytical Chemistry 2.0*. 1999. p. 543-664.
62. Mignani, A.G., et al., *Diffuse-Light Absorption Spectroscopy by Means of A Fiber Optic Supercontinuum Source - An Innovative Technique*, in *Sensors and Microsystems*, P. Malcovati, et al., Editors. 2010, Springer.
63. Barthes, B.G., et al., *Determination the Distribution of Soil Carbon and Nitrogen in Particle Size Fractions Using Near-Infrared Reflectance*

Spectrum of Bulk Soil Samples. Soil Biology & Biochemistry, 2008. **40**: p. 1513-1537.

64. Guerrero, C., R.A.V. Rossel, and A.M. Mouazen, *Special Issue 'Diffuse Reflectance Spectroscopy In Soil Science And Land Resource Assessment'.* Geoderma, 2010. **158**(1-2): p. 1-2.

65. Rossel, R.A.V., et al., *Visible, Near Infrared, Mid Infrared Or Combined Diffuse Reflectance Spectroscopy For Simultaneous Assessment Of Various Soil Properties.* Geoderma, 2006. **131**(1-2): p. 59-75.

66. Barthès, B.G., et al., *Determination of total carbon and nitrogen content in a range of tropical soils using near-infrared spectroscopy: influence of replication and sample grinding and drying.* Journal of Near Infrared Spectroscopy, 2006. **14**(5): p. 341-348.

67. Islam, K., B. Singh, and A. McBratney, *Simultaneous Estimation of Several Soil Properties by Ultra-Violet, Visible, and Near-Infrared Reflectance Spectroscopy.* Australian Journal of Soil Research, 2003. **41**: p. 1101-1114.

68. Soriano-Disla, J.M., et al., *The Performance of Visible, Near-, and Mid-Infrared Reflectance Spectroscopy for Prediction of Soil Physical, Chemical, and Biological Properties.* Applied Spectroscopy Reviews, 2014. **49**: p. 139-186.

69. Hardesty, J.H. and B. Attili, *Spectrophotometry and the Beer-lambert Law: An Important Analytical Technique in Chemistry*. 2010, Collin College.

70. Lau, K.-T., et al., *A Low-Cost Optical Sensing Device based on Paired Emitter-Detector LEDs*. 2005, Mitsubishi Electric Research Laboratories: Cambridge, Massachusetts.

71. Khopkar, S.M., *Basic Concepts of Analytical Chemistry*. Second Edition ed. 1998, New Delhi: New Age International (P) Limited.

72. Technologies, C. *Useful Formula*. 2017; Available from http://www.microspectra.com/support/usefulformulas.

73. Mohamad, M. and H. Manap, *The Optimal Absorption of Bilirubin Using an Optical Fiber Sensor.* Asian Research Publishing Network (ARPN) Journal of Engineering and Applied Sciences, 2015. **10**(19): p. 8762-8764.

74. Parnis, J.M. and K.B. Oldham, *Beyond the Beer-Lambert Law: The Dependence of Absorbance on Time in Photochemistry.* Journal of Photochemistry and Photobiology A: Chemistry, 2013. **267**: p. 6-10.

75. HAUSER, P.C., T.W.T. RUPASINGHE, and N.E. CATES, *A Multi-Wavelength Photometer Based on Light-Emitting Diode.* Elsevier Science, 1995. **42**(4): p. 605-612.

76. Hauser, P.C., T.W.T. Rupasinghe, and R. Tan, *A Simple Photometer Based on a New Tri-Colour Light-Emitting Diode.* Chimia, 1995. **49**: p. 492-494.

77. Santos, V.B.d., et al., *A Low-Cost Portable Microcontrolled Nephelometer for Potassium Determination.* Journal of the Brazilian Chemical Society, 2011. **22**(4): p. 726-735.

78. Kim, J.-S., et al., *Simple LED Spectrophotometer For Analysis of Color Information.* Bio-Medical Materials and Engineering, 2015. **26**: p. S1773–S1780.

79. Gombár, M., et al., *Construction of a Photochemical Reactor Combining a CCD Spectrophotometer and a LED Radiation Source.* Photochemical & Photobiological Sciences, 2012. **11**: p. 1592-1595.

80. Degner, M., H. Ewald, and E. Lewis, *LED-Based Spectroscopy – a Low-Cost Solution for High-Resolution Concentration Measurements e.g. for Gas Monitoring Applications*, in *5th International Conference on Sensing Technology*. 2011, IEEE. p. 145-150.

81. Wego, A., *Accuracy Simulation of an LED Based Spectrophotometer.* Optik-International Journal of Light and Electron Optics, 2013. **124**(7): p. 644-649.

