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Communication

Evaluation of the Reliability of In Situ, Real-Time Probes for Precise Determination of Nitrogen, Phosphorus and Potassium in Agricultural Crops

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Highlights

The results showed no significant correlation between the investigated in situ probe readings and soil N, P, or K concentrations measured in the laboratory in either clay-loam or sandy soils. This finding suggests that the NPK probes tested in this study are unable to provide reliable real-time measurements of soil N, P, and K concentrations:

What are the main findings?

- The investigated probes, for N, P, and K real-time determination, are not reliable
- The probes are not suitable for precise fertilization management.

What are the implications of the main findings?

- The use of the investigated N, P, and K probes can lead to erroneous evaluation of soil N, P, and K fertility.

Abstract

Reliable tools for assessing soil nutrient availability are essential for the accurate determination of fertilizer application rates. The aim of this study was to evaluate the reliability of commercially available electrochemical sensors for the real-time determination of water-soluble N, P, and K in soil as indicators of nutrient supply to crops. The experiment was conducted under both greenhouse and field conditions using seven probe models. Four probes (designated 1–4) were equipped with three sensors for the measurement of N, P, and K. Probes 5, 6, and 7 were equipped with sensors for N, P, K, electrical conductivity (EC), pH, soil temperature, and soil moisture, although probe 7 was manufactured by a different company. Each probe was inserted into 4 L pots filled first with a clay-loam soil and subsequently with a sandy soil. The soils were irrigated with nutrient solutions containing different concentrations of N, P, and K in order to modify nutrient concentrations in the soil solution and compare sensor readings with values obtained through standard chemical analyses. The results showed no significant correlation between probe readings and soil N, P, or K concentrations in either clay-loam or sandy soils. At the same time, all probes exhibited a constant relationship among N, P, and K readings regardless of soil texture or nutrient concentration. This finding suggests that the probe algorithms rely on a single measured variable that is subsequently converted into multiple output variables using

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fixed conversion coefficients. In conclusion, the NPK probes tested in this study were unable to provide reliable real-time measurements of soil N, P, and K concentrations.

Keywords: precision agriculture; urea; potassium chloride; metaphosphoric acid

1. Introduction

The availability of reliable tools for monitoring soil nutrient concentrations is crucial for establishing effective fertilization management strategies in agricultural systems. Although several proximal sensing probes are currently available on the market [1], they often present limitations related to operational complexity and measurement accuracy. Proximal sensing encompasses a range of technologies in which sensors operate in direct contact with the target object or at close range [2]. In well-aerated soils, nitrate (NO_3^-) represents the predominant form of nitrogen (N). It is dissolved in the soil water solution and can readily move along the soil profile with water flow; therefore, it is highly susceptible to leaching when soil moisture exceeds field capacity. Nitrate-N concentration varies widely as a consequence of mineralization, immobilization, root absorption, and other turnover processes. The mobility of other nutrients depends largely on soil properties. Soils with a neutral to slightly alkaline pH, fine textures (such as clay, clay loam, silt, and silt loam), and a high organic matter (OM) content typically exhibit a high cation exchange capacity (CEC), that diminish the concentration of cations, such as potassium (K^+) in the soil solution by retaining them on exchange sites, and limit their leaching potentials. Conversely, soils characterized by low pH, sandy texture, and low OM content generally have a low CEC, which increases the risk of cation leaching through the soil profile. Regardless of soil conditions, phosphorus (P) generally exhibits low mobility, as it tends to precipitate or associate with calcium (Ca^{2+}), aluminum (Al), and iron (Fe) hydroxides. Traditionally, soil nutrients can be measured by soil sampling and off-site laboratory measurements. Laboratory analysis is accurate and easy to perform; however, it is time-consuming and provides results only several days after sampling. Technologies currently available for on-site nutrient determination [3] can be classified according to the sensing principle employed as optical/radiometric, electrochemical, mechanical, and electrical/electromagnetic [4]. Electrical and electromagnetic sensor determinations are based on the measurement of soil solution electrical conductivity (EC) [4] and assess the soil's ability to conduct or store electrical charge by measuring either electrical resistivity or electromagnetic induction. Electromagnetic induction is generated by a transmitter–receiver system that does not require direct contact with the soil and produces a time-varying magnetic field, which induces electrical currents in the soil that are linearly related to its EC. Electrical conductivity has been shown to respond primarily to soil texture and soil moisture; therefore, these factors should be considered when EC is used to estimate soil nutrient availability. In acidic Brazilian soils, a positive relationship between EC and K^+ and Ca^{2+} concentrations was reported [4]. Similarly, a significant correlation between soil extract EC and nitrate was observed, with a coefficient of determination (R^2) of 0.98 [5], suggesting that EC measurements may provide information comparable to that obtained from nitrate analysis [6–8]. In contrast, in calcareous Italian soils, a satisfactory relationship between EC and NO_3^- was found only in clay soils (R^2 = 0.64), whereas no significant correlation was observed in loamy soils [9]. The objective of this short communication was to evaluate the performance of a commercial NPK probe designed to provide real-time measurements of N, P, and K under field conditions.

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2. Materials and Methods

2.1. Probe Description

The probes evaluated in this study are based on electrochemical sensing technology. Six probes manufactured by Weihai JXCT Electronic Technology Co., Ltd. (Weihai City, China; https://www.jxctiot.com/product1/product1177.html, accessed on 15 January 2026) were tested. Four of these probes were equipped with three electrodes designed to estimate soil solution concentrations of N, P, and K (Figure 1), whereas the remaining two probes also incorporated sensors for the measurement of soil pH, EC, temperature, and moisture. An additional probe from a different manufacturer (ComWinTop; CWT Co., Limited, Shenzhen, China—https://store.comwintop.com/products/soil-moisture-temperature-humidity-ec-ph-npk-sensor-7-in-1-rapid-soil-tester-meter, accessed on 15 January 2026) was also evaluated. This probe measures soil N, P, and K concentrations (mg kg^{-1}) over a range of 0–1000 mg kg^{-1} for N and 0–500 mg kg^{-1} for both P and K, with a reported accuracy of ±5% and a response time of 60 s. In addition to the N, P, and K sensors, it includes sensors for soil moisture, temperature, EC, and pH [10].

