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Emerging Soil Nutrient Monitoring Technologies: A Review

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ABSTRACT:

This paper reviews emerging real-time soil nutrient monitoring systems, including those integrated with machine learning (ML) and wireless communication technologies. Soil nutrients are critical for crop productivity, with fertilization schedules often optimized to meet market-driven harvest timelines. Timely crop maturity is essential to prevent shipment delays, and fertilizer quality strongly affects plant growth. Over-application can lead to soil pollution, whereas under-application reduces yield. Therefore, a precise, user-friendly, robust, and cost-effective nutrient monitoring system is essential for supporting global agricultural productivity. In this study, the advantages and limitations of existing nutrient measurement and monitoring techniques are comprehensively evaluated. As an example, variations in NPK nutrient content (nitrogen, phosphorus, and potassium) in organic-based fertilizer were analyzed

using both a pH meter and a microwave plasma atomic emission spectrometer.

KEYWORDS:

Soil nutrients, microwave sensors, microwave measurement techniques, spectroscopy methods, NPK monitoring, optical sensors, machine learning, organic fertilizer, oil palm residuals, electromagnetic spectrum.

Introduction :

Typically, fertilizer production at factories operates on a large scale, with finished products undergoing rigorous physical and chemical testing to verify compliance with predetermined specifications, particularly regarding (N), phosphorus (P), and potassium (K) and magnesium (Mg) percentages. Typically, mass-produced fertilizers have issues such as non-uniform mix of nutrients (NPK ratio mix), as shown in Fig. 1. Therefore, before each fertilizer package manufactured by the fertilizer factory must go through a quantity control test.

In addition, the N, P, and K are classified as macronutrients for crops, which are typically formulated with specific nutrient blends to address the diverse requirements of different crops. Crops are generally classified into three groups, namely root and tuber crops, fruit and flower crops, and leafy vegetables, each requiring different nutrient compositions and NPK ratios. Typically, root and tuber crops such as potatoes, carrots, and radishes need higher

potassium (K) levels. On the other hand, fruit and flower crops like tomatoes, chili, and strawberries benefit from higher phosphorus (P) to support flowering and fruiting. Leafy vegetables such as spinach, lettuce, and cabbage require higher nitrogen (N) to promote leaf growth.

In general, in spring, fertilizers with an N: P :K ratio of 16%: 6% :4% are often used, which promotes root growth and green lawns. In order to encourage the production of flowers and fruits, the ratio of N: P :K can be 3%: 20% :20%, where the nitrogen (N) content is low, while the phosphorus (P) and potassium (K) contents are high. For instance, in pineapple cultivation, optimal levels of nitrogen (15%), phosphorus (15%), and potassium (15%) are vital. Furthermore, pineapple growth at different stages requires different NPK ratios as tabulated in Table 1. These nutrient monitoring are crucial for ensuring healthy pineapple growth and timely maturity.

Table 1. Proposed N:P:K (and MgO) fertilizer ratio for Malaysian pineapple cultivation.

Crop	Age (months after planting)	N: P: K (:MgO)	
		First suggestion	Second suggestion
Malaysian Pineapple	1 to 3 months (Plant established)	15: 15: 15	15: 30: 15
	4 to 5 months (Vegetative growth)	-	28: 14: 18
	6 to 9 months (Flowering)	12: 12: 17 (:2)	15: 15: 30
	10 to 13 months (Fruit Growth)	-	15: 15: 30

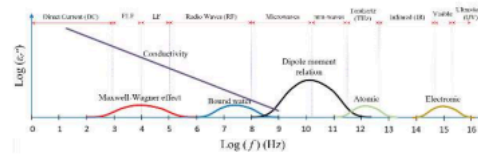


Fig. 1. The process of fertilizer production in large-scale industry.

Accurate measurement of essential macronutrients (N, P, K) in soil and fertilizers is critical for effective agricultural management; however, existing methods face limitations in sensitivity, accuracy, and practicality. Although widely used, conventional chemical techniques, such as the Kjeldahl, Dumas, dry ash, ascorbic acid, and flame photometry methods, are typically time-consuming and destructive.

Accurate, non-destructive indirect measurement techniques are increasingly needed to monitor NPK in soil and fertilizers. Various NPK nutrient testers are now commercially available, ranging from low-cost devices costing tens of US dollars to high-end professional instruments priced in the millions, depending on their functionality, reliability, and measurement accuracy. Current methods include electric conductivity (EC) probes, selective ion electrodes (ISEs), and spectroscopic techniques, such as infrared (IR), near-infrared (NIR), nuclear magnetic resonance (NMR), ultraviolet-visible (UV-Vis), atomic emission (AE), and atomic absorption (AA) spectroscopy. Each measurement technique operates within a specific frequency range, determined by the molecular interaction mechanisms of the fertilizer with different sensing sources

across the electromagnetic spectrum, as shown in Fig. 2.



Note: ELF, LF, and mm-waves stand for extremely low frequencies, low frequencies, and millimeter-waves, respectively.

