International Journal Of Public Mental Health And Neurosciences
ISSN: 2394-4668
(An Official publication of Sarvasumana Association)

Developing Fluorescence-Based Optical Biosensors for Quantification of Soil Nutrients

Initiative Towards Effective Soil Nutrient Management

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Abstract**—** *Fluorescence based optical biosensors which are integrated with the Internet of Things (IoT) technology presents the developmental approach to the tracking of real-time plant nutrients. This research focuses on developing the Optical biosensors to enhance agricultural productivity by altering and perfecting the fertilizer use and field testing them. These biosensors will observe the nutrient and will provide the data through the user interface. This paper aims to discuss the design, materials required, methodology used and the outcome of this innovative solution, which aims to address the issues like soil nutrient management challenges and support the sustainable agricultural practices.*

Index Terms **— Fluorescence, optical biosensors, real-time nutrient monitoring, IoT.**

I. INTRODUCTION

The agricultural productivity is heavily influenced by soil nutrient levels, and well-regulated systematic nutrient management is necessary for the optimal crop yields. Traditional methods for soil nutrient analysis are generally time consuming and the laboratory facilities are required, limiting their practical application for real-time monitoring. It has guided to the investigation of the newest and modern technologies like fluorescence-based biosensors which provides prominent sensitivity and preciseness for the detection of various analytes or specimens [1]. Combining these fluorescence-based biosensors with the IoT technology, we can be able to provide the farmers with the real-time data on the soil nutrients, making possible the accurate use of the fertilizers application and thus improving the crop nutrient management [2].

The fluorescence-based biosensors have the fluorophores which emits the light upon the excitation by the stimulus, which permits them for the detection and quantification of the specific nutrients in the soil. By combining them with the IoT modules these sensors can transmit the data to the cloud-based platforms allowing them for remote surveillance and analysis [3]. This combination guarantees the steady flow of the information from fields to farmers, assisting prompt and well-informed decision making. These technologies are essential for the modern precision agriculture, which relies on the accurate and real-time data to optimize the inputs and improve the yields [4]. Additionally, the use of nanomaterials in these sensors enhances their accuracy, sensitivity and specificity, making them ideal for detecting the low concentration of the soil nutrients [5].

The generation, advancement and the distribution of these biosensors may lead to the significant advancement in the agricultural productivity and sustainability. When the farmers are provided with the accurate information about the soil nutrient composition and concentration, they can make the reasonable decisions about the use of fertilizers allowing them reducing the waste and environmental impact [6]. In addition, the ability to monitor of these biosensors allows them for the rapid response to the changing condition of the soil, which in turn will improve the crop management practices. This research aims to create and implement a system of fluorescence-based optical biosensors for monitoring the plant nutrient in real-time, which will address the urgent need for sustainable and productive agricultural practices. The objectives of this research are –

- Develop and manufacture the biosensors which are able to detect the nutrient content in soil.
- Enable the real-time data transmission and remote tracking with the help of IoT modules.
- Conduction of extensive field test to determine the performance and dependency of the sensors.
- Provide farmers with resources to regulate the fertilizer use and improve crop yields.

II. Materials and Methodology

Materials used

- Fluorophores: Fluorescein, Rhodamine, Quantum dots
- Bioreceptors:
- Optical Components: Single mode Wi-fi module
- Transducers: Photodetectors, CCDs
- Microfluidic Chips: PDMS, Glass
- Electronic Conductors: Microcontrollers (Raspberry Pi 4 Module B), Data acquisition systems
- IoT modules: Wi-Fi module, Arduino Uno, Raspberry Pi 4
- Binding agents: (3-Aminipropyl)triethoxysilane (APTES)
- Solvent: Ethanol, deionized water
- Equipments: Spin coater, fluorescence spectrometer, optical fiber cleaver, fiber optic fusion splicer, optical power meter, analytical balance, pH meter, conductivity meter
- Data analysis software: Python, R Language

Methodology

1. Design and development of the sensor

1.1. Preparation of Sensor Surface

- Clean both the sides of glass slide thoroughly by using ethanol and deionized water and then dry them under the nitrogen flow
- Coat the glass slides in ethanol with (3-Aminopropyl)triethoxysilane (APTES) so that the amino groups are added to it for binding of fluorophores. Incubate it for an hour. Rinse it with ethanol and let it dry [7].