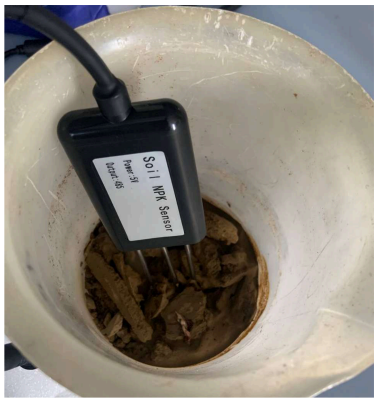

Figure 1. NPK probe used in the experiment.

2.2. Greenhouse Condition and Experiment Set up

The Weihai JXCT Electronic Technology probes were tested in a greenhouse experiment conducted at the Department of Agricultural and Food Sciences, University of Bologna, from November 2024 to February 2025. Greenhouse temperatures were maintained at 18/21 °C (night/day). Although two probes were equipped with additional sensors, only N, P, and K measurements were considered in this study. The six probes (designated 1–6) were sequentially tested in 4 L pots filled with either a clay-loam or sand soil, collected from the Department's experimental farm. The main characteristics of both substrates are reported in Table 1.

Table 1. Selected physical and chemical characteristics of sand and clay-loam soils used in the greenhouse experiment.

Soil Characteristics	Soil Type	
	Sand	Clay Loam
Sand (%)	96	31
Silt (%)	2	35
Clay (%)	2	35
pH	8.12	7.78
Calcium carbonate (%)	2	9
Organic matter (%)	traces	2.5
CEC (meq 100 g^{-1} DW^{-1})	4.71	31.4

DW = dry weight.

The pots were filled with approximately 4.5 kg of fresh soil and irrigated to field capacity, which averaged 21.9% (*w*/*w*; SD = 1.2%) for the clay-loam soil and 9.0% (*w*/*w*; SD = 1.8%) for the sand. Soil evaporation rates were also determined gravimetrically (by weighing a sample of 100 g of soil before and after oven drying) and averaged 47 ± 21 g day^{-1} for the clay-loam soil and 78 ± 13 g day^{-1} for the sand. Three concentrated stock solutions were prepared using urea (46% N), metaphosphoric acid (38.7% P), and potassium chloride (52.4% K) as sources of N, P, and K, respectively. The experiment started with the clay-loam soil. One probe was inserted into each pot, which was irrigated every four days with 160 mL of nutrient solution containing progressively increasing concentrations of N (Table 2). The same procedure was used for P and K, in sequence.

Table 2. Effect of the addition of N on soil N, P, and K concentration as determined by chemical analysis and by the 6 probes in 6 different pots; soils were fertilized with 160 mL of water with 6 different N concentrations obtained by a combination of nitrate and ammonium N.

Soil	Analytical N [1] (mg kg^{-1})	Analytical P (mg kg^{-1})	Analytical K (mg kg^{-1})	Probe N Reading	Probe P Reading	Probe K Reading
Sand	6.71	9.95	23.6	3.11	4.65	9.72
Clay loam	101	17.3	69.7	33.5	47.5	94.7
Significance	*** [2]	ns	***	***	***	***
N rate (mg L^{-1})						
0	6.51 c	22.8 a	42.2	18.2 b	25.8 b	52.0 b
200	35.2 bc	2.89 b	41.0	15.1 b	21.3 b	43.2 b
500	46.9 bc	2.18 b	65.6	16.9 b	23.8 b	47.9 b
1000	126 ab	0.780 b	54.9	19.6 b	30.2 b	55.7 b
2000	163 a	1.27 b	60.3	21.3 b	30.2 b	60.7 b
4000	210 a	0.642 b	73.8	40.8 a	57.2 a	115 a
Significance	***	*	ns	*	*	**
Probe/pot						
1	48.4 b	12.4	43.9	19.3	27.4	55.4
2	56.9 ab	13.7	52.5	20.6	29.1	58.7
3	74.3 a	15.9	51.0	20.2	28.6	57.6
4	64.0 ab	11.8	51.2	19.8	28.2	56.7
5	56.5 ab	15.5	49.6	23.5	33.1	66.6
6	43.3 b	14.2	43.2	13.3	20.0	38.0
Significance	***	ns	ns	ns	ns	ns
soil×rate×probe	***	ns	ns	ns	ns	ns

[1] N is the sum of nitrate and ammonium N analytically determined. [2] ns, *, **, ***: effect not significant or significant at $p \leq 0.05$, $p \leq 0.01$, or $p \leq 0.001$, respectively. Means followed by the same letter are not statistically different ($p \leq 0.05$).

Probe readings were recorded and transmitted to the control unit, which displayed the real-time results through the dedicated smartphone application for the whole duration of the experiment. The values shown here were collected immediately before and after each of the six N applications. The water solution application rate was adjusted to avoid any leaching losses. The same procedure was subsequently repeated for P and K, each applied four times at increasing concentrations. The entire experimental sequence was then repeated using the sandy substrate. At each measurement, approximately 100 g of fresh soil was collected using a cylindrical sampler (4 cm internal diameter, 9 cm length) to ensure sampling at the same depth as the probe electrodes (Figure 2). Soil samples were analyzed for water-soluble N, P, and K by mixing 10 g of soil DW with 100 mL of distilled water and shaking the suspension for 60 min. After sedimentation, the supernatant was filtered and analyzed chemically. Nitrate-N and ammonium-N, the main inorganic forms of soil N,

were determined using an autoanalyzer (AutoAnalyzer AA3; Bran + Luebbe, Norderstedt, Germany). Phosphorus and K concentrations were determined by inductively coupled plasma optical emission spectrometry (ICP-OES; Ametek Spectro Arcos, Kleve, Germany). Data were statistically analyzed to assess the ability of the probes to detect changes in soil N, P, and K concentrations.