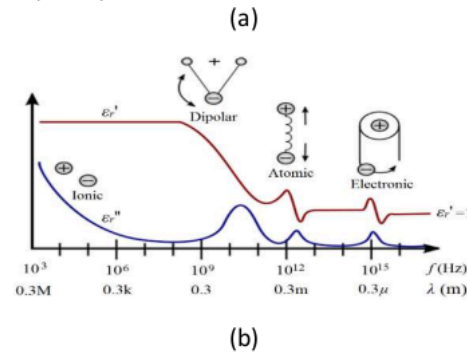


Fig. 2. (a) Relationship between the molecular mechanism of specimen under test, loss factor, ϵ_r'' , and operating frequency, f . (b) Frequency dependence of relative complex permittivity, $\epsilon_r = \epsilon_r' - j \epsilon_r''$.

Effective NPK monitoring contributes to better resource management, reducing the risk of over-fertilization, and supporting sustainable agricultural practices. Integration of AI in agricultural sensing systems can also drive innovation and reduce costs, aligning with policies that encourage technological advancement and economic efficiency in the agriculture sector. In this book chapter, the direct methods (chemical test methods, such as Kjeldahl technique) and indirect methods (using optical and electrical measurement principles) will be described and compared

in detail, including costs, facilities, advantages, disadvantages, and measurement principles/mechanisms.

Direct Chemical Test Methods :

Kjeldahl Method

The classical Kjeldahl method proposed by Johan Kjeldahl is one of the reference/standard methods for measuring nitrogen content in food, animal feed, and agricultural specimens (Sáez-Plaza *et al.*, 2013). The basic classic apparatus of this method is shown in Fig. 3. However, recently, there are lot of automatic Kjeldahl nitrogen analyzer has been commercialized to improve the sensitivity and accuracy of nitrogen measurement.

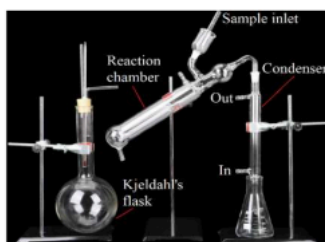


Fig. 3. Basic classic Kjeldahl test apparatus.

As mentioned above, recently, the total N content in the fertilizer can easily be determined using automatic Kjeldahl nitrogen analyzer (Lombardo *et al.*, 2017). In this study, the modern Kjeldahl test systems are used for monitoring NPK content in organic fertilizer, as shown in Fig. 4. Basically, the measurement method is divided into three steps: wet digestion, distillation, and sum of nitrogen bound in ammonium is estimated.

Step 1: Wet Digestion Process

Briefly, an amount (0.6 g) of organic fertilizer is accurately weighed and digested in the Kjeldahl digestion block as shown in Fig. 4 (a) for 2 hours (Gerhardt, 2018).

Step 2: Distillation Process

Up to 40 ml of distilled water and 70 ml of 32 % sodium hydroxide are added in the distillation step (Gerhardt, 2020).

Step 3: Nitrogen (N) Content Estimation

The distillate collected is then titrated with 0.1 M hydrochloric acid using methyl red and bromocresol green as indicator as shown in Fig. 4 (b). The total N content in the fertilizer samples is expressed as % N and it is calculated according to the formula as:

$$N(\%) = \frac{14(V_2 - V_1)M}{W} \quad (1)$$

where V_2 and V_1 are the volumes (mL) of HCl in specimen under test and control, respectively. Whereas, M and W are the molarity (mol L^{-1}) of HCl and the weight (mg) of specimen, respectively.

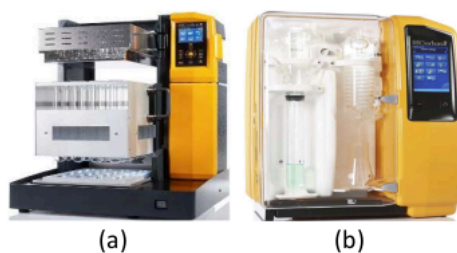


Fig. 4. (a) Kjeldahl digestion system. (b) Kjeldahl distillation system.

Dumas Method

Besides kjeldahl method, there are other methods for total nitrogen determination in agricultural products, such as dumas method proposed by Jean-Baptiste Dumas in 1826. By Dumas test, a small amount dried soil or fertilizer sample is heated in a nitrogen-analysis instrument to convert all nitrogen compounds into gases, which are purified and quantified by the detector to determine the sample's nitrogen content.

Indirect Test Methods :

An efficient method for non-destructive and precise monitoring of NPK in fertilizers is imperative (Muñoz *et al.*, 2013; Potdar *et al.*, 2021; Maria Khaydukova *et al.*, 2021; Silva *et al.*, 2023; Dattatreya *et al.*, 2024). Various NPK fertility nutrient testers are available in the market, ranging from low-cost options to high-end, multi-functional devices costing several hundred thousands of dollars. Each type of tester and measurement technique has its own advantages and disadvantages.

Electric Conductivity (EC) Probes

An electric conductivity (EC) probes made of three or five metal electrodes are the simplest, cost-effective, rapid, and most commonly used sensor for on-site NPK content monitoring (Baldi *et al.*, 2020; Maria Khaydukova *et al.*, 2021; Islam *et al.*, 2023). It is known that inorganic minerals in fertilizer product contains high ions and cause a high value of the corresponding potential (Sánchez-Monedero *et al.*, 2001). These probes measure the DC conductivity value of the soil, which correlates with the

NPK content. The DC potential value depends on the amount of NPK in the soil. However, they may lack sensitivity to small NPK amounts in dry fertilizer or soil and can be prone to errors due to non-uniform electrode surfaces in contact with different soil textures, unless tailored for specific soil types.

