

# Comprehensive Analysis of Nitrogen, Phosphorus, and Potassium Levels in Soil: Detection Methods and Agricultural Implications

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## ABSTRACT

Soil fertility is a critical determinant of agricultural productivity, with nitrogen (N), phosphorus (P), and potassium (K) being the primary macronutrients essential for plant growth. Accurate detection and analysis of these nutrients enable optimized soil management practices, improved crop yields, and sustainable agriculture. This study explores traditional chemical methods and modern spectroscopic approaches for determining soil NPK levels. By integrating laboratory-based techniques with emerging sensor technologies, this research aims to provide a robust framework for soil fertility assessment. The findings emphasize the importance of precise nutrient monitoring in mitigating over-fertilization, reducing environmental degradation, and ensuring food security.

## 1. INTRODUCTION

Soil serves as the foundation of agricultural productivity, providing essential nutrients required for plant growth. Among these, nitrogen, phosphorus, and potassium (NPK) are the primary macronutrients that significantly influence crop yield, soil health, and environmental sustainability. Nitrogen is crucial for protein synthesis and chlorophyll formation, phosphorus supports energy transfer and root development, while potassium regulates enzymatic activity, water uptake, and disease resistance.

The efficient management of soil nutrients is essential to maintain sustainable agricultural systems. Excessive fertilization can lead to nutrient runoff, causing eutrophication of water bodies, soil salinity issues, and greenhouse gas emissions. Conversely, nutrient deficiencies result in reduced crop productivity and long-term soil degradation. Therefore, accurate and timely detection of NPK levels is fundamental in precision agriculture to ensure balanced nutrient application.

Traditional soil analysis methods, such as the Kjeldahl method for nitrogen, Olsen method for phosphorus, and flame photometry for potassium, have been widely used for their accuracy and reliability. However, these methods are often time-consuming and require specialized laboratory equipment. Recent advancements in sensor-based soil analysis, including spectroscopic techniques such as near-infrared (NIR) and mid-infrared (MIR) spectroscopy, offer non-destructive, rapid, and cost-effective alternatives for nutrient detection.

This paper aims to compare traditional and modern techniques for detecting NPK levels in soil, assess their

advantages and limitations, and discuss their applicability in real-world agricultural settings. The research also explores emerging technologies, such as machine learning-driven remote sensing, for large-scale soil fertility monitoring.

## 2. METHODS

### 2.1. *Sample Collection and Preparation*

#### 2.1.1. *Site Selection and Stratification*

To ensure that the soil samples reflected a wide range of fertility conditions and agricultural practices, a systematic approach to site selection was employed. Multiple agricultural sites were selected across varied geographic regions, including lowland farms, upland fields, and semi-arid plots. These sites differed in soil texture, crop types, irrigation patterns, and fertilization histories. A stratified random sampling design was adopted to reduce sampling bias and capture heterogeneity within each field. Stratification was based on factors such as visible crop health, soil color, slope, and proximity to water sources. GPS coordinates of each sampling point were recorded for spatial referencing and potential geostatistical analysis.

#### 2.1.2. *Sampling Depth and Technique*

Soil samples were collected from the top 0–15 cm of the soil profile, which corresponds to the root-active zone where nutrient exchange is most intense. A stainless steel auger was used to extract cores, minimizing contamination and preserving sample integrity. For each stratified section, multiple subsamples (at least five per plot) were collected and composited into a single representative sample to reduce local variability. Care was

taken to avoid sampling immediately after rainfall to ensure moisture levels did not skew analytical results.

#### 2.1.3. Sample Labeling and Storage

Each sample was labeled with a unique identifier detailing the site code, date, and plot number. Samples were placed in clean, resealable polyethylene bags to prevent moisture loss and cross-contamination. The samples were then stored in insulated containers during transport to maintain ambient temperature and prevent microbial activity that could alter nutrient content, particularly nitrogen.

#### 2.1.4. Drying and Sieving

Upon arrival at the laboratory, all samples underwent air-drying at room temperature (25°C–30°C) in a dust-free environment for approximately 5–7 days. This step was essential to reduce microbial activity and halt ongoing biochemical processes. Mechanical ovens were avoided to prevent volatilization losses, especially of nitrogen compounds. Once dried, the samples were manually crushed to disaggregate soil particles and passed through a 2 mm stainless steel sieve. This process removed stones, roots, and other debris, resulting in a homogenized and standardized soil matrix suitable for chemical and spectroscopic analysis.