1.2. Immobilizing Fluorophore

- Dissolve the fluorophores (fluorescein for nitrates, rhodamine B for phosphate & quantum dots for potassium) in the phosphate-buffered saline such that the final concentration reaches 10 µM.
- The prepared fluorophore solution is drop-casted on the APTES-treated slides. Incubate them for two hours such that binding is allowed'
- Wash the slides again with phosphate-buffered saline to remove the remaining unbound fluorophores and let it dry under the nitrogen flow [8].

1.3. Integration of Optical Fiber

- Cleave the optical fiber with the use of an optical fiber cleaver to obtain the sharp end.
- Connect the optical fiber to the sensor with the use of an optical fiber fusion splicer.
- Align the optical fiber with area on the glass slide coated by fluorophore using a precision stage [9].

1.4. Integration of IoT Modules

- Measure the baseline signal by connecting the optical fiber to optical fiber meter
- Integrate the ESP8266 Wi-Fi module with Arduino Uno or Raspberry Pi for the wireless communication
- Program the microcontroller to collect the data (fertilizer and moisture content) from optical power meter and share it via the IoT modules [10].

2. Calibration and Testing

2.1. Calibration

- Prepare a series of standard nutrient solutions (nitrate, phosphate, and potassium) with known concentration (e.g., 0, 1,5,10,50,100 ppm) and label them [5].
- Dip the sensor in each solution and measure the fluorescence intensity using the spectrometer
- Plot the graph for the fluorescence intensity v/s nutrient concentration for each nutrient [8]

2.2. Testing

- Collect the different soil samples and mix 10g of soil in deionized water to prepare soil extracts. Shake it for an hour. Filter the extract [11]
- Measure the concentration of nutrient in the soil by using the calibrated biosensors
- To validate the accuracy, compare the biosensor readings with the standard laboratory measurements.

3. Data Analysis and Interpretation

3.1. Data Processing

- Data is imported directly into the data analysis app and it will provide the data in actual figures.

3.2. Interpretation and Feedback

- Analyze the data and take the correct actions against the data obtained.

III. Results

The fluorescence-based optical biosensors developed for detecting the soil nutrient content showed the reliable and consistent responses to their respective concentration ranges. The calibration curve obtained by measuring fluorescence intensity against the concentrations showed a clear and uniform relationship between the nutrient concentration and sensor response, which are necessary for the correct quantification.

The biosensor showed a linear and consistent increase in the fluorescence intensity with increase in the concentration of nitrate ions. It showed high sensitivity for the nitrate ions. However, slight deviations were observed at the higher concentrations, found out due to the saturation effects. These are very common in fluorescence-based detection methods. Biosensor showed the similar and consistent results for the phosphate ions and potassium ions. Proving that it can be used for wide range and is suitable for the detection of the higher concentrations. The irregular but anticipated increase in fluorescence intensity by potassium sustains the strength of the biosensor for real-time tracking. Hence helps the farmers for optimum use of fertilizers to avoid the underuse and overuse of fertilizers, preventing the soil degradation and environmental impact [11].

The integration of the IoT technology enabled us with real-time data transmission and monitoring. It also provides a user-friendly interface to the farmers to obtain the soil nutrient content information directly into the mobiles. The introduction of fluorescence-based optical biosensors overcomes the limitations of the traditional soil testing methods, which, generally are time-consuming and require specialized equipments and expertise [5].

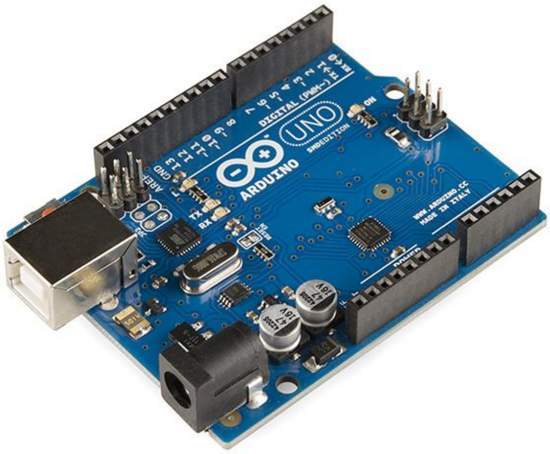


Fig. 1. Arduino uno

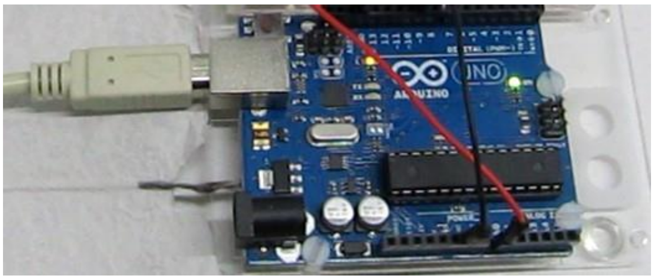


Fig. 2. Arduino uno connected with optical fiber (the other end is connected with slide).