Ion Selective Electrodes

An ion selective electrode (ISE) test method is an indirect test method to determine the activity of specific ions in aqueous solution by measuring the electrical potential, E (Joseph V. Sinfield *et al.*, 2010; Zhai *et al.*, 2022). Sometimes, the ion selective electrode is called specific ion electrode (SIE). The relationship between measured potential, E (in unit V) and specific ion concentration, C (in unit mg/L) in the solution under test is given as Nernst equation:

$$E = S \log_{10} C + K \quad (2)$$

where values of K and S depend on the ion elements being measured as well as the electrode structure. The unknown S and K can be determined from plot curve of E versus $\log_{10} C$. Fertilizer products containing different amounts of ions will cause the difference in exited conductivity in the fertilizer (Yagüe & Quílez, 2012; Chen *et al.*, 2021). Typically, nitrogen (N) in fertilizers is present as nitrate (NO_3^-) or ammonium (NH_4^+), while potassium (K) appears as potassium ions (K^+), and magnesium (Mg^{2+}). In contrast, phosphorus (P) is generally found in the form of phosphate ions (PO_4^{3-}). Indirectly,

the inorganic nutrient content in fertilizer is capable of correlating with measured potential.

For example, a calibration curve for nitrogen ions is obtained by preparing standard solutions of known concentration C and measuring the corresponding potential E . However, because ISEs rely on selective membranes that allow only target ions to pass, each ISE can measure only specific ions, and even then, the membranes are never perfectly selective. Other ions may still penetrate the membrane, and at higher concentrations, ion-ion interactions reduce ion mobility, causing the concentration near the membrane to differ from the true bulk value. These factors collectively lead to measurement inaccuracies when using ISEs.

Spectroscopy Methods

There are several types of spectroscopic measurement techniques, including nuclear magnetic resonance (NMR) (Sørensen *et al.*, 2015), infrared (IR) spectroscopy, near-infrared (NIR) spectroscopy (He *et al.*, 2005; Lin *et al.*, 2018; Rawankar *et al.*, 2018; Mustaqimah *et al.*, 2024; Xu *et al.*, 2024), ultraviolet-visible (UV-Vis) spectroscopy (Silva *et al.*, 2019; Potdar *et al.*, 2021; Silva *et al.*, 2023), microwave plasma atomic emission (MPAE) spectroscopy, and atomic absorption (AA) spectroscopy (Yang *et al.*, 2002; Marcos André Bechlin *et al.*, 2014).

Among these IR, NIR, and UV-Vis are classified as optical spectroscopic methods, whereas MPAE represents a

microwave-based spectroscopic technique. Both optical and microwave spectroscopy operate on similar fundamental principles, an electromagnetic wave interacts with the soil or fertilizer sample, and resulting response is analyzed to extract intrinsic fertilizer properties. These properties can then be correlated with the NPK content present in soil/fertilizer.

In optical spectroscopy, the key material parameter is the complex refractive index, $n = n' - jn''$, which describes how light propagates, reflects and attenuates within the soil or fertilizer. In microwave spectroscopy, the corresponding parameter is the relative complex permittivity, $\epsilon_r = \epsilon_r' - j\epsilon_r''$, which characterizes polarization and energy dissipation at lower frequencies (You, 2016). The relationship between n (optical) and ϵ_r (microwave) is given as $n^2 = \epsilon_r$. Differentiations between microwave and optical (infrared) methods are the application of operating frequency (Microwave: 300 MHz to 300 GHz; Infrared: 300 GHz to 430 THz) and excited source as shown in Fig. 4.

Fig. 5 shows the response of the relative complex permittivity, ϵ_r from Radio frequencies (RF) to Ultraviolet frequencies. At microwave frequencies, ϵ_r' and ϵ_r'' show the reaction caused by dipole relaxation phenomena of the substance in soil/fertilizer. While, at infrared frequencies, ϵ_r' and ϵ_r'' exhibit a significant reaction due to the resonant occurring between the molecular vibration of the substance and the infrared frequency. The

NPK content of fertilizer or soil is determined based on the absorbance and reflectance of the fertilizer/soil on the monochromatic light source when exposed to the source. Molecules of each element N, P, K resonate at a certain wavelength and exhibit significant resonance absorption effects at that wavelength. The wavelength ranges of source used by IR, NIR, UV, and Vis spectroscopy are 700–1000 nm, 780–2500 nm, 200–400 nm, and 380 nm to 780 nm, respectively. Unfortunately, various ions of N, P, and K has the same spectral characteristics and overlap of some wavelengths (Potdar *et al.*, 2021). Furthermore, this type of NPK measurement technique requires good environmental control and is less suitable for on-site measurements. Often, the technique also requires personnel with skills in using test equipment.

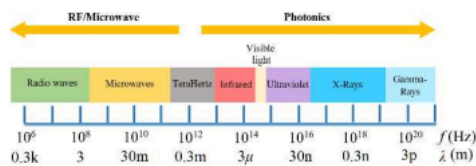


Fig. 5. Electromagnetic spectrum.