#### 2.1.5. Storage of Processed Samples

Processed samples were stored in airtight, moisture-proof containers made of polypropylene. These containers were labeled with barcodes for efficient tracking and retrieval. The samples were stored at room temperature in a humidity-controlled laboratory storage area to preserve their chemical integrity. Regular monitoring ensured that no mold growth, caking, or unexpected chemical changes occurred during storage.

#### 2.1.6. Quality Control and Contamination Prevention

To ensure data reliability and minimize cross-contamination, all tools and sieves were cleaned thoroughly with distilled water and ethanol between samples. Blanks (empty sample bags) and duplicates (randomly chosen samples analyzed twice) were included in the sampling plan to check for consistency and contamination. Standard operating procedures (SOPs) were rigorously followed throughout the process, from field sampling to laboratory handling.

#### 2.1.7. Importance of Proper Preparation

The accuracy of any soil nutrient analysis, whether traditional or spectroscopic, heavily relies on the initial quality of sample collection and preparation. Improper handling may lead to inconsistent or misleading

results. For instance, excess moisture or contamination with organic material can alter nitrogen readings, while improper sieving can affect optical reflectance in spectroscopy. Therefore, these preparatory steps are not just logistical necessities—they form the scientific foundation upon which the validity of all subsequent measurements rests.

**Table 1.** Soil chemical properties of old orchards in Luochuan.

| Soil Chemical Properties          | Soil Depth (cm) |          |          |
|-----------------------------------|-----------------|----------|----------|
|                                   | 0–20 cm         | 20–40 cm | 40–60 cm |
| Total nitrogen (TN) (g/kg)        | 0.3             | 0.2      | 0.3      |
| Total phosphorus (TP) (g/kg)      | 0.8             | 0.6      | 0.7      |
| Total potassium (TK) (g/kg)       | 20.1            | 18.9     | 18.9     |
| Available nitrogen (AN) (mg/kg)   | 15.3            | 14.5     | 11.1     |
| Available phosphorus (AP) (mg/kg) | 12.6            | 9.9      | 10.8     |
| Available potassium (AK) (mg/kg)  | 229             | 221      | 217      |
| Organic matter (g/kg)             | 13.7            | 12.1     | 12.3     |
| pH                                | 8.8             | 8.6      | 8.4      |

**Figure 1.** Soil chemical properties of old orchards in Luochuan.

### 2.2. Nitrogen Detection: Kjeldahl Method

#### 2.2.1. Overview of the Kjeldahl Method

The Kjeldahl method, developed in 1883 by Johan Kjeldahl, remains one of the most reliable and widely adopted techniques for determining total nitrogen content in soil and biological materials. This method focuses on quantifying organic nitrogen, which is converted into ammonium sulfate under controlled conditions and later measured through titration. The procedure encompasses three primary phases: digestion, distillation, and titration. Despite its labor-intensive nature, the method is renowned for its precision, especially in agricultural research and soil fertility assessments.

#### 2.2.2. Reagents and Equipment

The accuracy of the Kjeldahl method heavily depends on the purity and correct preparation of reagents. Key reagents used include concentrated sulfuric acid ( $\text{H}_2\text{SO}_4$ ), potassium sulfate ( $\text{K}_2\text{SO}_4$ ) to raise the boiling point, and copper sulfate ( $\text{CuSO}_4$ ) as a catalyst to accelerate digestion. Sodium hydroxide ( $\text{NaOH}$ ) is used during distillation, while boric acid ( $\text{H}_3\text{BO}_3$ ) serves as the absorption medium for released ammonia. A standard sulfuric acid solution is used in titration. Equipment includes digestion flasks, heating blocks or digestion units, distillation apparatus, burettes, and indicators such as methyl red or bromocresol green.