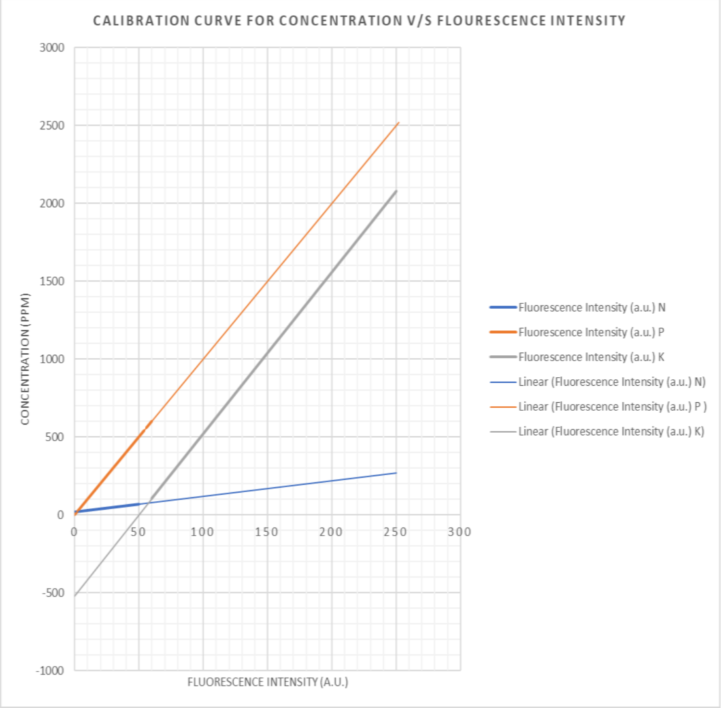
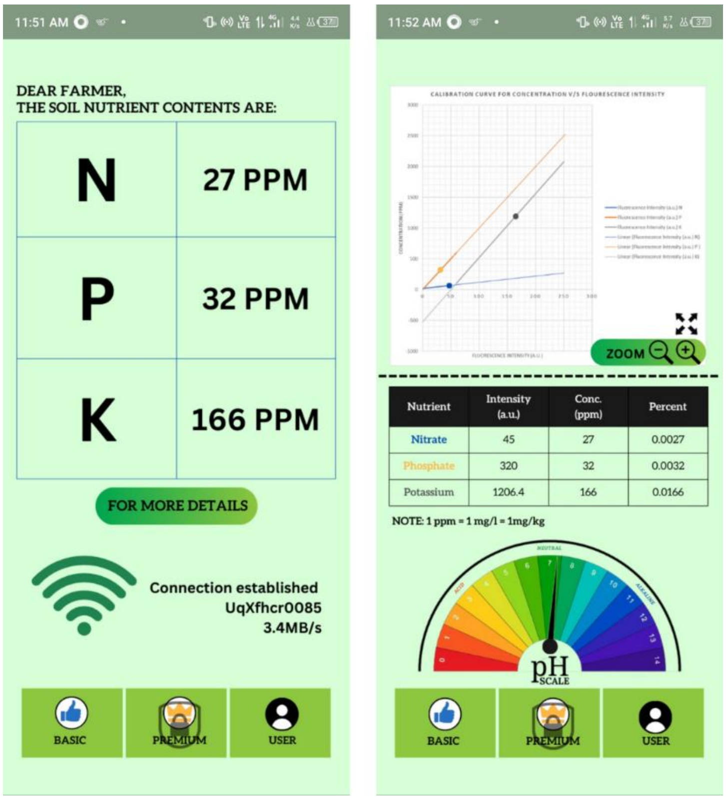


Fig. 3. Calibration Curve (Concentration (ppm) v/s fluorescence intensity (a.u.))