8 Nuclear Magnetic Resonance (NMR) Spectroscopy Methods

In nuclear magnetic resonance (NMR) spectroscopy, the fertilizer sample is positioned in a magnetic field, which causes certain nuclei to align with or against the field. When a radio-frequency (RF) is applied, these nuclei are excited from their equilibrium state and driven into resonance. As the nuclei relax back to their original alignment, they emit characteristic

RF signals. The emitted signals is detected with sensitive radio receivers and generate an NMR spectrum. The spectrum is used to quantify specific nuclei associated with nutrient components. Normally, version of ^{15}N , ^{31}P , ^{39}K , and ^{13}C NMR spectroscopy are used to monitor the nutrient in fertilizer or soil. For instance, ^{15}N NMR spectroscopy is implemented to examine specimen under test containing the ^{15}N nucleus.

Ultraviolet-Visible (UV-Vis) Spectroscopy (P and K Contents Test)

The UV–Vis spectroscopic module operates by measuring the interaction between ultraviolet light and the fertilizer sample. The sample is exposed to UV light within the wavelength range of 200–400 nm, and the absorption of light of the sample is measured. According to Beer's law, the absorbance, A of the sample is given as:

$$A = \epsilon b C \quad (3)$$

where ϵ is the molar absorptivity of the element dissolved in the specimen solution and b is the length of light path in specimen, respectively. While, C is the concentration of the element in the specimen solution. Once ϵ and b are known, the concentration, C can be determined from the measured absorbance, A . In practise, the absorbance, A is measured in term of light intensity, I . The relationship between A and I can be expressed in logarithm form:

$$A = -\log_{10} \left(\frac{I}{I_0} \right) \quad (4)$$

where I_0 and I are the intensity of incident light in a sample cuvette and the intensity of transmitted light. The Beer-Lambert law states that absorbance increases with both concentration, C and path length, b . A calibration curve is used to determine how absorbance varies with concentration. The UV-Vis spectrophotometer measures the strength of light passing through the sample compares it to light intensity through reference specimen using a photodiode for signal processing.

Near-Infrared (NIR) Spectroscopy (P and K Contents Test)

Far-infrared radiating ceramics are made of twenty or more inorganic compounds and trace metals or specific natural ores in different proportions, and then calcined at a high temperature of 1200 °C to 1600 °C, so that the ceramics can emit far-infrared rays of a specific wavelength. For instance, water molecules vibrate near 10 μm , far-infrared radiation in this range enhances molecular motion through resonance absorption. The commercial near-infrared (NIR) spectrophotometer is shown in Fig. 6.



Fig. 6. DRAWELL DW-S430 Near-infrared (NIR) spectrophotometer.

Microwave Plasma Atomic Emission Spectroscopy (P and K Contents Test)

Besides IR, NIR, UV, and Vis spectroscopy, atomic emission (AE) and atomic absorption (AA) spectroscopy are also widely used for N, P, and K detection (Yang *et al.*, 2002). In AE spectroscopy, atoms or molecules of N, P, or K are excited, such as by microwave plasma, and emit light at characteristic wavelengths, with emission intensity indicating their concentration. In contrast, AA spectroscopy measures the absorption of light by N, P, or K ions. Although commercial spectrometers provide straightforward P and K measurements, several sample-preparation steps are still required before fertilizer analysis can be performed. In this study, a microwave plasma atomic emission spectrometer (Agilent 4210) is used to measure P and K, as shown in Fig. 7. The technique is based on emission spectra generated when atoms are excited by microwave plasma, with elemental concentration determined from emission intensity. Although the method is straightforward, sample preparation is still required prior to measurement.

Step 1: Preparation of Standard Test Solutions

Up to 4.56 g and 1.91 g of $\text{Na}_2\text{H}_2\text{PO}_4$ and KCl were measured separately to prepare two stock solutions of 1000 mgL^{-1} consisting of each element in 1000 mL volumetric flasks. Deionized water was used to dissolve the salts and made up to the volume of 1000 mL. These stock solutions were further diluted 200 and 1000 times to prepare stock solutions of 5 mg L^{-1} and 1 mgL^{-1} for P and K, respectively.

From the newly prepared stock solutions, a series of standard solutions (100 mL each) with the concentrations of 50, 100, 200, 400, and 1000 μgL^{-1} (for P) and 10, 50, 100, 200, and 500 μgL^{-1} (for K) were prepared and they were used to obtain the calibration curves of signal intensity as a function of concentration of P and K standards, respectively, as tabulated in Table 2. The limit of detection (LOD) and limit of quantitation (LOQ) are determined according to the formulae of 3.3 s/S and 10 s/S, respectively (Lee *et al.*, 2015).

Step 2: Preparation of Fertilizer Samples

The digestion of fertilizer samples are modified from the method described by Yang *et al.* (2002) and each sample is conducted in triplicate. Briefly, 0.5 g of the fertilizer sample was digested with 9 mL of HNO_3 and 3 mL of HCl in a beaker at 80 °C for 1 h until a clear solution is obtained. The digested fertilizer is cooled to room temperature and filtered through a syringe filter to remove undissolved materials. The clear solution of the digested fertilizer is diluted 10-fold with deionized water before MP-AES analyses.