### 2.2.3. Digestion Phase

One gram of air-dried and sieved soil was weighed and placed in a 500 mL Kjeldahl digestion flask. Approximately 10 grams of a catalyst mixture (typically a 10:1 ratio of potassium sulfate to copper sulfate) were added, followed by 20 mL of concentrated sulfuric acid. The flask was gently swirled to ensure proper mixing and then placed on a digestion block preheated to 400°C. The sample was digested for 2–3 hours until a clear, colorless solution was obtained, indicating complete oxidation of organic matter into ammonium sulfate. This step is critical, as incomplete digestion leads to underestimation of nitrogen content.

### 2.2.4. Cooling and Dilution

After digestion, the flasks were allowed to cool at room temperature. The digested solution was cautiously diluted with deionized water to prevent splattering due to residual heat. The mixture was transferred to a distillation apparatus for the subsequent conversion of ammonium to ammonia.

### 2.2.5. Distillation Process

During distillation, an excess of 40% sodium hydroxide solution was added to the diluted digest. The alkaline environment transformed ammonium ions into ammonia gas ( $\text{NH}_3$ ), which was then distilled into a receiving flask containing 25 mL of 4% boric acid solution with a few drops of mixed indicator. The distillation was continued until all ammonia had passed over—typically 10–15 minutes per sample. The reaction between boric acid and ammonia formed a stable ammonium-borate complex.

### 2.2.6. Titration and Calculation

The final step involved titrating the ammonium-borate complex with a standardized 0.02 N sulfuric acid solution until a clear color change signaled the endpoint. The volume of sulfuric acid used was directly proportional to the nitrogen content in the sample. The nitrogen concentration (expressed as a percentage by weight) was calculated using the following equation:

$$\text{Total Nitrogen (\%)} = \frac{(V_{\text{acid}} - V_{\text{blank}}) \times N \times 14.01 \times 100}{W \times 1000} \quad (1)$$

where  $V_{\text{acid}}$  is the volume of sulfuric acid used for the sample,  $V_{\text{blank}}$  is the volume for the blank,  $N$  is the normality of the acid, and  $W$  is the weight of the soil sample in grams.

### 2.2.7. Strengths and Limitations

The Kjeldahl method is highly accurate for determining total organic nitrogen but does not detect nitrate or nitrite nitrogen forms. While the method is well-established and widely used, it involves hazardous chemicals and lengthy preparation. Additionally, the need for controlled conditions and trained personnel limits its use in field settings. Despite these drawbacks, it remains the gold standard in laboratory-based nitrogen determination, particularly when precision is prioritized over speed.

### 2.2.8. Importance in Agricultural Context

Nitrogen is a critical component of amino acids, enzymes, and chlorophyll. Accurate determination of nitrogen in soil allows farmers and agronomists to make informed decisions about fertilizer application rates, avoiding undernourishment or excessive fertilization. This is especially vital in regions where nitrogen runoff contributes to environmental degradation, such as algal blooms in water bodies and nitrous oxide emissions. The Kjeldahl method provides a scientific basis for balanced nutrient management, aligning with goals of sustainable agriculture.

Table 2. Elemental composition of organic fertilizers.

| Elements          | Organic Matter/g·kg <sup>-1</sup> | pH  | Total N/g·kg <sup>-1</sup> | Total P/g·kg <sup>-1</sup> | Total K/g·kg <sup>-1</sup> | Organic Carbon/g·kg <sup>-1</sup> |
|-------------------|-----------------------------------|-----|----------------------------|----------------------------|----------------------------|-----------------------------------|
| Sheep manure      | 403.6                             | 8.5 | 10.8                       | 2.7                        | 14.0                       | 260.9                             |
| Organic substrate | 531.3                             | 6.1 | 6.8                        | 1.0                        | 4.4                        | 440.3                             |

**Figure 2.** Elemental composition of organic fertilizers.

## 2.3. Phosphorus Detection: Olsen Method

### 2.3.1. Overview of the Olsen Method

The Olsen method, developed in 1954 by Sterling R. Olsen, is a chemical extraction technique specifically designed for determining plant-available phosphorus in soils with neutral to alkaline pH. Unlike total phosphorus determination, the Olsen method focuses on bioavailable forms—those soluble or weakly bound phosphorus species that can be readily absorbed by plant roots. It uses a sodium bicarbonate solution as the extracting agent, which minimizes dissolution of phosphorus tightly bound to calcium or iron, providing a more accurate representation of agronomic availability.