DEAR FARMER,
THE SOIL NUTRIENT CONTENTS ARE:

N	27 PPM
P	32 PPM
K	166 PPM

Connection established
UqXfhcr0085
3.4MB/s

Nutrient	Intensity (a.u.)	Conc. (ppm)	Percent
Nitrate	45	27	0.0027
Phosphate	320	32	0.0032
Potassium	1206.4	166	0.0166

NOTE: 1 ppm = 1 mg/l = 1mg/kg

Fig. 4. Data in figures on the mobile app interface

IV. DISCUSSION AND CONCLUSION

The advancements in the soil monitoring technology can be clearly seen through the development of fluorescence-based optical biosensors. These biosensors provide the accurate and real-time detection of the necessary nutrients like nitrate, phosphate and potassium. These nutrients are necessary for the optimum growth of the crops. With the application of modern technology like IoT and advanced nanomaterials, these biosensors overcame the limitations of labor-intensive traditional soil testing methods, generally need specialized equipments and expertise. The ability of these biosensors to detect the specific nutrients precisely and giving the prompt feedback to the farmers allows them to make the timely and informed decisions about the fertilizer applications. [5][11]. Integrating the IoT technology increases the usability and accessibility of the system, which enables the farmers to receive real-time data in actual figures on their mobiles, which will promote the adoption of this technology.

The utility and adaptability of the biosensors make them convenient to use in different agricultural environments, which may range from small farmlands to big agricultural companies. These biosensors showed their durability and dependability in the different surroundings, environmental conditions and soil types during their field testing, hence confirming their effectiveness in real-life conditions. This adaptability is necessary to address the worldwide issue of sustainable agriculture, where efficient resource control is the solution. [11]. Developing these biosensors indicates the significance of interdisciplinary studies, emerging skills in nanotechnology, sensor designing & development and agricultural sciences. Further advancements in the biosensors will be focused on broadening the nutrient pool which will be able to detect the variety of nutrients and improving the sensor design for long-term stability and durability. Ultimately, these biosensors provide us with an appropriate, effective and feasible method for the improving the optimum use of the agriculture, improving the crop yields, and supporting the sustainable agricultural practices which guarantees the food security and environmental preservation for our future generations.

REFERENCES

[1] W. Jin and J. D. Brennan, “Properties and applications of proteins encapsulated within sol–gel derived materials,” Analytica Chimica Acta, vol. 461, no. 1, pp. 1–36, Jun. 2002, doi: 10.1016/s0003-2670(02)00229-5.

[2] G. M. Whitesides, “The origins and the future of microfluidics,” Nature, vol. 442, no. 7101, pp. 368–373, Jul. 2006, doi: 10.1038/nature05058.

[3] K. T. V. Grattan and T. Sun, “Fiber optic sensor technology: an overview,” Sensors and Actuators. A, Physical, vol. 82, no. 1–3, pp. 40–61, May 2000, doi: 10.1016/s0924-4247(99)00368-4.

[4] N. De Acha, C. Elosúa, J. Corres, and F. Arregui, “Fluorescent sensors for the detection of heavy metal ions in aqueous media,” Sensors, vol. 19, no. 3, p. 599, Jan. 2019, doi: 10.3390/s19030599.

[5] X.-H. Zhao et al., “Graphene–DNAzyme Based Biosensor for Amplified Fluorescence ‘Turn-On’ Detection of Pb2+ with a High Selectivity,” Analytical Chemistry, vol. 83, no. 13, pp. 5062–5066, Jun. 2011, doi: 10.1021/ac200843x.

[6] A. P. F. Turner, I. Karube, G. S. Wilson, and P. J. Worsfold, “Biosensors: fundamentals and applications,” Analytica Chimica Acta, vol. 201, pp. 363–364, Jan. 1987, doi: 10.1016/s0003-2670(00)85361-1.

[7] R. Ludmerczki et al., “Fluorescence-based selective nitrite ion sensing by amino-capped carbon dots,” Environmental Nanotechnology, Monitoring & Management, vol. 16, p. 100573, Dec. 2021, doi: 10.1016/j.enmm.2021.100573.

[8] G. Rebollar-Pérez, J. Campos-Terán, N. Ornelas-Soto, A. Méndez-Albores, and E. Torres, “Biosensors based on oxidative enzymes for detection of environmental pollutants,” Biocatalysis, vol. 1, no. 1, Jan. 2016, doi: 10.1515/boca-2015-0010.

[9] M. Herrera-Domínguez, G. Morales-Luna, J. Mahlknecht, Q. Cheng, I. Aguilar-Hernández, and N. Ornelas-Soto, “Optical biosensors and their applications for the detection of water pollutants,” Biosensors, vol. 13, no. 3, p. 370, Mar. 2023, doi: 10.3390/bios13030370.

[10] M. S. U. Chowdury et al., “IoT based real-time river Water quality monitoring system,” Procedia Computer Science, vol. 155, pp. 161–168, Jan. 2019, doi: 10.1016/j.procs.2019.08.025.