Step 3: P and K Measurements Using Microwave Plasma Atomic Emission Spectrometer

The quantitation of P and K in the fertilizers are conducted using an Agilent 4210 MP-AES microwave plasma atomic emission spectrometer as shown in Fig. 7. The instrument was equipped with a liquid nitrogen Dewar which was used to provide nitrogen gas to run the microwave-induced

plasma. The sample introduction is composed of an SPS4 auto-sampler, solvent-resistant tubing, a double-pass cyclonic spray chamber, and an inert Flow Blurring nebulizer (OneNeb). The system is controlled through MP Expert software.



Fig. 7. Agilent 4210 MP-AES microwave plasma atomic emission spectrometer.

Table 2. Analytical characteristics of the MP-AES method.

Element	Concentration range ($\mu\text{g/L}$)	Regression equation	r^2	LOD ($\mu\text{g/L}$)	LOQ ($\mu\text{g/L}$)
P	1000 - 20000	$y = 0.0653x + 1029.1$	0.9912	1853.5	5616.7
K	10 - 5000	$y = 2.6231x + 119.79$	0.9996	36.8	111.5

Note: x is the concentration of respective metal element ($\mu\text{g/L}$); y is the signal intensity of respective metal element; r^2 is the square of regression coefficient; LOD standard for limit of detection; LOQ standard for limit of quantification.

LED/Fiber-Optic Light Sensing Techniques:

Recently, a simple and cost-efficient LED-based sensing method, commonly referred to as colorimetry, has been proposed to measure NPK content based on the color absorption characteristics of wet fertilizer/soil sample (Liu *et al.*, 2016; Regalado & Cruz, 2016). The measurement system consists of three or more LEDs as a

light source, such as red, green, and blue color light. The reason is that N, P and K exhibit stronger absorption in the blue (~470 nm), green (~530 nm), and red (~650 nm) chromatic light, respectively (Masrie *et al.*, 2017; 2018). The integration of LEDs as emitters/light sources and photodiodes as detectors forms a simple spectroscopic setup for directly detecting NPK nutrients. Typically, N, K, and P correspond to red, blue, and green wavelengths, respectively. In fact, the absorption wavelengths of soils containing N, P, and K are also different depending on the use of different chemical reagents and the type of soil as well as moisture content in the soil (Yusof *et al.*, 2016; Kim *et al.*, 2009). The measurement tolerance of this method is large, hence the detected NPK content is usually classified as "low", "medium" or "high", making the method unsuitable for detecting small concentration changes. Fig. 8 illustrates the operating principle of the fiber-optic NPK sensor. LEDs of different colours emit light through transmitting fibers, and the reflected light, dependent on the NPK content in the soil or fertilizer solution, is collected by a central receiving fiber. The phototransistor converts the light into an electrical signal, which is processed by a microcontroller to estimate NPK levels and display the results on an LCD.

Microwave Sensing :

Recently, a microwave sensing is an emerging technique for real-time, non-destructive, and precision measurement of N, P, and K content in fertilizers and soil. Its operating principle is based on how

microwave interact with the relative complex permittivity, $\epsilon_r = \epsilon_r' - j \epsilon_r''$ of fertilizer/soil.

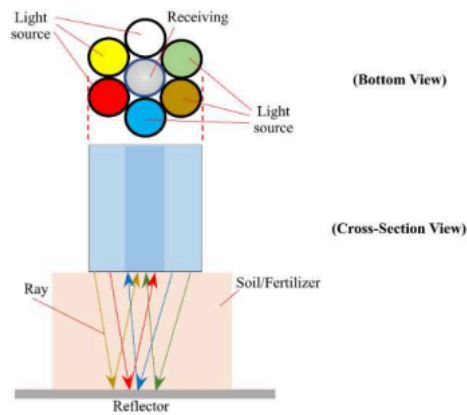


Fig. 8. Principle of optic fiber-based sensor.

The real part, ϵ_r' correlates to polarization molecules and moisture in the fertilizer/soil, and the imaginary part, ϵ_r'' relates to ionic movement and conductivity of NPK in the fertilizer/soil. The nitrogen ($\text{NO}_3^- / \text{NH}_4^+$) and potassium (K^+) are present in ionic form, which strongly influences imaginary part, ϵ_r'' when exposed to microwave fields.

In microwave sensing, a sensor operating within microwave frequency range is used to measure the reflection coefficient, S_{11} , the transmission coefficient, S_{21} or both, when the sensor head is in contact with the fertilizer or soil (You *et al.*, 2013). Transmission, S_{21} measurements may be performed in either the time-domain or the frequency-domain. In addition, microwave resonate sensors can detect NPK content by measuring shifts in resonant frequency, Δf and changes in the quality factor, Q (Lim *et al.*, 2026).

These parameters (S_{11} , S_{21} , Δf , and Q) correlate with NPK concentrations and can be analyzed using polynomial regression, ANN/ML algorithms, or PSO/GA optimization techniques. However, there are several limitations in NPK monitoring by microwave sensor, such as:

- (a) P detection is weaker due to low solubility of phosphate. P usually exists as insoluble phosphate (PO_4^{3-}) and has limited ionic mobility and causes weaker microwave interaction.
- (b) Moisture strongly affects permittivity; must be accounted for.
- (c) Soil heterogeneity can introduce variability.
- (d) Requires calibration models for different soil/fertilizer types.