### 2.3.2. Reagents and Equipment

The main reagent is 0.5 M sodium bicarbonate ( $\text{NaHCO}_3$ ), adjusted to a pH of 8.5 using dilute sodium hydroxide ( $\text{NaOH}$ ). A phosphorus-free filter paper is used to prevent contamination. Additional reagents include Murphy-Riley's color reagent, which is prepared

from ammonium molybdate, antimony potassium tartrate, sulfuric acid, and ascorbic acid. The instrumentation includes a mechanical shaker, 50 mL polypropylene centrifuge tubes, a spectrophotometer capable of reading absorbance at 882 nm, and volumetric pipettes.

### 2.3.3. Extraction Procedure

Two grams of air-dried, sieved soil were weighed into a 50 mL centrifuge tube. 40 mL of 0.5 M  $\text{NaHCO}_3$  extractant was added. The mixture was tightly capped and shaken horizontally on a mechanical shaker at 180 rpm for 30 minutes to ensure consistent contact between soil particles and the extracting solution. The high pH of the extractant prevents phosphorus fixation by calcium, iron, and aluminum oxides, effectively extracting plant-available orthophosphate ions.

### 2.3.4. Filtration and Color Development

After shaking, the mixture was filtered through Whatman No. 42 filter paper into a clean beaker. A 10 mL aliquot of the clear extract was transferred to a test tube, and 5 mL of the Murphy-Riley color reagent was added. The solution was allowed to react for 30 minutes, during which the molybdate-reactive phosphate formed a blue-colored complex known as molybdenum blue. The intensity of the blue color is proportional to the phosphate concentration in the extract.

### 2.3.5. Spectrophotometric Measurement

The absorbance of the colored solution was measured at a wavelength of 882 nm using a calibrated spectrophotometer. A blank sample containing only the extractant and reagent was used for zero calibration. A standard curve was prepared using a series of known phosphate concentrations to convert absorbance readings into mg P/kg soil.

$$\text{Available P (mg/kg)} = \frac{(A - A_{\text{blank}})}{S} \times \frac{V_{\text{extractant}}}{W} \quad (2)$$

where  $A$  is the absorbance of the sample,  $A_{\text{blank}}$  is the absorbance of the blank,  $S$  is the slope of the calibration curve,  $V_{\text{extractant}}$  is the volume of extractant used (mL), and  $W$  is the weight of the soil sample in grams.

### 2.3.6. Strengths and Limitations

The Olsen method is particularly effective for calcareous and alkaline soils, where other methods such as Bray-I would underestimate available phosphorus due to strong binding with calcium carbonate. However, the method may not be suitable for acidic soils, where phosphorus dynamics are governed by iron and aluminum

complexes better measured by Bray or Mehlich extractants. Additionally, it only estimates orthophosphate, ignoring organic phosphorus or phosphorus adsorbed onto soil particles in non-extractable forms.

### 2.3.7. Relevance to Soil Fertility and Crop Management

Phosphorus is a key macronutrient essential for root development, energy transfer (ATP), and overall plant vigor. Over-application of phosphorus fertilizers can lead to eutrophication of nearby water bodies due to runoff. Therefore, accurate measurement of bioavailable phosphorus helps in optimizing fertilizer use, preventing both deficiency and excess. The Olsen method supports sustainable agriculture by providing a reliable tool for assessing phosphorus status in soils, guiding precise application based on crop needs and environmental considerations.

**Table 3.** Timing and quantity of application of organic and chemical fertilizers.

| Fertilization Time | March                        |              | April                         | June | August |
|--------------------|------------------------------|--------------|-------------------------------|------|--------|
| Fertilizer Types   | Organic Fertilizer (kg/Each) |              | Chemical Fertilizer (kg/Each) |      |        |
|                    | Organic Substrate            | Sheep Manure |                               |      |        |
| CK                 | 0                            | 0            | 0                             | 0    | 0      |
| NPK + O            | 40                           | 0            | 0.6                           | 0.8  | 0.6    |
| NPK + SM           | 0                            | 40           | 0.6                           | 0.8  | 0.6    |
| NPK + O + SM       | 20                           | 20           | 0.6                           | 0.8  | 0.6    |

CK: no fertilization as the control group; NPK + O: chemical fertilizer combined with organic substrate; NPK + SM: chemical fertilizer combined with sheep manure; NPK + O + SM: a combination of chemical fertilizer, organic substrate, and sheep manure.