82. Rajak, A., et al., *A Simple Spectrometer using Various LEDs and a Photodiode Sensor for Photocatalytic Performance Evaluation.* Applied Mechanics and Materials, 2015. **771**: p. 17-20.

83. Stewart, A.G., et al., *Study of the Properties of New SPM Detectors.* Proceedings of SPIE - The International Society for Optical Engineering, 2006. **6119**.

84. Charbon, E., *Single-photon imaging in complementary metal oxide semiconductor processes.* Royal Society Publishing, 2014.

85. Sze, S.M. and K.K. Ng, *Physics of Semiconductor Devices*. 3rd ed. 2007, Hoboken, New Jersey: John Wiley & Sons.

86. *Si Photodiode*. Hamamatsu Photonics. p. 1-26.

87. *Measurement of Photodetectors*, in *Excercise 10: Laboratory of Optoelectronics*. Technical University of Lodz.

88. Piprek, J., *Introduction to Optoelectronic Devices Principles*, in *Introduction to Organic Electronics and Optoelectronic Materials*, S.-S. Sun and L.R. Dalton, Editors. 2008, CRC Press: United States of America. p. 25-46.
89. O'Toole, M. and D. Diamond, *Absorbance Based Light Emitting Diode Optical Sensors and Sensing Devices.* Sensors, 2008. **8**: p. 2453-2479.
90. Optics, O., *Fibers and Probes*.
91. Scientific, H., *A Guidebook to Particular Size Particles*. 2012.
92. Wang, C., et al., *Temperature and Soil Moisture Interactively affected Soil Net N Mineralization in Temperate Grassland in Northern China.* Soil Biology & Biochemistry, 2006. **38**: p. 1101-1110.
93. Milliken, R.E. and J.F. Mustard, *Estimating the Water Content of Hydrated Minerals Using Refelctance Spectroscopy II. Effects of Particle Size.* Icarus, 2007. **189**: p. 574-588.
94. Rashid, A.S.A., et al., *Development of Sustainable Masonry Units from Flood Mud Soil: Strength and Morphology Investigations.* Construction and Building Materials, 2016. **131**: p. 682-689.
95. Raftari, M., et al., *Evaluation of Kaolin Slurry Properties Treated with Cement.* Measurement 2014. **50**: p. 222-228.
96. Pauzi, S.A., *A Cullet-Kaolin Ceramic From Recycle Glass*, in *Faculty of Science*. 2011, Universiti Teknologi Malaysia: Malaysia. p. 107.
97. *SLS201L(/M)/ SLS202L(/M) Stabilized Tungsten Light Sources: User Guide*. Thorlabs. p. 21.
98. Samanta, S.S., *A Hand-Held Device for Non-Invasive Assessment of Beef Quality*, in *Electrical and Computer Engineering*. 2014, University of Alberta.
99. Marcus, T.C.E., et al., *Transmittance Optimization for high Sensitivity Ozone Concentration Measurement.* Sensors and Actuators B: Chemical, 2016(229): p. 528-533.
100. Tkachenko, N.V., *Steady State Absorption Spectroscopy*, in *Optical Spectroscopy: Methods and Instrumentation*. 2006, Elsevier: United Kingdom. p. 89-106.
101. *Si Photodiode*. 2017, Thorlabs. p. 4.
102. Nocita, M. and A. Stevens, *Soil Spectroscopy: An Alternative to Wet Chemistry for Soil Monitoring.* Advances in Agronomy, 2015. **132**: p. 1-21.

103. Ji, Y., et al., *Negative Absorption Peaks in Ultraviolet–Visible Spectrum of Water*. ChemistrySelect, 2016. **1**(13): p. 3443-3448.
104. McCauley, A., C. Jones, and K. Olson-Rutz, *Soil pH and Organic Matter*, in *Nutrient Management*. 2017, Montana State University.
105. McFarland, M.L., et al., *Managing Soil Acidity*. Texas A&M University.
106. Jr., J.B.J., *Plant Nutrition and Soil Fertility Manual*. 2012, USA: CRC Press.
107. Narayana, B. and K. Sunil, *A Spectrophotometric Method for the Determination of Nitrite and Nitrate.* Eurasian Journal of Analytical Chemistry, 2009. **4**(2): p. 204-214.
108. Al-Azzawi, A., *Light and Optics: Principles and Practices*. 2007, United State: CRC Press.
109. Foster, N.W. and J.S. Bhatti, *Forest Ecosystems: Nutrient Cycling*, in *Encyclopedia of Soil Science*, R. Lai, Editor. 2006, Taylor & Francis Group: Ohio, USA.
110. Thorlabs, *Si Photodiode*. 2017. p. 4.