PH Test :

In this work, the pH of the raw fertilizer is directly measured using the Hanna HI98127 pH tester. While, for fertilizer solution pH test, the fertilizer solution is prepared by adding deionized water in the ratio of 1:10 (1g : 10 mL) and the solution is left for 2 hours for maximum salts dissolution (Sánchez-Monedero *et al.*, 2001). The pH of the prepared solution is tested using pH tester. The pH values are noted when the readings are stabilized.

Organic-Based Fertilizer Specimens :

Up to 36 samples with different NPK ratios of the raw oil palm-based fertilizer samples are provided by Green Plant Organic Fertilizer manufacturer. The fertilizer samples are divided into two groups,

namely group A without containing 2% MgO and group B with 2% MgO, respectively, as listed in Table 3. It should be noted that the nutrient contents (NPK) in the fertilizer are initially notified by the manufacturer. All raw oil palm-based fertilizer samples are verified using third-party measurement techniques, specifically the pH test, Kjeldahl method, and microwave plasma atomic emission spectrometry (MP-AES).

Results and Discussion :

The raw oil palm residual mixture naturally contains a small amount of inorganic elements. The comparison of inorganic elements in each type of residual, as reported in the literature (Gurmit *et al.*, 1989; Su *et al.*, 2022), studied raw oil palm residual, and manufacturer labeling is listed in Table 4.

It should be noted that the studied raw oil palm residual is a mixture of various parts, such as empty fruit bunch (EFB), (MF), Palm frond (PF), Palm trunk (PT), palm kernel shell (PKS), and palm oil mill effluent (POME). The NPK content of inorganic elements in group A and group B fertilizer samples, measured using the Kjeldahl method and the MP-AES method, is listed in Table 5 and Table 6.

The pH of fertilizers in both a nearly dry state (< 20% moisture) and in solution has been measured. Both measurements yield significantly different pH values. It has been found that the pH of dry fertilizers is independent of the NPK content as shown by the pH values listed in Tables 5 and 6. This is likely due to the inactivity of the

inorganic elements in nearly dry fertilizers, which prevents the pH meter from detecting changes in pH between fertilizers with different N, P, or K contents. The pH measurements for all fertilizer solution samples in groups A and B , as listed in Tables 5 and 6, are re-plotted in Figs. 9 (a) and (b). The pH values appear to be closely related to the N, P, and K contents. Nearly all samples display alkalinity (pH > 7). However, when the N content exceeds 4%, the samples exhibit weak acidity, and when the N content exceeds ~ 9%, the pH returns to alkaline, as shown in Fig. 9 (b). Therefore, predicting the N content for samples N1-N6 in group B based on pH changes is unsuitable due to the ambiguity in N content ranging from 1% to 12%. The relationship between pH and NPK content has been modeled using the regression method, as detailed in Table 7. Overall, the pH measurements exhibit a clear trend when correlated with N, P, and K content (in %), achieving a fitting coefficient of $r^2 > 0.96$. Overall, the pH value of Set B samples (with 2% MgO) are higher than Set A (without 2% MgO), since the MgO is an alkaline element.

Conclusion :

Emerging NPK monitoring techniques are thoroughly reviewed, and their practical applications are demonstrated and explained. Recently, the application of artificial intelligence (AI) has significantly expanded into various fields, including precision agriculture (Rawankar *et al.*, 2020; Islam *et al.*, 2023; Ennaji *et al.*, 2023; Thorat *et al.*, 2023; Dattatreya *et al.*, 2024;

Sajindra *et al.*, 2024; Xu *et al.*, 2024). This AI-enable NPK monitoring system reduces the complexity of agricultural sensing equipment, as well as the associated costs and manpower requirements.

Table 3. Raw fertilizer sourced from Green Plant Organic Fertilizer manufacturer.

Sample	Group A (without 2% MgO)		
	N (%)	P (%)	K (%)
N1	1.5	~1.2	~3.15
N2	2.5	~1.2	~3.15
N3	3.5	~1.2	~3.15
N4	4.5	~1.2	~3.15
N5	5.5	~1.2	~3.15
N6	6.5	~1.2	~3.15
P1	~2.0	1.0	~3.15
P2	~2.0	2.0	~3.15
P3	~2.0	3.0	~3.15
P4	~2.0	4.0	~3.15
P5	~2.0	5.0	~3.15
P6	~2.0	6.0	~3.15
K1	~2.0	~1.2	3.0
K2	~2.0	~1.2	4.0
K3	~2.0	~1.2	5.0
K4	~2.0	~1.2	6.0
K5	~2.0	~1.2	7.0
K6	~2.0	~1.2	8.0
Sample	Group B (with 2% MgO)		
	N (%)	P (%)	K (%)
N1	1.5	~1.2	~3.15
N2	3.0	~1.2	~3.15
N3	5.0	~1.2	~3.15
N4	7.0	~1.2	~3.15
N5	10.0	~1.2	~3.15
N6	12.0	~1.2	~3.15
P1	~2.0	1.0	~3.15
P2	~2.0	3.0	~3.15
P3	~2.0	5.0	~3.15
P4	~2.0	7.0	~3.15
P5	~2.0	10.0	~3.15
P6	~2.0	12.5	~3.15
K1	~2.0	~1.2	3.0
K2	~2.0	~1.2	6.0
K3	~2.0	~1.2	9.0
K4	~2.0	~1.2	12.0
K5	~2.0	~1.2	15.0
K6	~2.0	~1.2	17.0

Table 4. Inorganic composition of raw oil palm residual (weight %).