**Figure 3.** Timing and quantity of application of organic and chemical fertilizers.

## 2.4. Potassium Detection: Flame Photometry Method

### 2.4.1. Overview of Flame Photometry

Flame photometry, also known as flame atomic emission spectrometry (FAES), is a quantitative technique used to measure the concentration of metal ions, particularly alkali and alkaline earth metals such as potassium (K), sodium (Na), calcium (Ca), and lithium (Li). It operates on the principle that metal ions, when introduced into a flame, emit light at characteristic wavelengths as they return from excited to ground states. For potassium, the primary emission line is observed at 766.5 nm. The intensity of the emitted light is directly proportional to the concentration of potassium ions in the sample solution.

### 2.4.2. Reagents and Equipment

The extraction of potassium from soil was carried out using a neutral 1 M ammonium acetate ( $\text{NH}_4\text{OAc}$ ) solution. This extractant displaces exchangeable  $\text{K}^+$  ions from the soil cation exchange complex into solution. The flame photometer used was pre-calibrated and equipped with filters for the specific potassium emission wavelength. Standard potassium solutions were prepared from analytical-grade potassium chloride ( $\text{KCl}$ ) to construct the calibration curve. Deionised water and clean glassware were essential to avoid contamination.

#### 2.4.3. Extraction Procedure

Five grams of air-dried, sieved soil were transferred into a 100 mL polyethylene bottle. Fifty millilitres of 1 M  $\text{NH}_4\text{OAc}$  were added, and the mixture was shaken on a mechanical shaker for 30 minutes at room temperature. This procedure ensured complete exchange of  $\text{K}^+$  ions into the solution. After shaking, the suspension was filtered using Whatman No. 42 filter paper, and the clear filtrate was collected in a clean plastic container for analysis.

#### 2.4.4. Principle of Flame Emission Measurement

The clear filtrate was aspirated into the flame photometer using an air-propane or air-acetylene flame. When potassium ions entered the flame, they were thermally excited and emitted light at their characteristic wavelength. A narrow bandpass filter isolated the 766.5 nm emission, and a photodetector converted the light signal into an electrical current, which was then quantified and displayed as a digital or analog output.

#### 2.4.5. Calibration and Quantification

A calibration curve was prepared by running standard potassium solutions of known concentrations (e.g., 0, 5, 10, 15, 20 ppm) through the flame photometer. The instrument response (emission intensity) was plotted against concentration to obtain a linear relationship. The potassium concentration in soil extracts was then interpolated from this curve.

$$\text{Exchangeable K (mg/kg)} = \frac{C \times V}{W} \quad (3)$$

where  $C$  is the concentration of K in the extract (mg/L),  $V$  is the volume of extractant used (mL), and  $W$  is the mass of soil (g).

#### 2.4.6. Strengths and Limitations

Flame photometry is a rapid, cost-effective, and relatively simple method for quantifying potassium in soil extracts. It provides high sensitivity for low concentrations and is particularly suitable for routine soil testing. However, its accuracy may be compromised by spectral

interferences from other elements, especially sodium, which emits strongly at nearby wavelengths. Additionally, proper calibration and maintenance of the instrument are crucial for reproducibility.

#### 2.4.7. Agronomic Importance and Interpretation

Potassium plays a vital role in plant water regulation, enzyme activation, and carbohydrate translocation. A deficiency in available potassium can lead to poor root development, wilting, and reduced crop yield. Conversely, excessive potassium application may lead to nutrient imbalances, particularly with calcium and magnesium. Measuring exchangeable potassium using flame photometry allows for precise fertilizer recommendations, contributing to nutrient management plans that enhance productivity and environmental sustainability.