Figure 2. Probe inserted in sand soil in the greenhouse experiment.

Also, the second probe, ComWinTop, was tested in an indoor experiment from June to July 2025. We placed the single probe into a 4 L pot filled with both a clay-loam and sand soil in sequence. The characteristics of the soils are the same as previously described and reported in Table 1. The pot was filled with approximately 4.5 kg of fresh soil and watered until field capacity. We used the same 3 concentrated solutions of N, P, and K previously described. The experiment started with clay-loam soil by setting 1 probe in each pot and watering the pot every 4 days with 160 mL of solution at increasing concentrations of N, in order to increase the nutrient concentration in soil solution, gradually. We registered the readings of the probe before and after each addition of N, P, and K. At each reading, we collected a sample of 100 g of fresh soil, as previously described, at the same depth as the electrodes, and we analyzed it as described above.

2.3. Statistical Analysis

The data were statistically analyzed using a factorial experimental design, with two soil types (sand and clay loam), six probes (1, 2, 3, 4, 5, and 6), and nutrient solution application rates ranging from six levels for N (0, 200, 500, 1000, 2000, and 4000), to four levels for P (0, 100, 400, and 800) and K (0, 50, 500, and 2000). When statistical analysis showed a significant effect of a factor, then means were separated by Student–Newman-Keuls test ($p < 0.05$).

2.4. Field Condition and Experiment Set up

Before (in 2024) and after (in 2025) completion of the greenhouse experiment, the six Weihai JXCT Electronic Technology probes were installed in the field, four in a vineyard and two in an apple orchard (Figure 3). Soil characteristics of the vineyard were previously described by [11], whereas those of the apple orchard are reported in Table 1. Probe readings were compared with chemical analyses of soil samples collected during the growing season,

in close proximity to each probe at the same depth as the sensing electrodes, without any addition of fertilizers.

Figure 3. Probe inserted into sandy soil during the field experiment.

2.5. Laboratory Calibration

In 2024, to evaluate the reliability of the measurements provided by the Real-Time NPK probe, a laboratory calibration was performed using aqueous solutions containing known concentrations of N, P, and K individually. Three separate stock solutions (1000 mg L^{-1} of each element) were prepared by dissolving the appropriate amount of ammonium nitrate (NH_4NO_3, 35% N), metaphosphoric acid (HPO_3), and potassium sulfate (K_2SO_4, 44,9% K) in Milli-Q® water. The stock solutions were then serially diluted to obtain the following concentrations (mg L^{-1}): 250, 125, 62.5, 31.2, 15.6, and 3.9. An additional solution consisting of Milli-Q® water only was also included as a blank control. For the calibration, the Real-Time NPK probes were immersed in a 200 mL beaker containing each test solution and left in place for approximately 15–20 min to allow the membranes to equilibrate with the solution. During this period, the probe measured the concentration of the target nutrient and transmitted the data to the control unit, which displayed the results through the dedicated smartphone application. Measurements were performed sequentially from the lowest concentration (blank control) to the highest concentration, with probe membranes rinsed with Milli-Q® water between successive measurements.

3. Results

3.1. Greenhouse Test

As expected, N addition increased soil N concentration, analytically determined, in both sandy and clay-loam soils (Table 2), showing a linear response to the applied rates. On average, soil N concentrations were higher in the clay-loam soil than in the sandy soil. Table 2 shows a significant interaction among soil type, N application rate, and probe readings. A detailed examination of the individual effects and their interactions was not pursued because it falls outside the scope of the present study, whose primary objective was to evaluate the overall reliability of the probe rather than its performance under specific soil and nutrient conditions. Nitrogen application did not affect soil K concentrations, while P showed a decrease following N addition (Table 2, upper third column). Regarding the response of the Weihai JXCT Electronic Technology probes, all six probes exhibited a similar pattern. The probes consistently reported higher N, P, and K concentrations in the clay-loam soil than in the sandy soil and showed an increase in readings only at the highest N application rate (4000 mg L^{-1}) (Table 2, upper section, last three columns). Analysis of

the soil samples collected from the different pots (Table 2, lower section) showed that only pot 3 had a significantly higher N concentration than pots 1 and 6, whereas no differences were detected for P or K concentrations. In contrast, no significant differences among probe readings were observed for the measured N, P, or K values (Table 2, lower section, last three columns).

No significant correlation was found between analytically determined soil mineral N concentrations and the values reported by the probes when data from the two soils were pooled (Figure 4). Similar results were obtained when the two soils were analyzed separately. Coefficients of determination were 0.11 and 0.05 for the clay-loam (Figure 5a) and sandy soils (Figure 5b), respectively. In the clay-loam soil, mineral N concentrations determined by laboratory analysis reached values close to 1000 mg kg^{-1}, whereas the maximum value reported by the probe was approximately 50 mg kg^{-1}. In the sandy soil, the maximum mineral N concentration was approximately 30 mg kg^{-1}, as determined by both laboratory analysis and probe measurements (Figure 5).

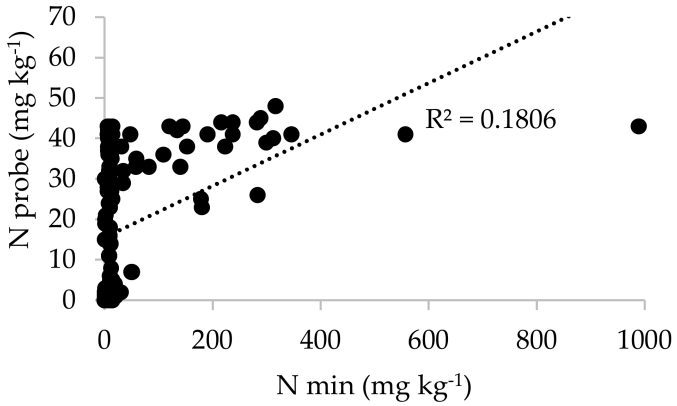

Figure 4. Correlation between mineral N soil concentration analytically determined and N estimated by all the 6 probes in both loam and sand soil. R^2 = coefficient of determination.

