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Leveraging IoT in Soil NPK Management in Nigerian Oil Palm Fields for Greater Yield and Sustainability: A Review

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Abstract: *Food security and environmental sustainability are important to a rising global population. This review explores the importance of Internet-of-things (IoT) technology adoption in soil nutrient management, especially the macronutrients (Nitrogen, Phosphorous, and Potassium or NPK) to crop yield optimization and environmental sustainability amongst other benefits. The architecture and flowchart of the system were discussed in brief as well as the benefits of IoT-based sensor nodes integrated with microcontrollers, communication module and cloud-based platforms with respect to improved yield, waste reduction, and fostering an eco-friendly environment. The Nigerian oil palm sector, being a stakeholder in achieving global food security is given special attention. Challenges of adopting this technology within the sector in Nigeria especially among smallholders and rural farmers include: high initial cost, lack of technical expertise, poor power supply and lack of internet connectivity amongst others. The review concludes by re-emphasizing the need for achieving global food security, while maintaining sustainable farming practices, by embracing smart technology and data-driven solution in soil nutrient management using IoT. Some of the recommendations for mitigating these challenges include: funding and support by government and donor agencies, providing training, and electric power supply and internet connectivity for rural farmers, and strengthening research institutions. There is a promising future for the technology uptake with a focus on improving data protection measures.*

Keywords: Internet-of-Things, Soil NPK Management, Sustainability, Oil Palm, Precision, Agriculture

INTRODUCTION

Nigeria produces the highest volume of oil palm in Africa, making her a global key player in the industry. Oil palm plantation drives the economy of nations and is a major source of livelihood among smallholder farmers in rural arears (FAO, 2020; Okoro *et al.*, 2019). The Nigerian oil palm sector, being a source of employment and foreign exchange earnings, is a major driver of her economy (Okon *et al.*, 2022). Regardless, low yield remains a major setback especially in comparism to major world sector players like Indonesia and Malaysia; resulting essentially from improper soil fertility management and inability to adopt smart technology amongs others. Nitrogen(N), phosphorus(P) and Potassium(K) or NPK are primary nutrients required to boost soil fertility and are either naturally present in the soil or in commercial fertilizer form.

Nitrogen is required for vegetation and green pigmentation, while phosphorous ensures proper root, seed, fruit and flower formation. Potassium is needed for stem and rapid plant growth (Kumar *et al.,* 2024). Traditional soil fertility management practices like manual sampling and laboratory analysis, besides failing to provide real-time data, are also time-consuming and labour-intensive (Akinola and Oladipo, 2021). Food security and sustainable agricultural practices is currently a national and global topic of interest; making smart technologies and data-driven solutions like the Internet-of-Things (IoT) inevitable in Nigeria's drive towards a viable and sustainable agro-economy; through its adoption in soil NPK management across oil palm fields. Precision agriculture, is a data-driven method of farming which besides improving crop yield and reducing production costs also prevents soil degradation (Zubair and Adebiyi, 2022). Emerging trends in IoT offer a transformative approach to boosting agricultural yield, e.g. IoT-based soil nutrient monitoring setup for providing real-time data on soil conditions deploys sensors, cloud computing, and data analytics (Adesina *et al.,* 2023). Through precise soil nutrient application in real-time, Iot systems have increased oil palm production. Adopting LoRa communication module in IoT soil management set-up in Malaysian plantations boosted yield by 15-20 percent following resource use optimization (Ruslan *et al.,* 2021). Smallholder farmers contribute largely to oil palm production in Nigeria; adopting IoT in their farming practices and processes will not only enhance productivity, but minimize labour and prevent loss of biodiversity caused by nutrient runoff. Mobile application can be incorporated into IoT system as a graphical user interface, allowing for remote monitoring of farmlands and fields, including weather conditions thereby enabling informed decisions on soil fertility management (Okafor *et al.,* 2021). With the help of artificial intelligence and machine learning algorithm in IoT cloud-based platforms, farmers can monitor trends based historical data, thereby contributing to smart decision-making process.