Element	Literature (Gurmit <i>et al.</i> , 1989; Su <i>et al.</i> , 2022)					This study	
	Empty fruit bunch (EFB)	Palm kernel shell (PKS)	Mesocarp fiber (MF)	Palm frond (PF)	Palm trunk (PT)	Raw palm residual (Kjeldahl & MP-AES)	Manufacturer labeling
N	0.56–0.88	0.36–0.7	1.09–3.12	0.19–0.71	0.40–0.44	1.12 ± 0.17	1.95–2.04
P	~0.1	–	–	–	–	0.82 ± 0.06	1.2–1.26
K	~2.5	–	–	–	–	3.76 ± 0.70	3.14–3.17
P ₂ O ₅	1.12–4.29	0.98–10.21	1.58–7.48	2.43–9.2	5.37–8.71	1.88	–
K ₂ O	39.98–53.73	1.29–10.38	1.99–15.55	8.29–39.8	24.50–44.5	4.53	–
MgO	3.68–8.75	1.77–14.36	4.20–50.83	1.93–16	1.15–15.60	–	–

Table 5. NPK contents and pH of the palm oil organic fertilizer samples without containing 2% MgO.

Samples	pH		Nitrogen ^a (%)	Phosphorus ^a		Potassium ^a	
	Solid	Solution		P (%)	P ₂ O ₅ (%)	K (%)	K ₂ O (%)
Set A (N1)	7.4	8.61	0.79 ± 0.09	0.11 ± 0.00	0.25	5.13 ± 0.39	6.18
Set A (N2)	8.7	7.41	1.73 ± 0.11	0.16 ± 0.03	0.37	5.42 ± 0.11	6.53
Set A (N3)	8.5	7.09	2.38 ± 0.18	0.03 ± 0.00	0.07	4.80 ± 0.21	5.78
Set A (N4)	8.4	6.89	2.89 ± 0.34	0.04 ± 0.00	0.09	5.18 ± 0.78	6.24
Set A (N5)	8.6	6.82	3.69 ± 0.16	0.01 ± 0.00	0.02	5.79 ± 0.80	6.98
Set A (N6)	8.5	6.78	5.18 ± 0.34	0.24 ± 0.13	0.55	5.47 ± 0.59	6.59
Set A (P1)	7.4	9.06	1.45 ± 0.47	0.08 ± 0.00	0.18	4.85 ± 0.55	5.84
Set A (P2)	7.5	8.62	1.49 ± 0.12	0.61 ± 0.14	1.40	5.42 ± 1.11	6.53
Set A (P3)	7.8	7.99	1.26 ± 0.74	3.21 ± 0.31	7.35	5.43 ± 0.84	6.54
Set A (P4)	7.5	7.85	1.21 ± 0.84	1.81 ± 0.59	4.14	5.41 ± 0.95	6.52
Set A (P5)	7.9	7.54	0.00	2.91 ± 0.53	6.66	4.90 ± 0.61	5.90
Set A (P6)	7.7	7.66	1.49 ± 0.17	4.13 ± 0.56	9.45	7.03 ± 0.50	8.47
Set A (K1)	7.8	9.44	1.54 ± 0.18	0.22 ± 0.09	0.50	6.00 ± 0.76	7.23
Set A (K2)	8.2	9.14	1.49 ± 0.34	0.25 ± 0.09	0.57	8.26 ± 0.42	9.95
Set A (K3)	7.9	8.64	1.49 ± 0.52	0.24 ± 0.04	0.55	9.35 ± 0.60	11.27
Set A (K4)	7.7	8.34	1.35 ± 0.16	0.23 ± 0.05	0.53	10.27 ±	12.37
Set A (K5)	8.0	8.21	1.35 ± 0.32	0.16 ± 0.04	0.37	12.49 ±	15.05
Set A (K6)	7.9	8.07	1.35 ± 0.04	1.13 ± 0.34	2.59	16.20 ±	19.52

^a Results are expressed as mean ± % RSD for triplicate analysis. The calculation of % N, % P₂O₅ and % K₂O were based on the conversion factors of % N = 1.00 × % N, % P = 0.437 × % P₂O₅ and % K = 0.83 × % K₂O, respectively.

Table 6. NPK contents of the palm oil organic fertilizer samples (Set B) with containing 2% MgO.