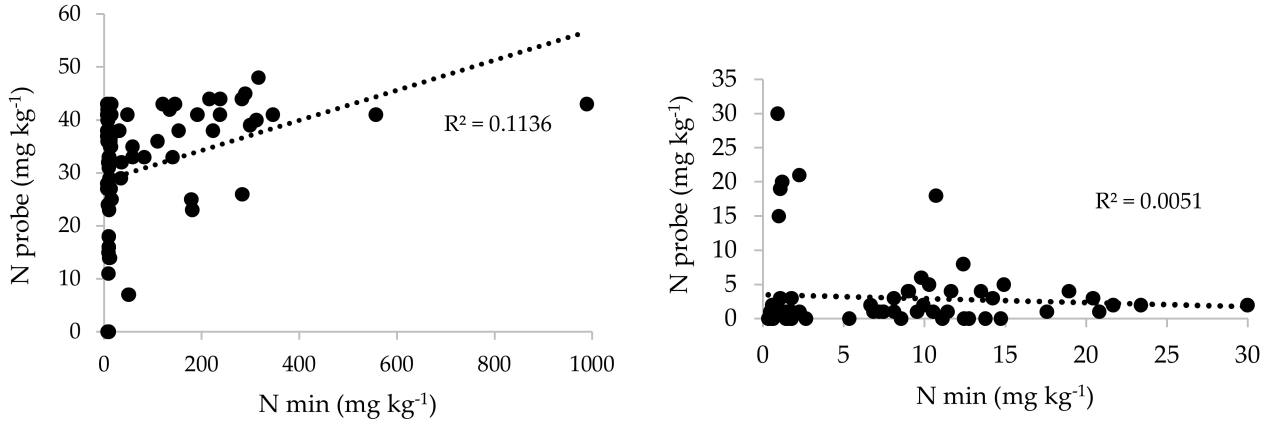

Figure 5. Correlation between mineral N soil concentration and N estimated by all the 6 probes in clay-loam (**a**) and sandy (**b**) soil. R^2 = coefficient of determination.

When the performance of individual probes was evaluated separately for each soil type, no significant correlation was found between probe readings and analytically determined soil N concentrations for any of the six probes (Figures 6 and 7). Coefficient of determination ranged between 0.08 for probe 3 in the sandy soil and 0.24 for probe 2 in the clay-loam soil (Figures 6 and 7).