Environmental sustainability is another benefit of IoT-based soil NPK management. Iot adoption combined with improved cultivation habits promotes sequestration of soil carbon, and mitigates the excessive application of fertilizers which could result in the release of greenhouse gas, leading to climate change. Through Precision agriculture and Variable Rate Technology (VRT), loss of soil fertility and emission of greenhouse gases can be checked by discouraging the practice of uniform fertilization of agricultural fields (Shaniware *et al.,* 2024). This can be achieved by ad Similarly, precision agriculture involving the deployement of IoT-based soil fertiity sensors impacts significantly on environmental sustainability by a 30 drop in fertilizer use, thus preventing nutrient runoff into water bodies and promoting healthy crop (Singh and Singh, 2024). Additionally, previous research shows that managing soil macronutrients through Arduino-based platforms curbs the menance of overfertilization thus leading to efficient use of resources and fostering an eco-friendly world (Bachhhav *et al.,* 2024). This review therefore examines the use of Iot-based systems in managing soil NPK levels with a focus on the benefits and challenges of adoption within the Nigerian oil palm sector especially amongst smallholder and rural farmers. Recommendattions for its seamless adoptions are also made with a view to boosting yield and creating a sustainable environment thus contributing to global food security and Sustainable Development Goals (SDGs).

2. IoT Applications in Soil NPK Management

2.1 Internet-of-Things Architecture and workflow for Soil Nutrient Monitoring

The setup consists of five major components:

i. *Soil Sensors:* Measures real-time moisture content, pH, temperature and NPK levels.
ii. Programmable boards like Arduino, ESP32, Raspberry Pi, and NodeMCU. Processes the raw data from sensors into usable form through the microcontrollers acting as the "brain" of the system. They also send the sensor data to the cloud-based platform, using communication modules like WiFi, GSM/GPRS, LoRaWAN, Bluetooth, and Zigbee.

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iii. Data Transmission Networks: Deploys wireless technologies like Zigbee, LoRa, and NB-IoT for data-to-cloud platform transmission (Eze *et al.*, 2021).

iv. Cloud-Based Analytics: Analysis and prediction of soil nutrient patterns and deficiencies using machine learning algorithm (Adebayo and Chukwuma, 2022).

v. Automated Decision Systems: Optimization of soil fertility via a recommended fertilizer administration plan (Okonkwo *et al.*, 2023).

Table-1 Description of processes

Process	Description
1. Data Collection	The soil sensor measures parameters in the soil and sends raw data to the microcontroller.
2. Data Processing	The microcontroller processes the raw data and converts it into useful information, e.g. soil NPK level.
3. Data Transmission	The processed data is sent to the cloud/server via a communication module/Protocol.
4. Data Storage and Analysis	The cloud/servers store the data and provide tools for analysis, manipulation, and visualization.
5. User Interaction (Interface systems)	The user accesses the data via the web dashboards or mobile applications, monitors trends, and receives alerts.
6. Actuation (Automation and Decision systems)	Based on sensor readings, the system automatically triggers an actuator device through a relay to effect the desired change.

2.2 Sensor-Based Soil Nutrient Monitoring

Precise and continuous monitoring of soil conditions by IoT sensors helps farmers apply fertilizer on demand. Studies show that adopting IoT sensors drops fertilizer wastage by 30% while improving oil palm yield by 20 % (Chukwu *et al.*, 2024).