Samples	pH		Nitrogen ^a (%)	Phosphorus ^a		Potassium ^a	
	Solid	Solution		P (%)	P ₂ O ₅ (%)	K (%)	K ₂ O (%)
Set B (N1)	8.0	8.41	0.98 ± 0.08	0.29 ± 0.03	0.66	5.61 ± 0.21	6.8
Set B (N2)	8.7	7.64	0.00	0.19 ± 0.01	0.43	5.20 ± 0.67	6.3
Set B (N3)	8.9	6.90	3.97 ± 0.62	0.24 ± 0.06	0.55	4.87 ± 0.43	5.9
Set B (N4)	8.8	6.95	6.02 ± 0.86	0.07 ± 0.00	0.16	4.36 ± 0.74	5.3
Set B (N5)	8.5	7.21	9.75 ± 1.04	0.73 ± 0.09	1.67	1.99 ± 0.77	2.4
Set B (N6)	8.2	7.91	15.17 ± 1.16	0.18 ± 0.03	0.41	3.77 ± 0.15	4.5
Set B (P1)	8.0	8.68	1.54 ± 0.17	0.38 ± 0.02	0.87	5.78 ± 0.95	7.0
Set B (P2)	7.9	8.35	1.31 ± 0.08	1.35 ± 0.43	3.09	5.82 ± 1.05	7.0
Set B (P3)	8.1	8.13	1.21 ± 0.06	3.33 ± 0.21	7.62	6.00 ± 0.29	7.2
Set B (P4)	8.2	7.90	1.49 ± 0.24	4.42 ± 0.13	10.11	6.06 ± 0.91	7.3
Set B (P5)	8.2	7.78	1.31 ± 0.54	7.02 ± 0.33	16.06	6.13 ± 0.41	7.4
Set B (P6)	8.5	7.86	1.07 ± 0.07	10.72 ± 0.62	24.53	6.38 ± 0.00	7.7
Set B (K1)	8.2	8.81	1.35 ± 0.66	0.26 ± 0.00	0.59	5.60 ± 0.27	6.8
Set B (K2)	8.2	8.45	0.00	0.30 ± 0.07	0.69	10.87 ±	13.1
Set B (K3)	8.1	8.08	1.21 ± 0.13	0.79 ± 0.02	1.81	16.87 ±	20.3
Set B (K4)	8.1	8.09	1.31 ± 0.69	0.18 ± 0.05	0.41	20.17 ±	24.3
Set B (K5)	8.0	8.09	1.26 ± 0.16	0.38 ± 0.01	0.87	22.49 ±	27.1
Set B (K6)	8.2	7.87	1.17 ± 0.34	0.44 ± 0.07	1.01	22.57 ±	27.2
N:P:K = 5%: 5%: 10%	-	6.86	2.99 ± 0.74	4.04 ± 0.14	9.24	11.56 ± 0.59	13.93
N:P:K = 12%: 12%: 17%	-	6.52	0.51 ± 0.33	14.05 ± 0.88	32.15	17.54 ± 0.95	21.13
Raw organic residual	6.7	7.93	1.12 ± 0.17	0.82 ± 0.06	1.88	3.76 ± 0.70	4.53

^a Results are expressed as mean ± %RSD for triplicate analysis. The calculation of % N, % P₂O₅ and % K₂O were based on the conversion factors of % N = 1.00 × % N, % P = 0.437 × % P₂O₅ and % K = 0.83 × % K₂O, respectively.

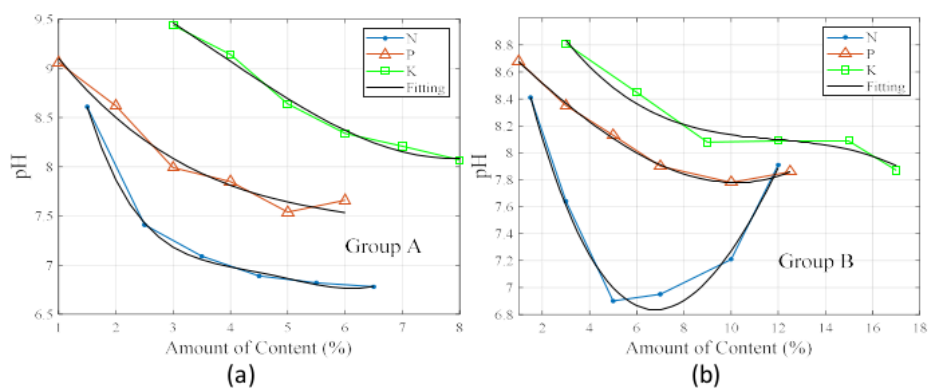


Fig. 9. pH of the (a) group A and (b) group B fertilizer solutions.

Table 7. Regression polynomial model of pH with respect to N, P, and K content.

Group	Element	pH	r ²
A	N (1.5-6.5 %)	$\text{pH} = \begin{cases} 0.01375N^4 - 0.2590740741N^3 + 1.817013889N^2 \\ -5.740945767N + 13.93441096 \end{cases}$	0.99874
	P (1.0-6.0 %)	$\text{pH} = \begin{cases} -0.006944444444P^3 + 0.1346428571P^2 \\ -0.9576984127P + 9.932857143 \end{cases}$	0.97526
	K (3.0-8.0 %)	$\text{pH} = \begin{cases} 0.007962962963K^3 - 0.09067460317K^2 \\ -0.04943121693K + 10.21119048 \end{cases}$	0.99173
B	N (1.5-12.0 %)	$\text{pH} = \begin{cases} -0.001677995396N^3 + 0.08163112627N^2 \\ -0.8761499517N + 9.548094535 \end{cases}$	0.98462
	P (1.0-12.5 %)	$\text{pH} = \begin{cases} 0.0003893661405P^3 + 0.002280190674P^2 \\ -0.1678011914P + 8.840256417 \end{cases}$	0.99833
	K (3.0-17.0 %)	$\text{pH} = \begin{cases} -0.0008556174707K^3 + 0.03046825871K^2 \\ -0.3773197175K + 9.71637207 \end{cases}$	0.96416

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