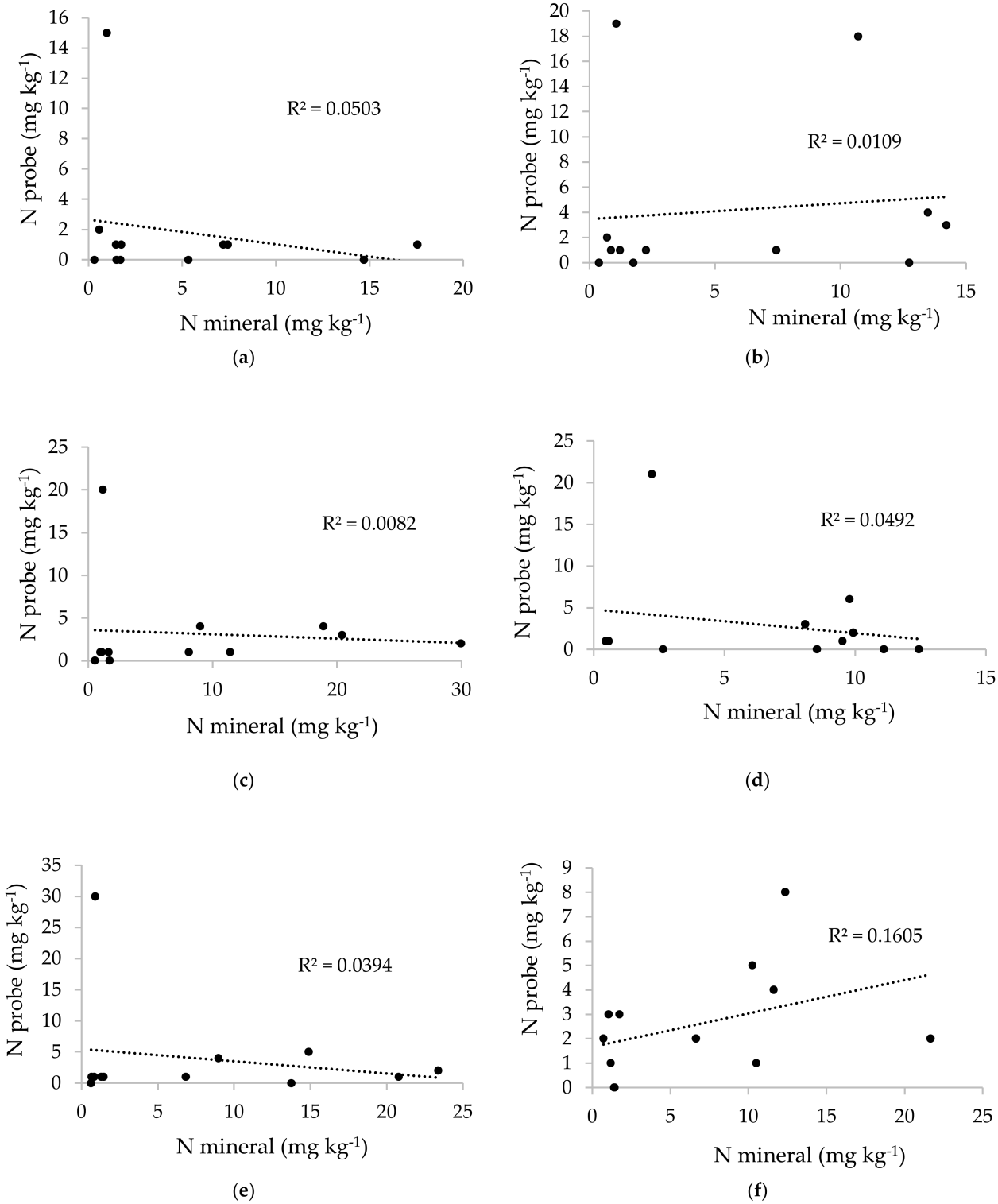

Figure 6. Correlation between mineral N soil concentration analytically determined and N estimated by every single probe in sandy soils; probe 1 (**a**), probe 2 (**b**), probe 3 (**c**), probe 4 (**d**), probe 5 (**e**), and probe 6 (**f**). R^2 = coefficient of determination.

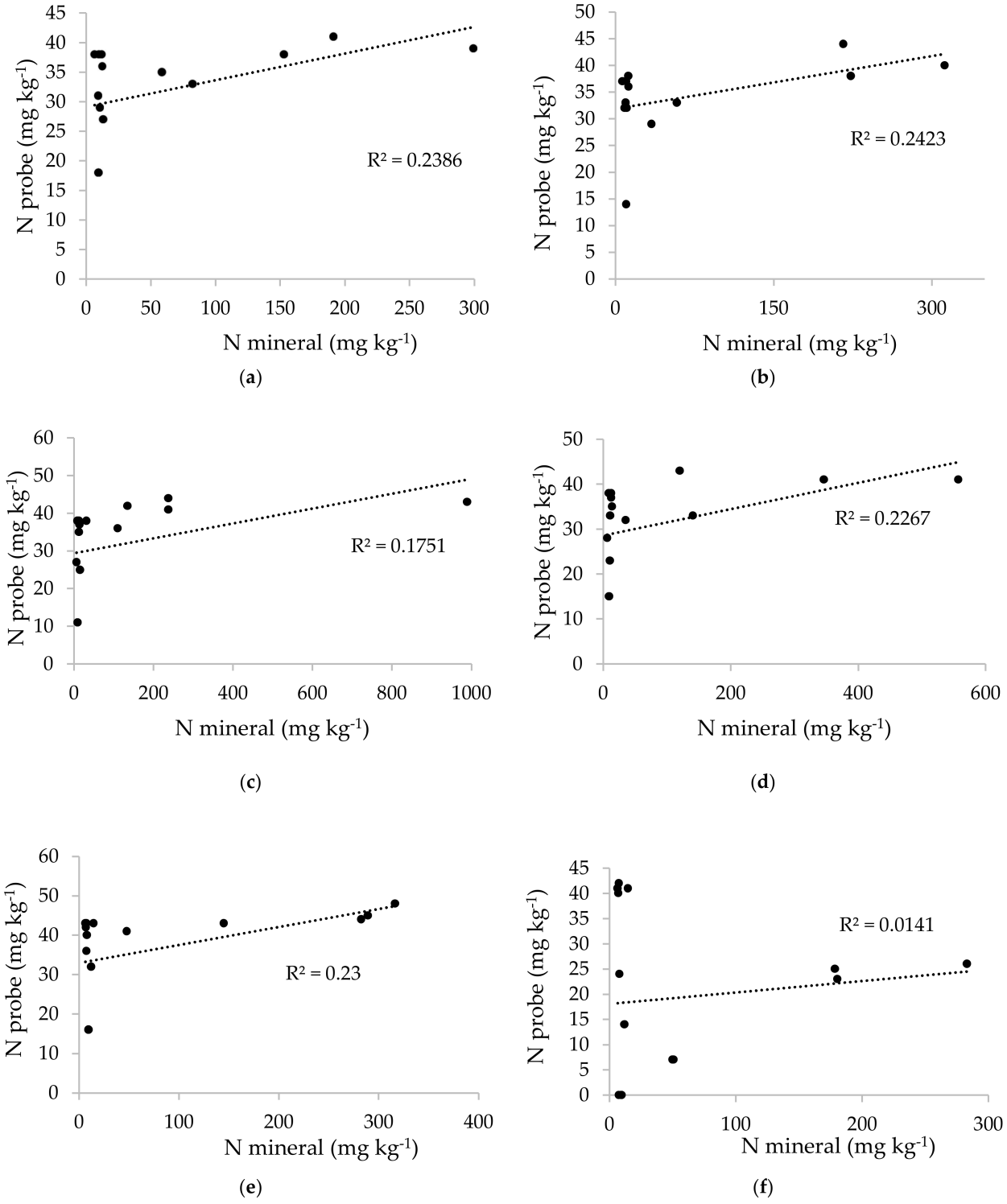

Figure 7. Correlation between mineral N soil concentration analytically determined and N estimated by every single probe in clay-loam soils; probe 1 (**a**), probe 2 (**b**), probe 3 (**c**), probe 4 (**d**), probe 5 (**e**), and probe 6 (**f**). R^2 = coefficient of determination.

As expected, P application increased the concentration of water-soluble P in the soil (Table 3). However, the increase was not linearly related to the application rate, as no significant differences were observed as induced by the different P rates (Table 3, upper section, second column). As observed for N, soil P concentrations were generally higher in the clay-loam soil than in the sandy soil (Table 3). The tested probes were insensitive to P addition, showing similar readings across all application rates. On average, probe readings

were higher in the clay-loam soil than in the sandy soil (Table 3). When individual pots were considered (Table 3, lower section), pots 5 and 6 exhibited higher water-soluble P concentrations than pots 1 and 4. In contrast, the probes reported higher P, N, and K values in pot 5 than in pot 6 (Table 3, columns 3–5).