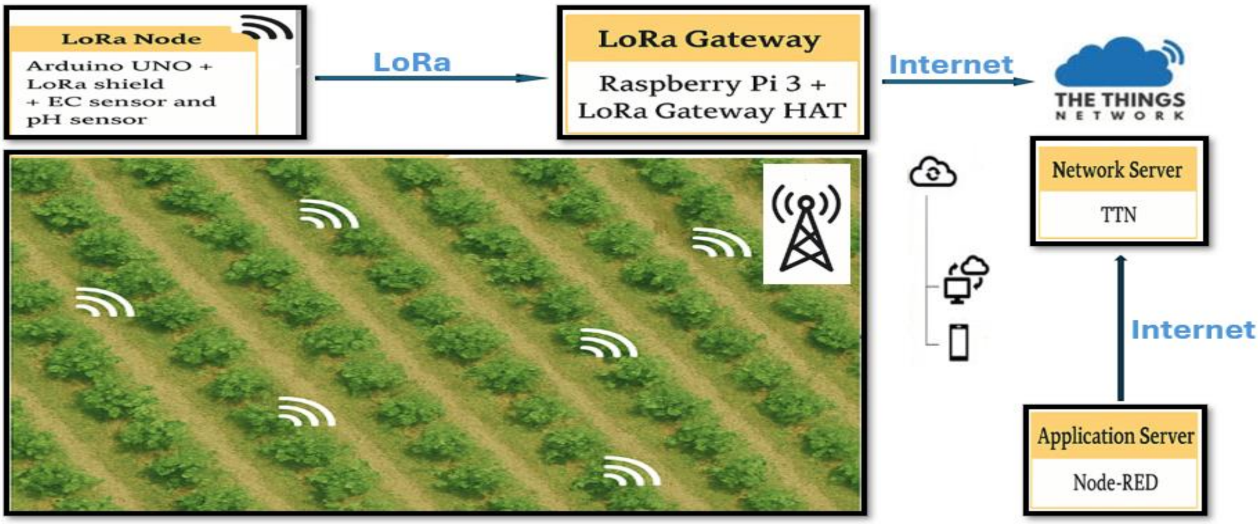

Fig. 1 LoRaWAN for Oil Palm Soil Monitoring (Goh *et al.*, 2023)

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3. Benefits of IoT Innovation in Soil NPK Management

In the area of yield improvement, IoT-enabled precision nutrient management in the tropics helps optimize soil nutrient levels, leading to increased bunch yield per hectare (Adegbite and Olatunji, 2023). Also, resource use efficiency is achieved by providing precise soil nutrient requirements to plants, thus preventing wastage while saving costs. Additionally, IoT real-time soil data enables precision in fertilizer application, minimizing nutrient runoff into water bodies, thereby preventing pollution and promoting sustainable environment and agricultural practices (Adebayo and Chukwuma, 2022). Again, automation of soil management practices using IoT eliminates tedium and drudgery associated with traditional methods; it also reduces operational costs. IoT intervention in soil nutrient management enables remote and continuous real-time monitoring of soil parameters and can be scaled to larger agricultural farmlands.

4. Challenges of IoT Adoption Among Nigerian Smallholders

Amidst the above benefits, IoT adoption in the Nigerian oil palm industry faces a myriad of challenges, such as high initial setup costs. Smallholder farmers often grapple with the high cost of sensor hardware and cloud facilities (Akinola and Oladipo, 2021). These smallholders contribute 80percent to the total volume of palm oil production in Nigeria (Olawepo *et al.,* 2021). Again, arising from poor network coverage, connectivity issues are common in rural settlements, thereby limiting real-time data transmission (Eze *et al.,* 2021). Operating IoT systems requires a certain level of education and training; hence, technical expertise is a huge gap, particularly among rural dwellers who contribute significantly to Nigeria's agricultural output (Bamigboye and Ademola, 2016). IoT-based management process involves huge data transfer; thus, data security and privacy issues can be a huge challenge.

5. Future Prospects

Advancements in IoT affordability and rural connectivity could improve its adoption in Nigeria. Governments, through policy-making and investment in agricultural technology, can help ameliorate the situation (Chukwu *et al.,* 2024). This can be achieved through improved funding profile of agricultural research institutes like the Nigerian Institute for Oil Palm Research (NIFOR), and also Universities. Additionally, training of researchers and extension workers on Precision Agriculture (PA) and other Climate-Smart Agriculture (CSA) methods for onward dissemination of knowledge to smallholders should be encouraged by government. Private sector intervention in the area of funding and other forms of partnership with government bodies is also key. In the same vein, rural electrification or investment in renewable energy sources for remote off-grid locations should be prioritized by relevant stakeholders and key sector players. Adoption of IoT-based soil management holds a promising future for the Nigerian oil palm industry considering her need to boost production, promote sustainability and regain her pride of place as a major world player in the sector. The increasing global demand for palm oil for both domestic consumption and industrial use will progressively drive the need to adopt systems, technologies and methods that will boost productivity, enhance efficiency, and promote sustainability in the sector. Also, as the world experiences a radical shift from manual methods to automated systems with industry 4.0 at the forefront, there is a likelihood of a crash in the price of Information Technology infrastructure and embedded electronic components, making IoT systems affordable to under-resourced farmers. Incorporating data-privacy and data protection measures will open a new vista of research in future IoT-based soil NPK management projects.

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CONCLUSION

Food security and environmental sustainability are paramount in a rising global population. With the Nigerian oil palm industry a major stakeholder, leveraging IoT in the sector especially among smallholders through deployment of soil sensor technology, microcontrollers, communication channels and cloud-based platforms alongside actuators will improve yield, reduce waste and produce a sustainable environment for all; while repositioning Nigeria as a major global player in the oil palm market. This will in turn contribute to solving the global food crisis and climate change thus achieving some of the United Nations sustainable development goals.

CONFLICT OF INTEREST

There is no conflict of interest for this research review.

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