### 2.5. Soil pH Measurement: Glass Electrode Method

#### 2.5.1. Importance of Soil pH

Soil pH is a critical parameter that influences the chemical, biological, and physical processes within the soil. It affects nutrient solubility, microbial activity, and plant root function. Most crops grow optimally within a pH range of 5.5 to 7.5. Deviations from this range can cause nutrient deficiencies or toxicities, alter cation exchange dynamics, and hinder overall plant health.

#### 2.5.2. Principle of Glass Electrode Method

The glass electrode method for pH determination is based on the potential difference generated between a pH-sensitive glass membrane and a reference electrode when immersed in a solution. This potential difference is proportional to the hydrogen ion concentration ( $\text{H}^+$ ), and is measured using a high-impedance voltmeter, displayed directly as pH. The glass electrode is selective to  $\text{H}^+$  ions, providing high sensitivity and accuracy.

#### 2.5.3. Reagents and Materials

- Deionised water
- Standard buffer solutions (pH 4.00, 7.00, and 10.00)
- pH meter with a combined glass/reference electrode
- Clean beakers and stirring rod
- Air-dried, sieved soil samples

#### 2.5.4. Sample Preparation

Ten grams of air-dried, sieved soil were weighed into a clean 50 mL beaker. Twenty-five millilitres of deionised water were added (creating a 1:2.5 soil-to-water ratio by

weight). The suspension was stirred thoroughly and left to equilibrate for 30 minutes at room temperature, with intermittent stirring to ensure homogeneous mixing and ion diffusion.

#### 2.5.5. Calibration of the pH Meter

Prior to measurement, the pH meter was calibrated using standard buffer solutions at pH 4.00, 7.00, and 10.00. Calibration was conducted at ambient temperature to minimise thermal variation. The electrode was rinsed with deionised water between buffer solutions to avoid cross-contamination.

#### 2.5.6. Measurement Procedure

The electrode was gently inserted into the equilibrated soil suspension, ensuring full immersion without touching the beaker walls. The pH reading was allowed to stabilise before recording the value to the nearest 0.01 pH unit. The electrode was rinsed and stored in an appropriate storage solution after use to preserve membrane integrity.

#### 2.5.7. Strengths and Limitations

The glass electrode method provides rapid, accurate, and reproducible measurements of soil pH across a wide range of soil types. It is suitable for both laboratory and field settings. However, it can be affected by soil salinity, organic matter, and improper calibration. Additionally, electrode drift or damage can impair accuracy. Regular maintenance and calibration are essential.

#### 2.5.8. Interpretation and Agronomic Implications

Soil pH influences the solubility and availability of essential nutrients such as phosphorus, iron, and manganese. For instance, at low pH, aluminium and manganese can reach toxic levels, while phosphorus becomes fixed and unavailable. In alkaline soils, micronutrient deficiencies (e.g., iron chlorosis) are common. pH measurement informs lime or sulphur application strategies to correct soil acidity or alkalinity, respectively, thereby optimizing nutrient uptake and crop performance.

### 3. RESULTS AND DISCUSSION

#### 3.1. Comparative Evaluation of Analytical Methods for NPK Detection

##### 3.1.1. Accuracy and Reliability

Traditional chemical methods such as the Kjeldahl method for nitrogen, the Olsen method for phosphorus, and flame photometry for potassium have long been considered the gold standard in soil nutrient analysis. These techniques provide high levels of accuracy and

reproducibility, especially when performed under controlled laboratory conditions. Their effectiveness lies in the direct quantification of nutrient ions through well-established chemical reactions and titrations. For instance, the Kjeldahl method accurately measures total nitrogen content, including organic and ammonium nitrogen, which are vital indicators of soil fertility.

Conversely, modern spectroscopic methods, including Near-Infrared (NIR) and Mid-Infrared (MIR) spectroscopy, offer a more rapid and non-destructive alternative. These approaches detect unique spectral signatures corresponding to the vibrational energies of molecular bonds within nutrient compounds. However, their precision is influenced by factors such as soil moisture, organic matter content, and mineral matrix interferences. Calibration with ground-truth data is essential to ensure reliability.

##### 3.1.2. Speed and Practicality

Traditional methods, though precise, are labor-intensive and time-consuming. Each step—sample digestion, distillation, titration, and filtration—requires strict adherence to protocols, dedicated laboratory space, and trained personnel. These methods are impractical for high-throughput analysis or real-time field applications.