Table 3. Effect of the addition of P on soil P concentration as determined by chemical analysis and on P, N, and K as determined by the 6 probes in 6 different pots; soils were fertilized with 160 mL of water with 4 different P concentrations obtained from metaphosphoric acid.

Soil	Analytical P (mg kg^{-1})	Probe P Reading	Probe N Reading	Probe K Reading
Sand	6.95	4.91	3.27	10.2
Clay loam	9.51	47.3	33.2	94.1
Significance	*** [1]	***	***	***
P rate (mg L^{-1})				
0	1.60 b	25.9	18.1	51.7
100	21.8 a	28.6	20.1	57.5
400	31.9 a	22.8	16.1	46.1
800	27.5 a	28.1	19.6	56.5
Significance	***	ns	ns	ns
Probe/pot				
1	4.52 b	25.8 ab	18.1 ab	52.1 ab
2	8.90 ab	27.5 ab	19.5 ab	55.5 ab
3	7.31 ab	27.2 ab	19.2 ab	54.8 ab
4	5.18 b	26.7 ab	18.8 ab	53.8 ab
5	13.2 a	31.2 a	22.1 a	62.9 a
6	10.7 a	18.1 b	11.8 b	33.9 b
Significance	***	*	**	**
soil × rate × probe	***	ns	ns	ns

[1] ns, *, **, ***: effect not significant or significant at $p \leq 0.05$, $p \leq 0.01$ or $p \leq 0.001$, respectively. Means followed by the same letter are not statistically different ($p \leq 0.05$).

As expected, K application increased soil K concentration (Table 4, second column). However, this effect was observed only at the highest application rate. As previously observed for N and P, soil K concentrations were generally higher in the clay-loam soil than in the sandy soil (Table 4). The probes responded to the highest K application rate (2000 mg L^{-1}) by reporting higher K values compared with the lowest rate (50 mg L^{-1}). However, the same response was also observed for N and P, despite the fact that only K had been added (Table 4, columns 3–5, upper section). When individual pots were considered, no significant differences in soil K concentration were detected among pots (Table 5, lower section, second column). In contrast, probe readings for K, N, and P were consistently higher in pot 5 than in pot 6 (Table 4).

The performance of the probes in the two soils was further evaluated through correlation analysis. When all observations collected from the different probes and soils were pooled, a linear relationship was observed among the three nutrients when analyzed in pairs. In particular, the values reported for N and P were almost perfectly correlated, with an R^2 close to 1.0 (Figure 8). A similarly strong relationship was observed between P and K (Figure 9). Inspection of the regression equations revealed that the ratios among the values reported for the three nutrients were remarkably constant. The ratio between N and P values was approximately 1.4, whereas the ratio between K and P values was approximately 2.0. Consequently, the relationship among the three outputs remained essentially unchanged regardless of soil type, nutrient treatment, or probe, with fixed ratios of N:P = 1.4, K:P = 2.0, and N:K = 2.8.

Table 4. Effect of the addition of K on soil K concentration as determined by chemical analysis and by the 6 probes in 6 different pots; soils were fertilized with 160 mL of water with 4 different K concentrations obtained by potassium chloride.

Soil	Analytical K (mg kg^{-1})	Probe K Reading	Probe N Reading	Probe P Reading
Sand	23.2	9.72	3.11	4.65
Clay loam	58.5	97.7	35.0	49.8
Significance	*** [1]	***	***	***
K rate (mg L^{-1})				
0	40.1 b	47.4 ab	16.6 ab	23.7 ab
50	21.5 b	37.3 b	12.8 b	18.3 b
500	9.94 b	55.9 a	19.7 ab	27.7 ab
2000	101 a	51.8 a	28.8 a	40.8 a
Significance	***	***	***	***
Probe/pot				
1	37.3	46.9 ab	17.7 ab	24.5 ab
2	38.5	49.2 ab	18.2 ab	25.7 ab
3	39.1	50.1 ab	18.5 ab	26.1 ab
4	40.7	49.0 ab	18.0 ab	25.7 ab
5	41.3	57.6 a	21.3 a	30.0 a
6	35.4	31.7 b	12.4 b	19.0 b
Significance	ns	**	***	**
soil × rate × probe	ns	**	**	*

[1] ns, *, **, ***: effect not significant or significant at $p \leq 0.05$, $p \leq 0.01$ or $p \leq 0.001$, respectively. Means followed by the same letter are not statistically different ($p \leq 0.05$).

Table 5. Soil N, P, and K concentrations as detected by chemical analysis and real-time probes, on 1 July 2024.

Probe [1]	Probe Readings			Laboratory (mg kg^{-1})		
	N	P	K	N	P	K
1	43	61	122	6.24	8.28	41.5
2	39	55	110	5.31	6.04	60.8
3	44	62	125	18.6	24.6	40.3
4	44	62	125	33.4	4.95	48.9
5	43	61	122	49.3	1.62	68.7
6	61	85	171	24.2	2.56	45.7

[1] Probe 1, 2, 3, and 4 in the vineyard; probe 5 and 6 in the apple orchard.

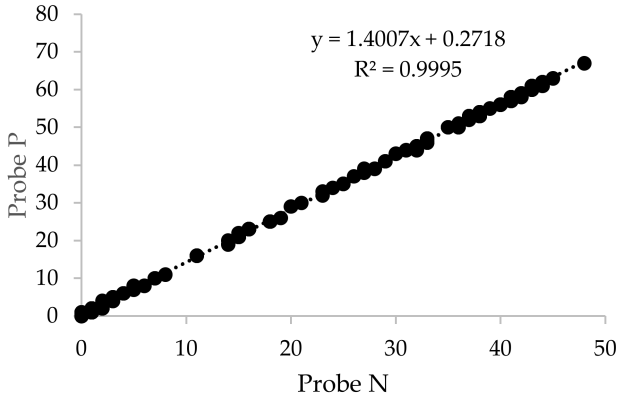

Figure 8. Correlation between available soil N and P concentrations as estimated by the probes. R^2 = coefficient of determination.