[11] A. Bharti, U. Jain, and N. Chauhan, “From lab to field: Nano-Biosensors for real-time plant nutrient tracking,” Plant Nano Biology, vol. 9, p. 100079, Aug. 2024, doi: 10.1016/j.plana.2024.100079.

[12] S. Postolache, P. Sebastião, V. Viegas, O. Postolache, and F. Cercas, “IoT-Based Systems for Soil Nutrients Assessment in Horticulture,” Sensors, vol. 23, no. 1, p. 403, Dec. 2022, doi: 10.3390/s23010403.

[13] DavidJ. Monk and DavidR. Walt, “Optical fiber-based biosensors,” Analytical and Bioanalytical Chemistry/Analytical & Bioanalytical Chemistry, vol. 379, no. 7–8, Jun. 2004, doi: 10.1007/s00216-004-2650-x.

[14] F. Chiavaioli, F. Baldini, S. Tombelli, C. Trono, and A. Giannetti, “Biosensing with optical fiber gratings,” Nanophotonics, vol. 6, no. 4, pp. 663–679, Jun. 2017, doi: 10.1515/nanoph-2016-0178.

[15] B. Kempegowda, “Real-Time soil monitoring system for the application of agriculture,” International Journal of Engineering Science and Computing, vol. 6, no. 5, pp. 5326–5331, May 2016.

[16] S. Nagabooshanam, S. Sharma, S. Roy, A. Mathur, S. Krishnamurthy, and L. M. Bharadwaj, “Development of field deployable sensor for detection of pesticide from food chain,” IEEE Sensors Journal, vol. 21, no. 4, pp. 4129–4134, Feb. 2021, doi: 10.1109/jsen.2020.3030034.

[17] N. Verma and M. Singh, “Biosensors for heavy metals,” BioMetals, vol. 18, no. 2, pp. 121–129, Apr. 2005, doi: 10.1007/s10534-004-5787-3.

[18] Biswas, “Quantum dots as functional nanosystems for enhanced biomedical applications.,” J. Biol. Regul. Homeost. Agents., vol. 38, no. 3, pp. 1831–1857, Mar. 2024.

[19] J. O. Bockris, B. E. Conway, and R. E. White, Modern aspects of electrochemistry. 2002. doi: 10.1007/b114168.

[20] S. Bidmanova, M. Kotlanova, T. Rataj, J. Damborsky, M. Trtilek, and Z. Prokop, “Fluorescence-based biosensor for monitoring of environmental pollutants: From concept to field application,” Biosensors & Bioelectronics/Biosensors & Bioelectronics (Online), vol. 84, pp. 97–105, Oct. 2016, doi: 10.1016/j.bios.2015.12.010.

[21] A. K. Singh, S. Mittal, M. Das, A. Saharia, and M. Tiwari, “Optical biosensors: a decade in review,” Alexandria Engineering Journal /Alexandria Engineering Journal, vol. 67, pp. 673–691, Mar. 2023, doi: 10.1016/j.aej.2022.12.040.

[22] D. Grieshaber, R. MacKenzie, J. Vörös, and E. Reimhult, “Electrochemical Biosensors - Sensor principles and architectures,” Sensors, vol. 8, no. 3, pp. 1400–1458, Mar. 2008, doi: 10.3390/s8031400.

[23] A. Soussi, E. Zero, R. Sacile, D. Trinchero, and M. Fossa, “Smart Sensors and Smart Data for Precision Agriculture: A review,” Sensors, vol. 24, no. 8, p. 2647, Apr. 2024, doi: 10.3390/s24082647.

[24] D. Zhang and Q. Liu, “Biosensors and bioelectronics on smartphone for portable biochemical detection,” Biosensors & Bioelectronics/Biosensors & Bioelectronics (Online), vol. 75, pp. 273–284, Jan. 2016, doi: 10.1016/j.bios.2015.08.037.

[25] E. Yeshno, S. Arnon, and O. Dahan, “Real-time monitoring of nitrate in soils as a key for optimization of agricultural productivity and prevention of groundwater pollution,” Hydrology and Earth System Sciences, vol. 23, no. 9, pp. 3997–4010, Sep. 2019, doi: 10.5194/hess-23-3997-2019.

[26] A. Sharma, M. Majdinasab, R. Khan, Z. Li, A. Hayat, and J. L. Marty, “Nanomaterials in fluorescence-based biosensors: Defining key roles,” Nano-structures & Nano-objects, vol. 27, p. 100774, Jul. 2021, doi: 10.1016/j.nanoso.2021.100774.