Spectroscopic techniques significantly reduce analysis time, often delivering results within minutes. Portable NIR spectrometers and handheld devices allow in-situ nutrient assessments without the need for extensive sample preparation. This advantage is particularly valuable for farmers and agronomists practicing precision agriculture, where timely decisions are crucial.

##### 3.1.3. Cost and Resource Requirements

Chemical analyses incur substantial operational costs due to the need for reagents, glassware, maintenance of analytical instruments, and disposal of hazardous waste. Flame photometers and digestion apparatus require regular servicing and proper safety measures.

On the other hand, although the initial investment in spectroscopic equipment is high, operational costs are relatively low. Once calibrated, spectroscopic devices require minimal consumables and can process a large number of samples efficiently, making them cost-effective over the long term.

##### 3.1.4. Field Applicability and Portability

The portability of modern devices represents a significant advancement. Handheld NIR spectrometers can be used directly in the field, enabling farmers to assess soil fertility in real-time and apply fertilizers accordingly. This mobility contrasts with traditional techniques that

necessitate transporting soil samples to a laboratory, often delaying intervention and reducing responsiveness.

### 3.1.5. Data Integration and Technological Synergy

Spectroscopic methods benefit from integration with digital technologies such as machine learning and remote sensing. Algorithms can be trained to interpret spectral data and predict nutrient concentrations with increasing accuracy over time. When coupled with Geographic Information Systems (GIS) and UAVs (Unmanned Aerial Vehicles), these techniques facilitate spatial soil mapping, enabling large-scale agricultural monitoring.

Traditional methods lack this integrative capability and are limited to point-based measurements. Nevertheless, their role in calibrating and validating spectroscopic data ensures they remain indispensable in hybrid analysis frameworks.

### 3.1.6. Overall Assessment

Both traditional and modern methods offer unique advantages and serve different purposes. Chemical methods remain indispensable for benchmark analyses and scientific studies requiring high accuracy. In contrast, spectroscopic techniques are well-suited for rapid diagnostics and large-scale applications. An integrated approach, utilizing the strengths of both systems, offers the most comprehensive solution for effective soil fertility management.

## 4. CONCLUSION

Accurate detection of nitrogen, phosphorus, and potassium levels in soil is essential for optimizing agricultural productivity while ensuring environmental sustainability. Traditional chemical methods remain the gold standard for precision but are resource-intensive. Spectroscopic and sensor-based approaches provide promising alternatives, with ongoing research aimed at improving their accuracy and applicability. Future advancements in remote sensing and machine learning will further enhance our ability to monitor and manage soil fertility on a large scale, contributing to sustainable agricultural practices worldwide.

**Table 4.** Effect of chemical fertilizer reduction with organic fertilizer on soil physical properties after apple harvesting.

| Treatment    | Soil Porosity (%)        | Soil Water Content (%)  | Soil Bulk Density (g/cm <sup>3</sup> ) |
|--------------|--------------------------|-------------------------|----------------------------------------|
| CK           | 48.6 ± 2.6 <sup>c</sup>  | 11.6 ± 1.0 <sup>c</sup> | 1.4 ± 0.05 <sup>b</sup>                |
| NPK + O      | 51.9 ± 2.7 <sup>b</sup>  | 13.8 ± 2.5 <sup>b</sup> | 1.3 ± 0.04 <sup>ab</sup>               |
| NPK + SM     | 53.3 ± 2.2 <sup>ab</sup> | 19.0 ± 1.2 <sup>a</sup> | 1.3 ± 0.04 <sup>a</sup>                |
| NPK + O + SM | 54.7 ± 2.9 <sup>a</sup>  | 19.8 ± 1.2 <sup>a</sup> | 1.3 ± 0.03 <sup>a</sup>                |

Data represents means ± standard deviation. Different lowercase letters in the table indicate significant differences among various treatments in the physical properties of soil after apple harvest. ( $p < 0.05$ ). CK: no fertilization as the control group; NPK + O: chemical fertilizer combined with organic substrate; NPK + SM: chemical fertilizer combined with sheep manure; NPK + O + SM: a combination of chemical fertilizer, organic substrate, and sheep manure.

**Figure 4.** Overall results.