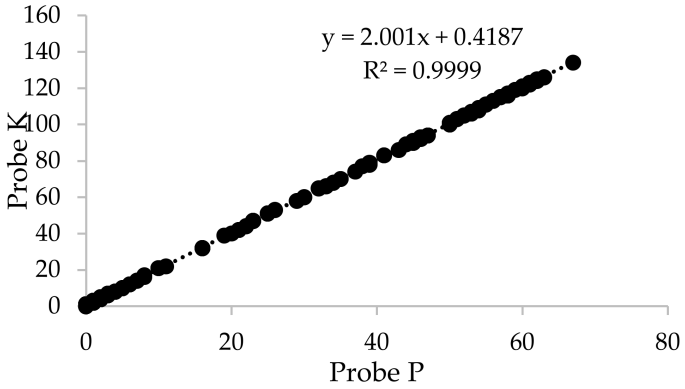

Figure 9. Correlation between P and K soil concentrations as estimated by the probes. R^2 = coefficient of determination.

Similar results were obtained with the second probe model, ComWinTop (Figure 10).

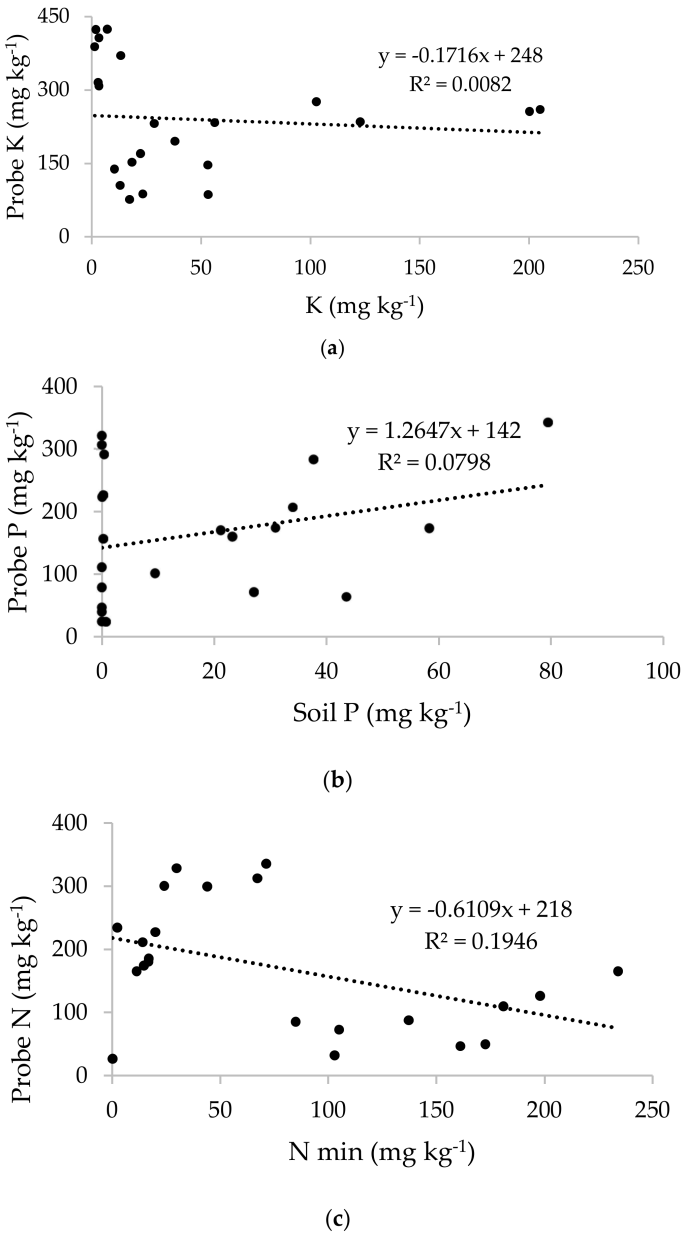

Figure 10. Correlation soil K and K estimated by the ComWinTop probes (**a**), soil P and P estimated by the probes (**b**), soil N and N estimated by the probes (**c**).

No significant correlation was found between soil N, P, and K concentrations determined by laboratory analyses and the corresponding values reported by the probe ComWinTop. In contrast, as observed for the previous probes, a correlation was found among the N, P, and K values reported by the sensor (Figure 11).

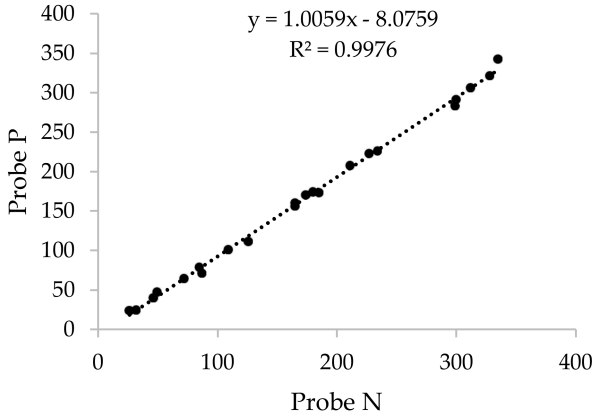

Figure 11. Correlation between N and P estimated by the probe ComWinTop. R^2 = coefficient of determination.

3.2. Field Trial

The results obtained under field conditions were consistent with those observed in the greenhouse experiment, showing no significant correlation between probe readings and analytically determined nutrient concentrations throughout the growing season. As an example, Table 5 shows the data collected on 1 July 2024, in the field and after analytical laboratory determinations.

3.3. Laboratory Calibration

Table 6 shows that probe readings increased with increasing N concentration in the aqueous solution. As the N concentration increased from 0 to 250 mg N L^{-1}, the probe readings for N also increased, from 0 to 42, with a similar response observed for all tested probes. However, the same increasing trend was also observed for the P and K readings, despite the fact that neither P nor K was added to the calibration solutions.

Table 6. Probe readings in response to increasing N concentrations in aqueous solutions.

Solution N (mg L^{-1})	Probe Readings																	
	N						P						K					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
15.6	4	4	4	5	8	7	6	6	6	7	12	10	12	12	13	14	24	21
31.2	14	11	14	11	22	22	20	15	20	16	31	31	41	31	40	31	63	63
62.5	28	27	29	28	36	39	39	38	40	39	50	55	78	76	81	79	101	110
125	36	34	36	35	41	42	50	48	51	50	58	58	101	96	102	100	116	117
250	42	42	42	43	47	79	58	59	59	60	65	111	117	119	119	121	131	222

A similar pattern was observed when the probes were tested in solutions containing only P or only K. As shown in Table 7, increasing P concentrations in the aqueous solution resulted in higher P readings; however, the probe also reported increasing N and K values, although neither nutrient was present in the solution. Likewise, Table 8 shows that

increasing K concentrations resulted in higher K readings, while the probe simultaneously reported increasing N and P values, despite the absence of these nutrients from the solution.

Table 7. Probe readings in response to increasing P concentrations in aqueous solutions.

Solution P (mg L^{-1})	Probe Readings																	
	P						N						K					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.9	1	0	0	1	1	0	0	0	0	0	1	0	2	1	1	2	2	1
15.6	13	9	10	10	15	21	9	7	7	7	10	15	27	19	21	20	30	42
31.2	31	20	18	22	28	26	22	14	13	16	20	18	63	41	37	45	57	52
62.5	43	43	44	45	53	53	31	31	31	32	38	38	87	87	89	91	107	107
125	54	55	56	56	63	89	39	39	40	40	45	64	109	110	113	113	126	179
250	63	61	60	71	65	178	45	44	43	51	47	127	127	123	120	142	131	200

Table 8. Probe readings in response to increasing K concentrations in aqueous solutions.

Solution K (mg L^{-1})	Probe Readings																	
	K						N						P					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.9	2	0	1	4	1	0	0	0	0	1	0	0	1	0	0	2	0	0
15.6	8	8	10	8	15	13	3	2	3	3	5	4	4	4	5	4	7	6
31.2	23	18	36	21	35	0	8	6	13	7	12	0	11	9	18	10	17	0
62.5	63	59	63	66	85	78	22	21	22	23	30	28	31	29	31	33	42	39
125	87	89	96	81	115	113	31	31	34	28	41	40	43	44	48	40	57	56
250	115	116	118	118	129	275	41	41	42	42	46	98	57	58	59	59	64	137

4. Discussion

The greenhouse experiments clearly demonstrated that the in situ, real-time probes evaluated in this study are unable to provide reliable estimates of soil N, P, and K concentrations. Indeed, no significant correlation, through statistical analysis, was found between probe readings and chemical analyses carried out in the laboratory, despite more than 160 individual determinations. Furthermore, variations in soil texture (sand versus clay-loam), soil moisture, and temperature did not improve the relationship between probe outputs and analytically determined nutrient concentrations. The field trial confirmed the greenhouse results. Under greenhouse conditions, soil moisture was maintained close to field capacity, and temperature remained relatively constant (21 °C), whereas under field conditions, soil moisture fluctuated considerably between irrigation events, and air temperatures ranged from approximately 15 °C to more than 30 °C. Despite these contrasting environmental conditions, probe performance remained unsatisfactory, indicating that the limitations observed were intrinsic to the sensing system rather than being related to specific environmental conditions. The results suggest that N, P, and K values are not measured independently. Instead, nutrient estimates may be derived from a single parameter through the application of fixed conversion coefficients. Consequently, the probes consistently maintained fixed relationships among the three reported nutrients. This hypothesis was confirmed by the results obtained in the aqueous solutions, which showed that the probes responded to dissolved ions but were unable to discriminate among individual nutrients. When the probes were tested in water, their response to dissolved ions was greater than under soil conditions, suggesting that the presence of suspended and dissolved organic

and inorganic constituents in the soil solution reduces probe sensitivity. Similar results were previously reported [12] for the same JXCT probe, where the authors hypothesized that the probes function as conductivity meters, measuring electrical conductivity (EC) and deriving ion concentrations using an equation. Nevertheless, the relationships among the N, P, and K readings were essentially the same as those observed under soil conditions. In one probe type, the ratios were approximately N:P = 1.4, K:P = 2.0, and N:K = 2.8, whereas in the second probe type, the corresponding ratios were N:P = 0.9, K:P = 1.8, and N:K = 1.7. These fixed ratios are difficult to reconcile with actual soil nutrient dynamics. In most agricultural soils, nitrate-N is typically the dominant dissolved nutrient in the soil solution, whereas P generally occurs at much lower concentrations because of precipitation and adsorption reactions involving Ca, Al, and Fe compounds. Therefore, the nearly perfect correlations observed among N, P, and K readings are not consistent with the expected behavior of these nutrients in soil. Although the objective of this study was not to compare individual probe models, the results indicate differences in sensitivity among the tested instruments. Nevertheless, all probes tested in this study exhibited the same fundamental limitation: the absence of a meaningful relationship between sensor outputs and analytically determined soil nutrient concentrations. The nearly perfect correlations observed among N, P, and K readings suggest that the probes do not measure the three nutrients independently. Rather, the outputs appear to be derived from a single measured variable and subsequently converted into N, P, and K values through fixed conversion factors.

5. Conclusions

In conclusion, these specific probes evaluated in the experimental conditions of this study were unable to provide reliable real-time, in situ measurements of soil N, P, and K concentrations. Based on the results obtained under both greenhouse and field conditions, their use for fertilizer management decisions cannot be recommended. The probes responded to changes in the ionic strength of the solution but failed to selectively identify individual nutrients, making them unsuitable for the quantitative determination of N, P, and K in either soil or aqueous solutions.

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